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Design and Analysis of a Piezoelectric Linear Motor Based on Rigid Clamping

Chao Yi, Cunyue Lu, Lingwei Quan

***Abstract*—**Piezoelectric linear motors have the characteristics of great electromagnetic compatibility, high positioning accuracy, compact structure and no deceleration mechanism, which make it promising to applicate in micro-miniature precision drive systems. However, most piezoelectric motors are employed by flexible clamping, which has insufficient rigidity and is difficult to use in rapid positioning. Another problem is that this clamping method seriously affects the vibration efficiency of the vibrating unit. In order to solve these problems, this paper proposes a piezoelectric stack linear motor based on double-end rigid clamping. First, a piezoelectric linear motor with a length of only 35.5 mm is designed. This motor is mainly composed of a motor stator, a driving foot, a ceramic friction strip, a linear guide, a pre-tightening mechanism and a base. This structure is much simpler and smaller than most similar motors, and it is easy to assemble as well as to realize precise control. In addition, the properties of piezoelectric stack are reviewed and in order to obtain the elliptic motion trajectory of the driving head, a driving scheme of the longitudinal-shear composite stack is innovatively proposed. Finally, impedance analysis and speed performance testing were performed on the piezoelectric linear motor prototype. The motor can measure speed up to 25.5 mm/s under the excitation of signal voltage of 120 V and frequency of 390 Hz. The result shows that the proposed piezoelectric stacked linear motor obtains great performance. It can run smoothly in a large speed range, which is suitable for various precision control in medical images, aerospace, precision machinery and many other fields.

***Keywords*—**Elliptical trajectory, linear motor, piezoelectric stack, rigid clamping.

I. INTRODUCTION

At present, with the rapid development of precision control in aerospace, medical imaging, bioinformatics, bionic control, these fields are in desperate need of new driving devices with higher precision to obtain higher accuracy [1]–[5]. Compared with the traditional electromagnetic motors, linear piezoelectric motors have been widely used and studied, due to their better performances such as power self-locking, compact structure, higher positioning accuracy and easy to miniaturize [6], [7].

Piezoelectric motor refers to a class of piezoelectric devices, using the inverse piezoelectric effect of piezoelectric materials. This kind of motor applies specific excitation signals on the piezoelectric elements, so that these elements can produce deformation and output the specified displacement or regular movement [8], [9]. When the regular vibration of this element is used for continuous output, this element could constitute a piezoelectric motor [10]. According to different working modes, linear piezoelectric motors can be divided into resonant and non-resonant linear motors [11].

Nowadays, there are several commercially available piezoelectric motor products, such as the linear motor manufactured by Nanomotion Ltd. This product adopts the composite resonance mode of longitudinal mode and bending mode as the working mode. However, the resonance mode is not stable, and the natural frequency of stator is easily influenced by the temperature change and leads to drift. These problems adversely affect the performance of the motor [12].

Till now, many achievements have been made in Chinese researches on non-resonant linear motors which have the advantages of large input force and high bidirectional repetition accuracy. But, such motors are difficult in clamping [13], [14]. In addition, most commercial piezoelectric actuators choose to adopt flexible clamping mode. Due to the lack of rigidity in the flexible clamping mode, these actuators even with high cost are hard to be used in rapid positioning. Besides, the positioning accuracy will also be affected by the flexible parts and the structure will be too complex to install. Another problem is that the clamping will seriously influence the vibration efficiency of the vibrating body.

In this paper, a non-resonant piezoelectric linear motor with two rigid ends is proposed, based on the characteristics of piezoelectric stack. It is suitable for ultra-precise positioning which needs to provide large stiffness and driving force.

II. BASIC CHARACTERISTICS OF PIEZOELECTRIC STACK

A. Vibration Mode of Piezoelectric Ceramic

The inverse piezoelectric effect d_{33} and d_{15} is usually used when piezoelectric motors are excited to vibrate [15]. When the electric field is applied to the polarization direction of piezoelectric ceramic, under the action of d_{33} inverse piezoelectric effect, the ceramic will produce the deformation parallel to the polarization direction as shown in Fig. 1. This effect is widely used in various piezoelectric ceramic transducers. By using the inverse piezoelectric effect of piezoelectric ceramics, the ultrasonic linear motor based on Langevin bending transducer was developed by Canon Inc. This motor was commercialized in 1990 to apply in the focusing system of camera lenses [15].

