A Linear Ultrasonic Motor for Positioning Stages

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Abstract: In this paper, a linear ultrasonic motor for the positioning of stages was described. The positioning stage driven by the linear ultrasonic motor has a very simple and compact structure, which consists of a linear guide and the linear ultrasonic motor. The linear ultrasonic motor is just a 50 mm x10 mm x 3mm rectangular plate. Quick response, high resolution and large working range are the attractive characteristics of this new type of linear positioning stages. The testing results are: moving range 200 mm (variable depending on the linear guide), no-load speed 40 mm/s, ratings 21mm/s/200gf, holding force 600gf, starting thrust 450gf, resolution <60nm, response time of 12ms from stationary status to constant velocity (40mm/s) with a initial mass of 150g.

Key words: piezoelectric elements, linear ultrasonic motor, positioning stage

1. Introduction

The conventional linear positioning stage is normally driven by a stepping motor. Therefore, a ball screw mechanism is required to transform the rotary motion into linear motion. In order to overcome the drawback of existing linear stages such as backlash, complex structure and low rigidity, we turn to the family of linear ultrasonic motors for direct actuation of the linear positioning stages. Some desirable characteristics of ultrasonic motors like high torque densities at low speed, fast response, self locking, flexibility in the structural design, etc. [1, 5] make them the legitimate candidate for hi-resolution and long-travel intermittence motion generating purposes. Several types of linear ultrasonic motors have been developed: e.g., traveling wave-type linear ultrasonic motors [2, 3], hybrid transducer-type linear ultrasonic motors [4] and linear ultrasonic motors using multi-mode vibrators. The linear ultrasonic motors in literatures require two transducers or two groups of piezoelectric elements to operate and possess complex structures.

The multi-mode vibrator type linear motors which are driven by a single phase standing wave, have simpler structure. However two vibration modes must be simultaneously excited to make this linear ultrasonic motor work, and the dimensions of the elements of the multi-mode linear motors must be strictly designed to harmonize the eigenfrequencies of the two vibration modes [1]. Hence, the flexibility of the design of this linear motor is not enough to suit various linear guides.

In this paper we use a standing wave linear ultrasonic motor to act as the direct actuator of the linear positioning stage. This linear ultrasonic motor is simple in structure, just a 50 mm x10 mm x 3mm rectangular plate type vibrator, and requires only one standing wave to function. The linear positioning stage that employs this new standing wave linear ultrasonic motor consists of a linear guide, a linear ultrasonic motor vibrator which is mounted onto the slider of the linear guide and a plate of frictional material attached beneath the guide rail. Notable advantages of the new stage are as follows: simple and compact structure, direct driving with no backlash, quick response, high rigidity, high resolution, infinite working range which depends only on the linear guide used. An x-y positioning table can be created by arranging three of this individual linear guide perpendicularly.

2. Design of the linear ultrasonic motor

2.1. Mechanism of the linear ultrasonic motor

Ultrasonic motor works using the mechanical vibration energy produced by the anti-piezoelectric effect of the piezoceramic. Generally in a ultrasonic motor a plate of frictional material is required to be pressed on the vibrator to transform the mechanical vibration into actuating force or torque. The linear ultrasonic motor described in this paper consists of a rectangular vibrator plate that has three teeth on one side and a piezoceramic plate bonded on the other as shown in figure 1.

The teeth are used to amplify the vibration. A pre-load is applied on the vibrator by pressing it against a plate of frictional material which is mounted beneath the linear guide rail.

When AC voltage is applied onto the piezoceramic in the ultrasonic frequency range, a standing wave will be excited in the vibrator as shown in figure 2 and the particles on the surface of the teeth will form diagonal motion.

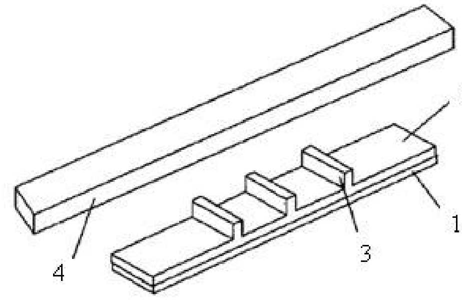

Fig.1. The liniar ultrasonic motor: 1- piezoceramic plate; 2- rectangular vibrator plate; 3- teeth; 4 frictional material.

