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Nano-Positioning System Using Linear Ultrasonic Motor with "Shaking Beam"

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Abstract. In this paper the ultrasonic linear motor based on shaking beam and nano-positioning mechanical system were investigated. The advantages of the ultrasonic linear motor are high resolution, no magnetic noise generation due to the DC characteristics of the piezoelectric device, high servo rigidity, high holding torque and none additional brake system. It was confirmed that ultrasonic linear motor is suitable for nano-motion positioning with various speeds at close-loop control. The ultrasonic linear motor based on shaking beam was described and the nano-positioning systems using the ultrasonic linear motor were investigated.

Keywords: nano-positioning, ultrasonic linear motor, shaking beam, resolution

1. Introduction

High-speed and high-accuracy positioning systems are essential elements in advanced manufacturing systems such as in the semiconductor industry. Demands on new displacement transducers, which can adjust exact position or drive objects with high accuracy, have increased significantly.

An ultrasonic motor using powerful ultrasonic mechanical vibrations generate from piezoelectric actuator is an attractive device in its development and applications. It is entirely different from the present motors, which utilize interactions of electric and magnetic fields. It is generally said that ultrasonic motors have the following specific characteristics; stable operation with low velocity and high torque, which is suitable for the direct drive, quick response, and excellent controllability of starting, stopping, and reversing, small and lightweight structures, and no electronic disturbances.

There are many distinct constructions of actuators that are used to transform mechanical vibrations of piezoelectric vibrators into the linear or rotational movement of the slider [1–3]. A new idea for the elliptical trajectory formation of the actuator for piezoelectric linear ultrasonic motors is introduced in this paper. Based on the elliptical trajectory formation, a new construction of the actuator, called the "shaking beam" was developed. The elliptic trajectory of the contact point is achieved by superposing two resonance vibration modes of the actuator i.e., longitudinal and flexural vibrations. And finally, the nano-positioning system using the linear ultrasonic motor and the motion controller for nano-position were established.

2. Principle of Shaking Beam Actuator

One of the purposes of developing a new actuator was to achieve as large a traction force of the motor as possible. The traction force or rotational moment of the ultrasonic motor is proportional to the actuator held-down force to the moving element of the motor [1, 2]. However, an increase of the traction force results in the loss of the balance of interaction vibration modes used for elliptic trajectory achievement of the contact point.

We realized a new closed trajectory formation principal of the actuator. This principle is based on the

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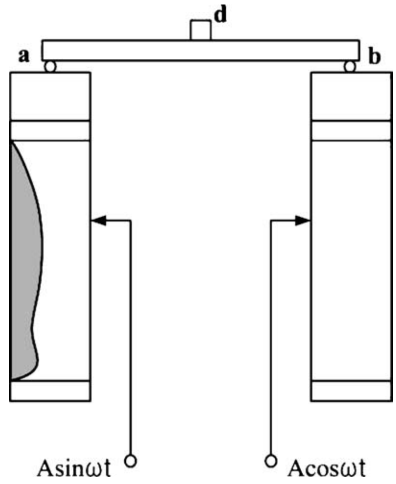

Fig. 1. Mechanical system of shaking beam.

exciting the ends of the shaking beam indicated by ab in Fig. 1 and by two sources of the harmonic vibrations that have identical frequency, but phases are different by $\pi/2$ [6].

It needs to analyze shaking beam in which free ends vibrate harmonically with the phase difference $\pi/2$. Each half wave converter which concentrates the ultrasonic vibration can be applied two sinusoidal electrical voltages such as $A \sin \omega t$ and $A \cos \omega t$.

Figure 2 shows the position of the beam through every quarter of vibration period. From movement diagrams we can see that middle point d of the beam has movement of closed trajectory and movement of the beam looks like beam shaking as Fig. 2.