When the applied electric field is perpendicular to the polarization direction of piezoelectric ceramic, the

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piezoelectric ceramic will produce the tangential deformation, as shown in Fig. 2, under the action of the inverse piezoelectric effect of the constant d_{15}. Usually the piezoelectric strain constant value of the piezoelectric strain constant d_{15} is about 2-3 times larger than the value of d_{33} [15]. Using the d_{15} mode can enhance stator amplitude and improve motor performance, but at the same time, it makes the motor manufacturing process more difficult. At present, the piezoelectric motors based on d_{15} inverse piezoelectric effect have not been widely used. Therefore, to solve this problem, this paper innovatively proposed a strategy based on longitudinal shear composite piezoelectric stack motor.

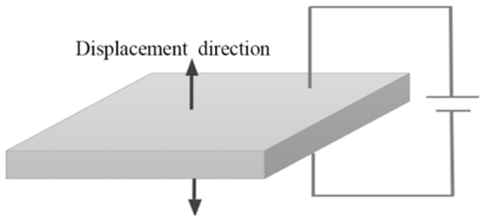


Fig. 1 The deformation direction of d_{33} mode

B. Displacement Characteristics of Piezoelectric Stack

Piezoelectric stack has the advantages of large output force in non-resonant state, large deformation displacement and good position repeatability, which is based on the principle of physical series and electrical parallel connection of piezoelectric ceramic sheets, and realize the effect of output amplitude superposition of piezoelectric ceramic.

Fig. 3 shows that the piezoelectric stack consists of piezoelectric ceramic sheets, insulators and electrodes. The layers of piezoelectric ceramic sheets are insulated from each other. Table I shows the basic parameters of piezoelectric stack used in this paper.

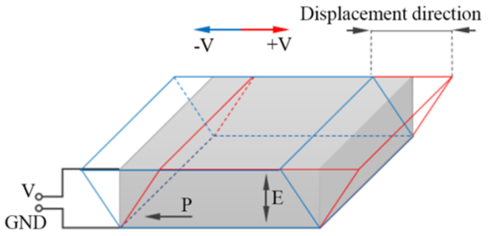


Fig. 2 The deformation direction of d_{15} mode

The deformation displacement of the longitudinal elements and shear elements of piezoelectric stack can be expressed as the following formulae.

$$\Delta x = d_{33}U = l_1 d_{33}E \tag{1a}$$

$$\Delta y = d_{15}U = l_2 d_{15}E \tag{1b}$$

Among the formulae, Δx means the longitudinal deformation and Δy means the shear deformation. l_1 and l_2 represent the length of longitudinal stack and shear stack, respectively. Besides, E is the electric field intensity and U is the voltage applied to ends of stack.

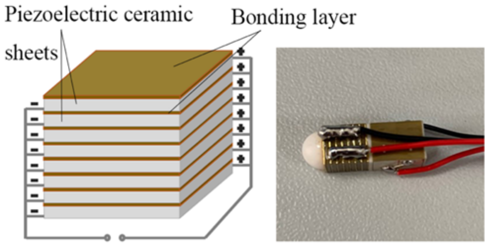


Fig. 3 Construction principle and diagram of piezoelectric stack

Because of the characteristic of piezoelectric stack, when using the piezoelectric stack to excite the linear piezoelectric motor, the stator does not need to work in the resonance state to push the load movement, which broadens the working frequency of the motor.

TABLE I
THE PRINCIPLE PARAMETERS OF PIEZOELECTRIC STACKS

	Longitudinal Stack	Shear Stack
Size	5.0×5.0×6.0 mm	5.0×5.0×6.0 mm
Piezoelectric Constant	d_{33}: 710pC/N	d_{15}: 900pC/N
Displacement	7.0 μm ± 20%	7.0 μm ± 20%
Material	THP51	THP51
Driving voltage	0-150 V	± 200 V

III. MOTOR STRUCTURE AND MOTION PRINCIPLE

A. Motor Structure

The motor stator shown in Fig. 4 consists of two composite piezoelectric stacks and a driving foot. Each composite stack consists of a piezoelectric ceramic longitudinal stack and a shear stack. The installation structure of the left and right composite stacks is completely symmetrical. And the double-end rigid installation is realized by the hard connection of the end hemisphere on the installation base, which is conducive to the uniform distribution of external forces on the installation surface of the stack. The elastic element is mounted between the base and the contact head for counteracting the reaction force when the head is driven.