The diagonal motion will be transformed into frictional thrust force onto the vibrator by the frictional material. Pushed by the thrust force the vibrator will move along the frictional material plate. Forward and back motion of the vibrator can be achieved by allowing the vibrator to resonate in mode(5,0) or mode(6,0) respectively. For instance, in fig.2, a) all teeth are on the left of the standing wave crests. When the standing wave of mode(5,0) is excited the particles on the surface of the teeth will form a left diagonal motion which makes the vibrator advance in the x-direction. Vice versa as illustrated in fig.2, b), when the standing wave of mode(6,0) is excited, teeth on the right of the wave crests will momentarily y form right diagonal motion.

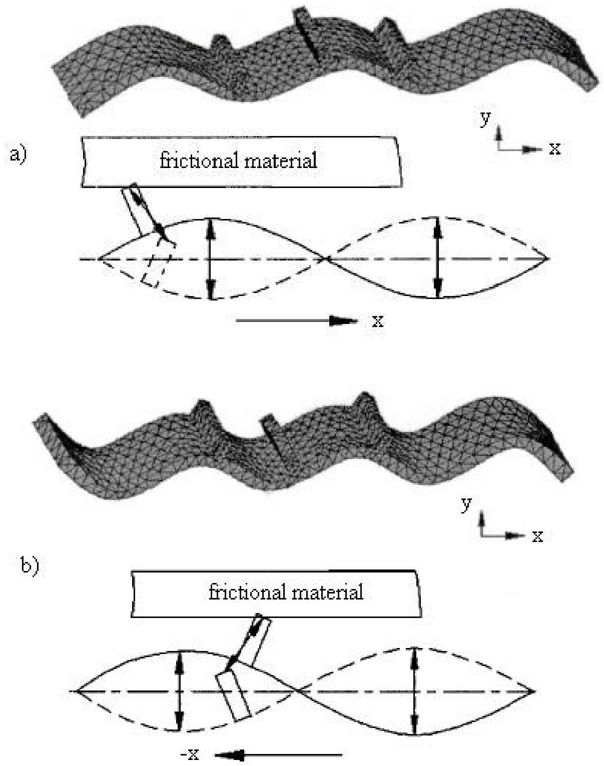

Fig.2. Direction moving achieved by different vibration mode: a) – vibration mode (5, 0); b)- vibration mode (6, 0).

This time, the vibrator will move in the negative xdirection. Here we will take the vibration mode(5,0) as an example to simply demonstrate how the particles of the teeth form the diagonal motion. The standing wave can be expressed as:

$$y = A\sin\left(\frac{x}{\lambda}2\pi\right)\sin(\omega t) \qquad (1)$$

where A, λ and ω represent vibration amplitude, the wave length and the angular frequency, respectively. Assuming the teeth are stiff enough to be perpendicular to the contour of the standing wave, we can obtain the trajectory of the particles on the surface of the teeth:

$$\begin{cases} \Delta x_M = K_x \sin(\omega t) \\ \Delta y_M = Ky \sin(\omega t) \end{cases} \qquad (2)$$

where:

$$K_x = -LA\frac{2\pi}{\lambda}\cos\left(\frac{x_M}{\lambda}2\pi\right); \quad K_y = A\sin\left(\frac{x_M}{\lambda}2\pi\right)$$

and L is the heigh of the teeth, x_M is the position of the teeth along x – axis. Since the teeth are on the left of wave crests, we have:

$$\cos\left(\frac{x_M}{\lambda}2\pi\right) > 0; \quad \sin\left(\frac{x_M}{\lambda}2\pi\right) > 0 \qquad (3)$$

hence: $K_x<0$ and $K_y>0$

Therefore, equation (2) represents the left diagonal motion. In the same way we can obtain the same motion equation for the particles of the teeth in fig.2, b). The motion equation is the same as equation (2) derived above. Since the teeth are now on the right side of the wave crests, we have:

$$\cos\left(\frac{x_M}{\lambda}2\pi\right) < 0; \quad \sin\left(\frac{x_M}{\lambda}2\pi\right) > 0 \qquad (4)$$

$K_x > 0$ and $K_y > 0$

This equation represents right diagonal motion of lhe teeth.

2.2. Design of the linear ultrasonic motor

According to the principle of the linear ultrasonic motor demonstrated above, the key of designing lies in the determination of the positions of the teeth. It means to find out the zones to put teeth in, which are on the left of the wave crests of the standing wave mode (5,0) and also on the right of the wave crests of mode (6,0). We used the software ANSYS5.5 to compute the vibration models and resonant frequencies. The material parameters of the elements are shown in Table 1.