If rotating or linearly moving slider would be pressed to the middle point 'd' of the shaking beam, rotational or linear vibrating motor would be obtained. The speed of the moving part of the motor depends on shaking beam's vibration amplitude, frequency, and normal pressure on the linear actuator because driving force depends on the friction between moving part and contacting part.

3. Experimental Results and Discussion

3.1. Measurement of Displacement in Shaking Beam

The measuring points of the actuator are indicated in Fig. 3 as the numbers (1–9).

The each displacement in the specified points of shaking beam was measured by laser vibration meter. The measurement of the oscillatory vibrations in the following points are shown in Fig. 4(a), where 7 is longitudinal vibrations of the right shoulder of actuator, 8 is normal components contacting with a mobile element of the actuator, and 2 is tangential components, contacting to the mobile element of the motor. Dependences are visible precisely concurrence of the maximum oscillatory speeds on working frequency of one shoulders actuator (*7*) and contacting elements (*8*). It is shown that displacement of 8 point has a good resonant condition in spite of smaller than 7 or 2 point.

The tangential component of its oscillatory speed and the motor speed can be changed according to height of contacting point as shown in Fig. 4(b). It is necessary to pay attention that the change of points 2 and 3 in the field of the work motor is identical, and that also specifies resonant properties of driving bar (contacting part).

3.2. Characteristics of the Linear Ultrasonic Motor

The ultrasonic linear motor was fabricated as Fig. 5 and its size was $40 \times 34 \times 20$ mm^3. The properties of

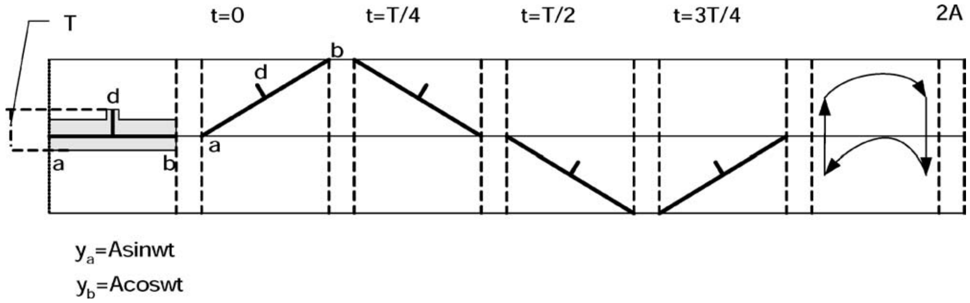

Fig. 2. Positions of the shaking beam through every quarter of the vibrations period.

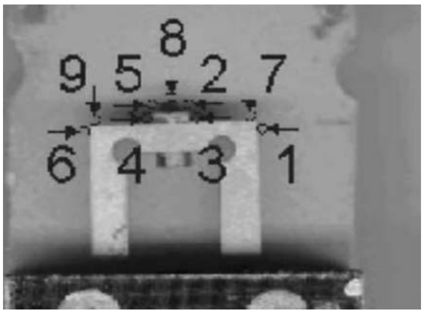

Fig. 3. Measuring points of the actuator.

the linear ultrasonic motor are dependent on the contacting materials of the moving element and the linear ultrasonic actuator. The contacting material and lining material are used alumina (Al_2O_3). The mechanical properties of the linear ultrasonic motor, such as speed and thrust force are measured in resonance condition with resonance frequency about 69 kHz, the applied voltage on ceramic depends on static pressure between the motor and alumina plate as shown on Fig. 6.

