Improvement of the low speed controllability of a V-shaped, two bolt-clamped Langevin-type transducer, ultrasonic linear motor

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Abstract:
A V-shaped, two bolt-clamped Langevin-type transducer, ultrasonic linear motor VSM was developed. In this study, the low speed controllability of the VSM was improved by the development of a new driving principle in which a feedback control was applied. The speed of the VSM was more than 1500mm/sec and the velocity error was approximately 0.2% when driven at 1000mm/sec. Ten nm step driving also could be obtained, and 1 nm resolution was observed. In the combination of a fast mode and a micro-motion mode, the stage was settled to a target position of ±1 nm.

1. INTRODUCTION

In semiconductor manufacturing using such techniques as Critical Dimension SEM or Electron Beam Lithography, electromagnetic noise is prevented in order to maintain or improve performance. In the further development of semiconductor manufacturing equipment, the piezoelectric ultrasonic linear motor is considered a prospective actuator that does not produce electromagnetic noise, though it requires both higher operational speeds and nanometer-order resolution. On the other hand, a light and compact driving system can be realized by using an ultrasonic motor due to its lower speed and higher thrust or torque instead of an electromagnetic motor (1,2,3).

Linear ultrasonic motors, however, have a limitation in that they cannot provide high thrust. Yun reported an ultrasonic motor design that could achieve a velocity of 0.5 m/s and a thrust of more than 100 N (4). This motor is based on the so-called L1B2 type, and uses a Langevin-type transducer which can provide high power. A drawback of this design, however, is its holding system since in principle it has a single nodal point. Thus, its settling time is relatively longer and its static stability is lower. A complex holding system has been proposed using two Langevin-type transducers that vibrate at the same frequency as the motor and is attached to the end of the motor (5).

We have previously reported a V-shaped, two bolt-clamped Langevin-type transducer, ultrasonic linear motor: the VSM (6). This motor design includes two nodal vibration points. Thus, the motor can be easily fixed and stabilized using these two points. This stable holding system is expected to result in high static stability. The speed of the motor was more than 1.5 m/s and 25 N in a same setting. In the case of a speed lower than 1 mm/s, the motion was achieved by using inertial and slip motions. A 1 nm resolution was observed using DC driving.

However, a problem arose regarding the motor’s low speed controllability. The VSM had a large voltage dead zone as well as a velocity dead zone. Sometimes reverse motion was observed under a lower driving voltage. Low speed controllability is quite important for closed loop control, thus the present study investigated the problem regarding low speed controllability.

2. A NEW DRIVING PRINCIPLE FOR THE VSM

2.1 Structure of the VSM and its previous driving principle

Fig. 1 shows the dimensions of the VSM. Two bolt-clamped Langevin-type transducers are conjoined at

![Fig. 1 Configuration of the VSM](image-url)
right angles to each other and come in contact with each other at their tips. The head block and the holding block are made of duralumin, while the bolts and nuts are made of stainless steel. The head block has a horn structure which is designed to enhance the displacement of its vibration. A piezo element consists of two pieces composed of 7-layers of co-fired piezo-ceramics called “NA” manufactured by NIHON CERATEC Corp. (Japan). “NA” is a hard piezoelectric material having the following parameters: d33 ~ 290x10-12m/V, tanδ< 0.5%, and a mechanical quality factor (Qm) ~ 1500. Phosphor bronze plates were used as electrodes. A friction material was attached to the tip of the head block.

These Two transducers were operated by applying two sine wave electric sources at the same frequency with, in principle, a 90-degree phase difference (two-phase driving). Elliptical motion was then generated at the tip of the motor.

Fig. 2 shows the voltage-speed dependency of the VSM. The weight of the moving part of the stage, which was used to measure the speed, was 1kg with a stroke of 300mm, i.e., a 1 kg stage. The minimum speed is more than 100mm/sec. When the driving voltage was decreased to under 18Vrms, the driving direction of the stage was sometimes reversed.

2.2 Motion of the VSM’s tip induced by two-phase driving.

Fig. 3 shows the motion of the VSM’s tip measured using a laser Doppler vibrometer. The driving voltage was 2Vrms. A quite flat elliptical motion is shown under the condition without a pre-load. However, linear motion was generated by applying a 3.5N pre-load. This linear motion was then tilted. Usually the direction of movement depends on the direction of rotation of the motor’s tip. On the other hand, if the tip’s motion is linear, the direction depends on the motion’s tilt angle. Moreover, the tilt angle was unstable in the experiments. Thus, this elliptical motion might be too flat to maintain at a lower driving voltage.