Table 1

Element	Steel	Piezoceramic
Mass Density (Kg/m^3)	7,8	7,5
Poisson Ration	0,33	-
Yong`s Modulus (Gpa)	210	-
s_{11}^D (x 10^{-12}m^2/N)	-	12.5
s_{12}^D (x 10^{-12}m^2/N)	-	-4,125
g_{31} (V m/N)	-	0,01139
β_{33}^T (x 10^8 m/F)	-	1,1309

where s_{11}^D, s_{12}^D, g_{31}, β_{33}^T are piezoelectric parameters of the, piezoceramic. The calculated frequencies of mode(5,0) and mode(6,) by ANSYS5.5 are 27 KHz and 37 KHz. According to the vibration model by FEM we select three proper zones to put three teeth as shown in fig. 2.

The linear positioning stage using the piezo-on-slider type linear USM consists of a linear guide, a rectangular vibrator and a plate of frictional material as shown in figure 3.

The vibrator is a rectangular thin plate that can be designed to fit onto the slider of various commercially available linear guides. A thin plate of frictional material is mounted beneath the guide rail. This plate of friction material plays the role of the stator by which the vibrator will be in constant contact with. Since the driving mechanism is by friction, springs are utilized to provide pre-load pressure onto the vibrator. When voltage is applied to the vibrator, it will be forced to propel forward or backward along the guide rail by the frictional forces.

The positioning stage looks completely like a linear guide that can generate motion by itself. It is extremely convenient to install or un-install the stage.

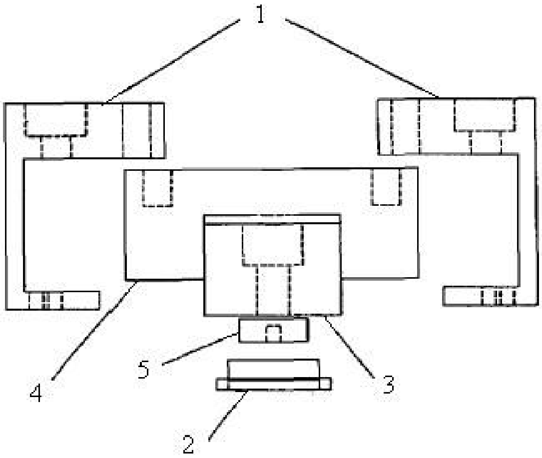

Fig. 3 Installation of the linear positioning stage:
1 – support; 2 – linear ultrasonic motor; 3 – rail; 4 – slider; 5 – frictional material.

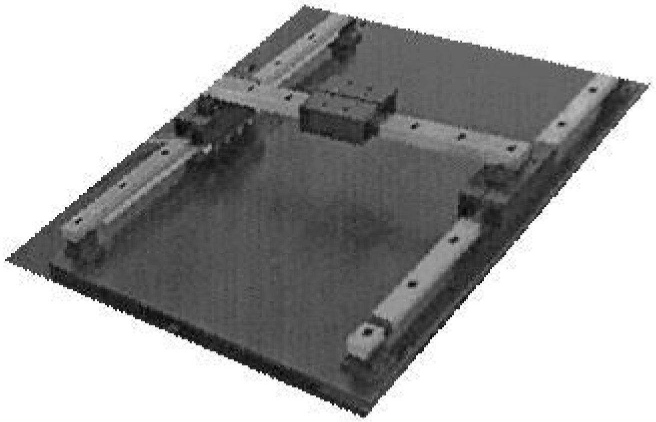

Fig.4. X-Y positioning table

Furthermore the moving accuracy is completely dependent on the linear guides used. Using three of these linear positioning stages, we are able to build a x-y positioning table as shown in figure.4. External circuit is used to regulate the input frequency and voltage for the control of the positioning stage.

3. Experimental results

The fundamental characteristics of the linear positioning stage have been tested. The experimental resonant frequencies mode(5,0) and mode(6,0) are 31 kHz and 22 kHz respectively. The tested frequencies are lower than that of calculation by ANSYS5.5. This is mainly due to the bonding of the piezoceramic. The epoxy layer will reduce the rigidity of the vibrator. The relation between driving speed and the thrust force can be measured by an evaluation system as follows.Normal force is being kept constant when the actuator is statically pressed onto the friction material by the springs. The driving speed can then be determined by the relative speed measurement of the slider loaded with weights equivalent to the driving force. Figure 5 represent the experimental results between the thrust force vs the driving speed. The straight-line graph resembles the characteristics of a DC motor. The graph indicates that when the thrust force is 300gf, the speed is approximately 23mms-]. The starting and holding force were also tested and was found to be around 500gf and 700gf respectively.