3.3. Nano-Positioning System

Nano-positioning system using the linear ultrasonic actuator was consisted of the base part (**1**) and moving part (**2**), ultrasonic linear motor (**3**), and embedded linear encoder to ensure nanometric precision as shown in Fig. 7. The nano-positioning system was designed to move one direction with respect to the fixed frame and the embedded linear encoder measured this movement and transferred data to control system. The nano-positioning system had a large stroke. For compensation of systematic and random errors we used two modes of control system, course and fine modes. Choice of them depends on moving length and can be chosen automatically by control system. If working length is long the system uses the course mode at first, i.e. continuously operating in resonant condition of ultrasonic linear motor with high speed. When movement on certain goal is approached, the system provides the fine mode, which is characterized by pulse control of ultrasonic linear motor. For decrease the random error during stop process, time delay (50 ms) between steps in pulse mode or between the course and fine modes is used. Time delay depends on the inertia of the

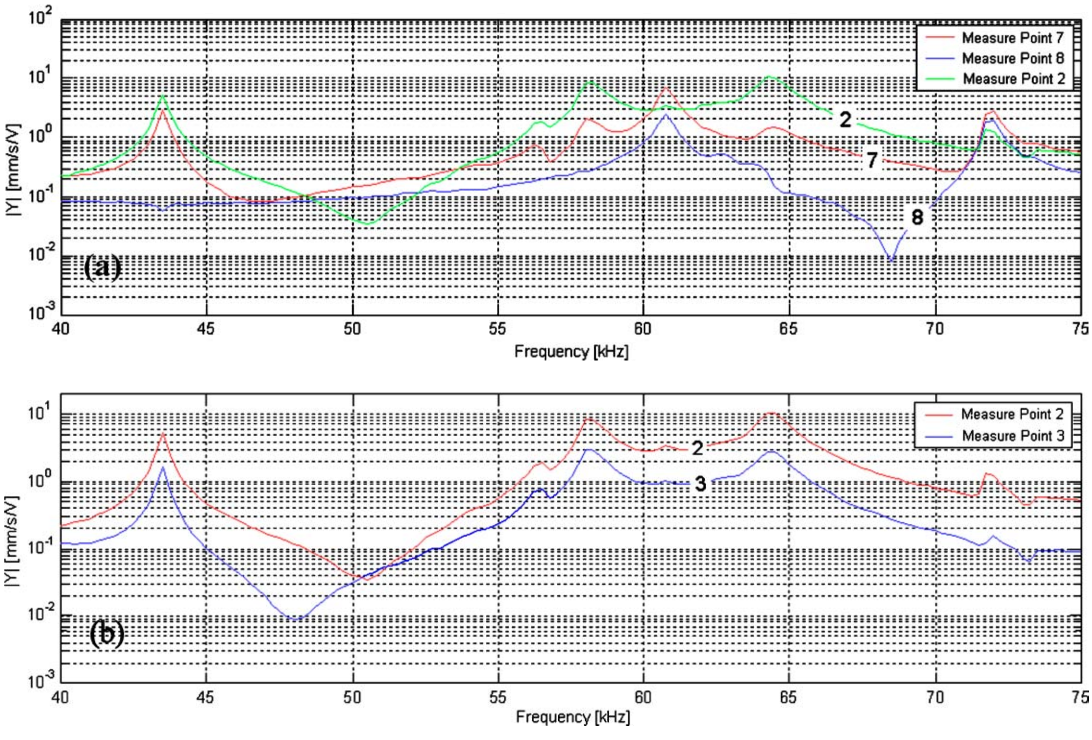

Fig. 4. Entrance admittance of measuring point of the actuator.

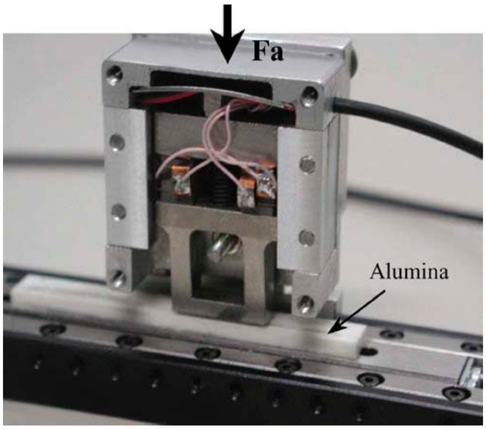

Fig. 5. The ultrasonic linear motor.