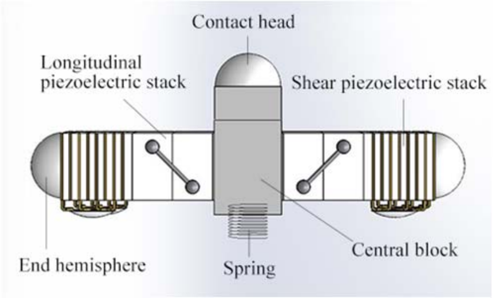


Fig. 4 Schematic diagram of motor stator

The designed platform of the linear motor is shown in Fig. 5, which includes the piezoelectric linear motor, friction ceramic strip, a cross roller guide and a linear grating ruler, in which the linear grating ruler is used to measure the speed of the motor. In order to avoid the frictional slip between the stator and the mover, a flexible hinge structure is designed to provide elastic support. The total length of the motor in this paper is only 35.5 mm, and the diameter of the vibrator is 5 mm. The miniature degree of the structure exceeds that of most similar linear motors.

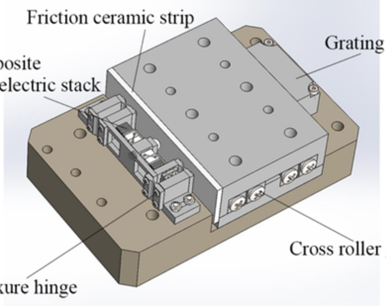


Fig. 5 The platform of the designed linear motor

B. Motion Principle

Fig. 6 shows the four operating states of a piezoelectric linear motor. There are four groups of piezoelectric stacks used in the stator, which are indicated by serial numbers from 1 to 4. Among them, stack 1 and stack 4 are piezoelectric ceramic shear deformation segments, and stack 2 and stack 3 are longitudinal deformation segments. When the shear stack 1 and stack 4 are synchronized in the exciting electric field, actuator will arch or sag, thereby causing the driving head to contact with or disengage from the driven object. When the longitudinal stack produces an opposite longitudinal deformation under the action of an opposite phase of the excitation electric field, the actuator is laterally displaced. However, the lateral total length of the actuator is constant, which keeps the constant pre-pressure.

When the phase difference between the excitation signal applied by the longitudinal deformation segment and the excitation signal applied on the shear deformation segment is close to 90 degrees, a certain driving point on the driving head generates an ellipsoid of motion. The driving head produces a continuous motion by frictionally driving the moving parts that are in contact with. The longitudinal shear composite deformation piezoelectric ceramic actuator can be used as an actuator as well as a motor by continuous deformation.

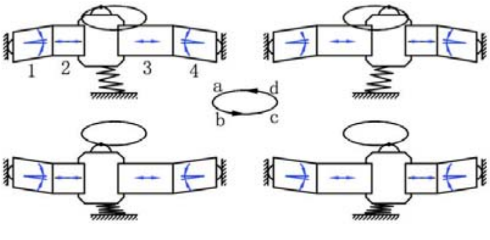


Fig. 6 Working state of the piezoelectric linear motor

IV. Experimental Study on the Designed Piezoelectric Linear Motor

A. Prototype of Piezoelectric Linear Motor

According to the motion principle and structural design of the motor, a prototype shown in the Fig. 7 was produced. The outer dimension of the piezoelectric stack composite unit is 5 mm × 5 mm × 12 mm with a total motor length of 35.5 mm.

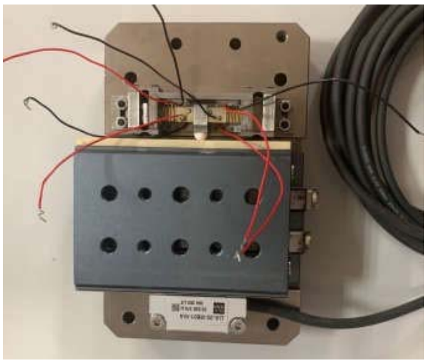
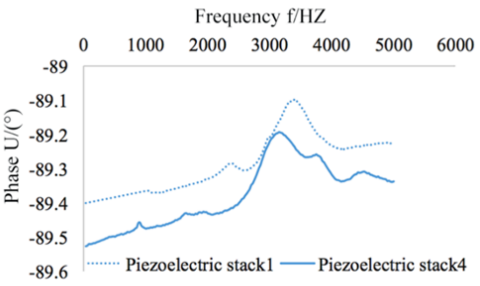