A laser displacement sensor was put to use to determine the resolution of the positioning stage. By controlling the period of the input signal and detecting the displacement of the slider, we can then ascertain the resolution of the positioning stage. Results are displayed in figure6. The x- axis denotes the time per step and the y - axis denotes the maximum displacement in one step. The highest achievable resolution was found to be 40 nm when the time per step is 0,12ms.

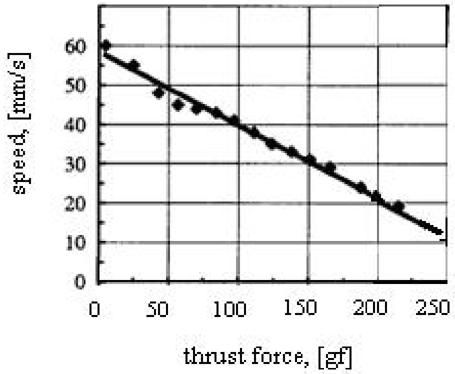

Fig. 5 Relationship of speed vs thrust force

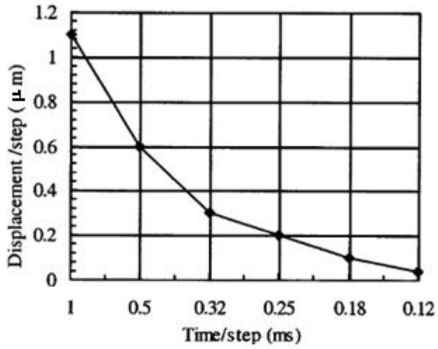

Fig.6 The resolution of the positioning stage.

An accelerometer was utilized to test the response time of the stage. Whenever the slider is being actuated by an input pulse, it will first accelerate, attain constant velocity and decelerate upon the termination of the signal. By attaching the accelerometer onto the slider, we can detect this acceleration and deceleration sequence. Thus we are able to obtain the response time, defined as the time taken for the vibrator to reach constant velocity upon actuation from the oscilloscope. As illustrated in figure7, the curve on the top represents a square wave that is used to control the actuation of the stage. The curve below shows the acceleration and deceleration profile of the stage upon actuation. The downhill pulse depicts acceleration and the upward pulse denotes deceleration.

With duration from the input view of the accelerating zone it is the pulse (the uphill square pulse) till the end of the accelerating pulse (zero acceleration, constant velocity 40mm/s is achieved). The response time was found to be 12ms when 150g initial mass is mounted on the slider of the positioning stage.

4. Conclusion

Though the advantages of the linear ultrasonic motor used in this positioning stage prove to be abundant, it also has its own drawbacks. Friction wear between the stator and the vibrator increases with time. Thus a friction material with a high coefficient of friction and a high wear resistant is generally desired. Since the ultrasonic motors are direct drive motor, the pre-load pressure will influence the initial thrust force and speed of the slider. Large pre-load pressure generates higher thrust force but at the expense of a lower driving speed. Vice versa, a lower pre-load pressure results in a lower thrust force but higher driving speed. Therefore, depending on the requirements, the optimal thrust force should be adjusted accordingly. Future work will include a more thorough investigation into the relationship between the contact surface of the stator and the friction material as it plays the most crucial role in generating motion. Since vibrational motion is transmitted directly from the piezoelectric element to the stator via an epoxy interface, another area of interest will be in the bonding effect between the piezoelectric ceramic and the stator on the ultrasonic motor.

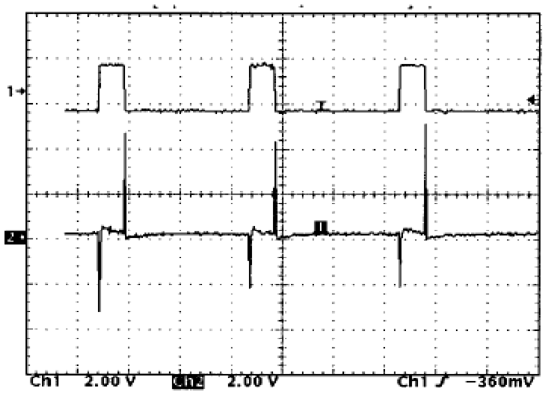

Fig. 7. The response time of the positioning stage.

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