The speed of the VSM can also be controlled by the driving frequency or the phase difference between two driving voltages. The variation in velocity as a function of driving frequency is shown in Fig. 4. The weight of the moving part of the stage was 2.1kg and the stroke was 450mm. The slider was made of alumina. The phase shift of the two electric sources was 90 degrees. The velocity was measured at the end of the stage by applying a specific
2.3 A motion of the VSM’s tip induced by single phase driving

Fig. 6 shows the motion of the tip of the VSM under the application of a single electric source instead of two-phase voltages with 90 degree shifts, i.e., single phase driving. In this case, the motions with or without a pre-load were always linear and the tilt angle was stable. These results indicate that low speed controllability could be improved by single-source driving.

Fig. 7 shows the velocity of the VSM induced by single-source driving using a 1kg stage. In this test, reverse motion was not observed and a 30mm/sec minimum driving speed was obtained. The maximum speed was more than 1500mm/sec. This shows that a feedback control system can be designed for the VSM.

3. Characteristics of the VSM

3.1 A feedback control system for the VSM

One of the VSM’s features is that it can be driven by DC voltage. Nanometer-order resolution has been obtained by employing feedback [7]. We designed and built a feedback control system which has two modes, one being a fast mode involving single-phase driving and the other being a micro-motion mode achieved by DC driving. The fast mode is a type of PID controller which utilizes a velocity loop and a position loop with dead zone compensator [8]. A block
diagram of this mode is shown in Fig. 8. In the micro-motion mode, driving voltage is incremented or decremented by a certain value in accordance with a plus or minus sign indicating the difference between reference and current positions.

Since the stroke of the VSM driven by DC is limited, its positioning accuracy in fast mode must be greater than its stroke. Otherwise, switching from the fast mode to the micro-motion could not be realized. In addition, when displacement due to a disturbance is larger than the stroke, positioning by means of the micro-motion mode cannot be continued. Then, “inertial driving” is set to a micro-mode [7]. The VSM can be driven using inertia and friction as below. If the right side and the left side of the VSM’s piezo elements are exposed to plus and minus DC voltage, respectively, the tip of the VSM moves in the driving direction. If an acceleration of the VSM’s tip motion multiply a weight of a moving part is larger than friction force between the VSM’s tip and the slider, the VSM’s tip slips from the slider. When the one-way motion is quicker to slip while the other-way is slow to carry the slider, the VSM will be able to make the slider moving unlimitedly.

Fig. 8 Block diagram of the fast mode of the feedback control system

Fig. 9 shows an example of “inertial driving”. The moving part of the stage was 2.1kg. The slider and the tip of the motor were made of alumina and the friction coefficient between these alumina was approximately 0.2 to 0.3. The driving voltage was 80Vpp of a saw wave. When the driving voltage was increased slowly, the stage moved forward roughly 0.25 to 0.3μm, and when the driving voltage was decreased rapidly the stage reversed its direction quickly by around 0.1 to 0.2μm.

3.2 Characteristics of the VSM in the fast mode of the feedback control system

The characteristics of the VSM employing the feedback control system were measured. The stage, which was the same as that used in Fig. 7 (a 1kg-stage), and a stage whose

Fig. 10 Dynamic position error and velocity error during 1m/s driving

Fig. 11 Dynamic position error and positioning accuracy of the VSM
moving part was 10kg (a 10kg-stage), were used in this test. The position sensor was a BL55 equipped with a BD95
designed according to special specifications) made by Sony
Manufacturing Systems Corp. Its resolution is 1nm and
maximum response speed is 2m/sec.

Fig. 10 shows the dynamic positioning error and the
velocity error using the 1kg-stage in the fast mode. In
1000mm/sec driving, the dynamic positioning error was
less than ±1μm and the velocity error was less than ±0.2%.