Fig. 7 Prototype of the designed motor

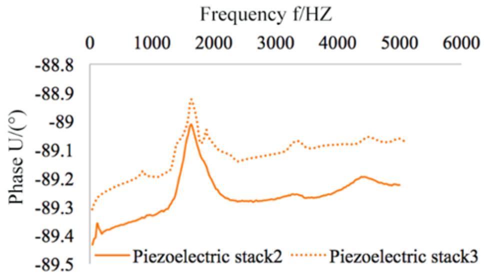
B. Impedance Analysis of the Piezoelectric Linear Motor

Based on the operating mechanism of the non-resonant piezoelectric motor, the resonant frequency of the piezoelectric stack should be avoided as much as possible during operation. In this paper, impedance test of four piezoelectric stacks is performed using an impedance analyzer model WK6500B. Resonance frequency point is determined by scanning from low frequency to high frequency, afterwards determining the frequency range in which the piezoelectric linear motor operates smoothly. The results of this experiment are shown in Fig. 8.

After the frequency scanning of two longitudinal stacks and two shear stacks, it can be concluded that the resonance frequency of longitudinal stacks is around 1600 Hz and the resonance frequency of shear stacks is around 3000 Hz. To ensure the working performance of non-resonant piezoelectric linear motor, the working frequency of the motor should be far from this frequency range. Besides, the characteristic of piezoelectric stack determines that the operating frequency cannot be too high. Except for the frequency limitation, it is also easy to occur material breakdown, overheating and depolarization when the current is too large. So in this paper, the operating frequency is set under 500 Hz.



(a) Longitudinal stack



(b) Shear stack

Fig. 8 Frequency sweeping result of the stator

C. Test of Speed Characteristic

The experimental device for the speed test of the piezoelectric linear motor is shown in the Fig. 9. We set the voltage at 120 V and adjust the signal generator to output different frequencies. Under this condition, the different motor speed performance is tested by using the grating ruler as well as the oscilloscope, the resolution of the grating ruler is 5 μm.

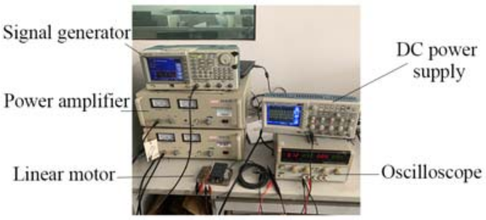


Fig. 9 Experimental device

The obtained velocity-frequency curve is shown in Fig. 10. From this figure, it is concluded that this linear motor can smoothly run in the selected frequency range and the speed response is relatively ideal. Its performance is well in low frequency. But the problem within the experiment is that the motor is slightly hot when the frequency is high.

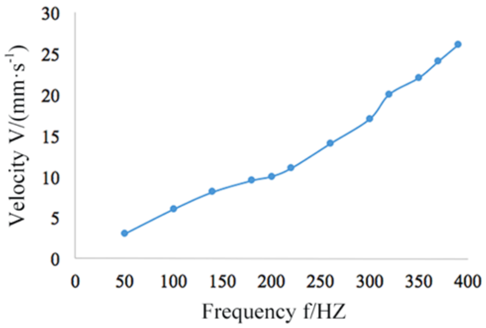


Fig. 10 Velocity-frequency curve of motor

V. CONCLUSION

In this paper, a non-resonant piezoelectric stacked linear motor is proposed, based on the composition of longitudinal and shear stacks. After analyzing the basic characteristics of the piezoelectric stack, a piezoelectric linear motor with a length of only 35.5 mm was designed. Its structure is simpler and smaller than most similar motors and it is easy to assemble and can obtain precise control. In addition, shear stack was innovatively used for non-resonant linear motors, and the amplitude of the inverse piezoelectric effect based on the constant d_{15} is greater than the amplitude based on d_{33}. All of these designs improve the motor performance. The designed motor also achieved speed of 25.5 m/s with the voltage 120 V and the frequency 390 Hz. It obtained good dynamic performance, smooth operation and a large dynamic speed range, which is suitable for the precision control in fields like medical images and bionic control. In the later stage, it is necessary to carry out further study on piezoelectric ceramic materials and heat dissipation device to make the motor applying in high frequency workplaces.

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