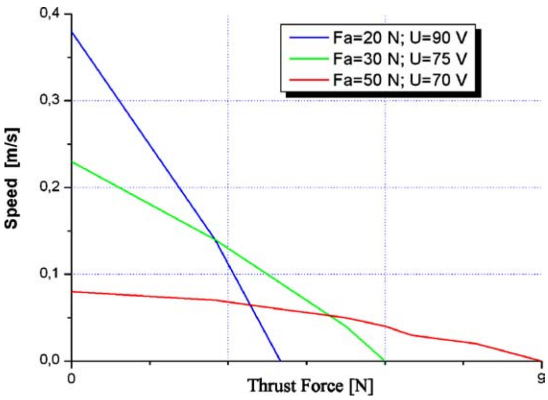

Fig. 6. The mechanical properties of the linear ultrasonic motor.

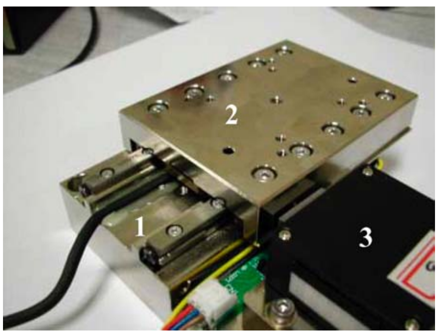

Fig. 7. Nano-positioning system.

mechanical system and in present stage is less than 10 ms. The control system uses 35 μs duty circle for control of ultrasonic linear motor in fine mode. This is approximately 2.5 period of resonant frequency of ultrasonic linear motor.

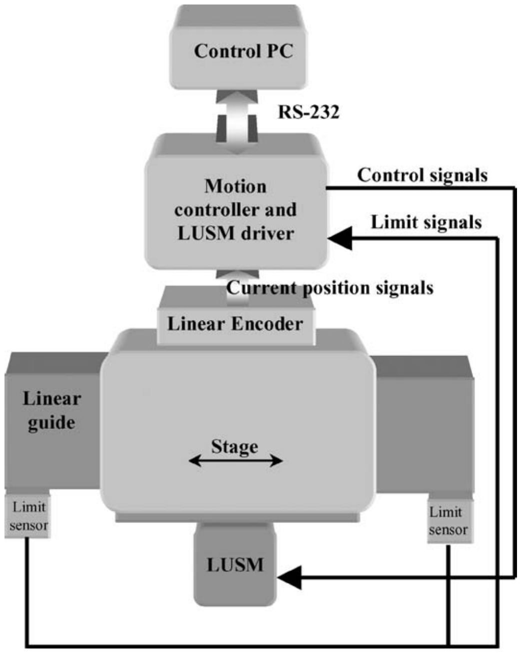

Fig. 8. Block diagram of nano-positioning system.

Block diagram of the nano-positioning system using the ultrasonic linear motor is illustrated in Fig. 8. The system is composed of the linear ultrasonic motor fixed on the stage with pre-load, linear guide, linear encoder (Canon: ML-16/80 with effective length 80 mm, linearity of 0.2 μm, 20 nm of output resolution, and 150 mm/s maximum response speed). The phase shifted sinusoidal-wave voltages are generated in the driver part of control system. Micro controller provides the speed control of the ultrasonic motor and moving stage positioning following by output data of linear encoder. This information can be displayed and controlled by PC or internal interface of motion control system. The system has maximum feeding velocity 300 mm/s at open-loop control and the feeding velocity is decreased by control system in close-loop mode.

4. Conclusions

New principle of closed trajectory formation for the linear ultrasonic motor has been developed using the shaking beam actuator. The experimental investigation of the actuator has been confirmed an opportunity to achieve elliptical trajectory with the help of the stable mode vibration. Motion controller with compensation function, which includes a PID filter followed by a low-pass filter provided the nano meter resolution of the one-directional nano-positioning system based on the linear ultrasonic motor was created.

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