A velocity profile and a position error using the
10kg-stage without micro-motion mode are shown in Fig.
11. The velocity profile was in the shape of an s-curve and
acceleration/deceleration was 0.5m/sec2. A positioning
error was large in the profile’s in rise and decay. The dead
zone compensation of the feedback control system did not
appear to perform as intended. The positioning accuracy was around 0.3μm. The
positioning accuracy strongly depends on the PID parameter. However, an accuracy of less than 0.3μm was
not obtained. The positioning resolution of the VSM was
then observed.

Fig. 12 shows the step motion of the VSM with the
application of a 50Vrms AC source in the form of a burst
waveform of 1.5 wavelengths. The VSM did not function
under 40Vrms and under a less than 1.0 wavelength at
50Vrms. The one-step distance was 60 to 80nm. A
positioning accuracy of 1/10 is considered a level of
resolution sufficient for driving. Therefore, a positioning
accuracy of 0.3μm was deemed reasonable.

3.3 Characteristics of the VSM in the feedback control
system’s micro-motion mode

Fig. 13 shows a 10nm step motion of the 1kg-stage, its
resolution appearing almost equal to the resolution of the
sensor.

3.4 Characteristics of the VSM in a combination of the
fast mode and the micro-motion mode

The VSM can settle a slider to a target position within
less than micrometer order in the fast mode, and can settle
within nanometer order in the micro motion mode. The
feedback control system was then set to change
automatically from the fast mode to the micro motion mode
when the position was less than 3 μm closer to the target
position.

Fig. 14 shows the positioning error of the VSM when
using the 10kg-stage. The stage was driven 100mm at a
speed of 100mm/sec and an acceleration of 0.5m/sec. The
driving mode was changed from the fast mode to the
micro-motion mode at around 1.35sec. Two-step stair-like
motions are shown in Fig. 14 in the micro-motion mode.
These motions are reverse motions in “inertial driving”. It

Fig. 12 Step Motion by applying 1.5 wave voltage

Fig. 13 10nm step motion of the stage by DC
driving

Fig. 14 Positioning error in the micro-motion mode
required a relatively long time, but finally, the stage was settle to a target position of ±1nm.

4. CONCLUSION

The low speed controllability of the VSM was improved by the investigation of a new driving principle. Two-phase driving makes the motion of the VSM’s tip elliptical but very flat and unstable at a lower driving voltage. This unstable elliptical motion can be shifted to an unstable linear tilted motion by applying a pre-load. Because of the unstable tilt angle, the driving direction of the VSM is unstable at a lower driving voltage. On the other hand, single-phase driving makes the motion of the VSM’s tip linear but stable. Thus, the direction of the VSM is stable at lower driving voltages. A maximum speed of more than 1500mm/sec was achieved by single-phase driving.

A feedback control system, which utilizes a fast mode and a micro-motion mode, was then applied to the VSM. The velocity error was around 0.2% during driving at 1000mm/sec. Ten nm step-driving was also possible, with 1nm resolution being observed. In the combination of the fast mode and the micro-motion mode, the stage was settled to a target position of ±1nm.

REFERENCES

[8] “SB1291-NM MANUAL”, pp51, NANOMOTION LTD.
Improvement of the low-speed controllability of a V-shaped, two bolt-clamped Langevin-type transducer, ultrasonic linear motor

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The low speed controllability of a V-shaped, two bolt-clamped Langevin-type transducer, ultrasonic linear motor (VSM) was improved by the development of a new driving principle. In two-phase driving, the tip motion was plani-elliptical. This elliptical motion was deformed into tilted linear motion by applying a pre-load at lower driving voltages. In addition, the tilt angle was unstable. Due to the unstable tilt angle, the driving direction of the VSM was unstable at lower driving voltages. On the other hand, single-phase driving made the VSM’s tip motion tilt consistently in a linear fashion. This tilt angle, however, was stable. Thus, the driving direction of the VSM was found to be stable at lower driving voltages. Single-phase driving achieved a maximum speed of more than 1500mm/sec. A feedback control system, which has a fast mode and a micro-motion mode, was then developed for the VSM. The velocity error was around 0.2% when driven at 1000mm/sec. Ten nm step-driving could also be obtained, with a 1nm resolution being observed. Using a combination of the fast mode and the micro-motion mode, the stage could be settled to a target position of ±1nm after traveling a certain distance.

Fig. A positioning error in the micro motion mode.