Miniaturization of a V-Shape Transducer Ultrasonic Motor

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The miniaturization of a V-shaped transducer ultrasonic motor (VSM) was carried out. The head block design and nut length were optimized to match resonance frequencies without coupling asymmetric and spurious vibrations. The volume of the new miniaturized VSM was 58% of that of the original VSM. The speed, thrust, and resolution of the new VSM compared favorably with those of the original VSM. A massive ceramics linear stage was driven by the new VSM working in the sole-use VSM feedback control system. For a traveling distance of 20 mm, the stage motion was controlled to remain in the target position plus or minus 1 nm within 350 ms.

1. Introduction

In the semiconductor manufacturing industry, the critical dimension scanning electron microscope (CD-SEM) is one of the key pieces of equipment used to inspect semiconductors. Currently, nanometer-range positioning technologies without electromagnetic noise are essential. The piezoelectric ultrasonic motor is the most suitable motor for the driving source of the positioning system, because it does not contain a magnet or a coil. In addition to this nonmagnetic feature, the use of the piezoelectric ultrasonic motor makes the positioning system simple and small, since it drives a stage directly by friction without a ball screw or a transmission. In essence, what is needed is a smaller but high-speed, high-thrust, and high-resolution ultrasonic motor. However, the trend in the investigation of ultrasonic motors is toward miniature size and small thrust. There are a few reports describing a high-thrust linear ultrasonic motor and a high-speed and large-thrust ultrasonic motor using two sandwich-type transducers has been proposed. The ultrasonic motor driving method has been improved to obtain superior performances in control systems.

In this study, we experimented with the miniaturization of an ultrasonic motor. We fabricated several massive ceramics linear stage systems driven by ultrasonic motors and used them to investigate motion control performance of the motor.

2. Miniaturization of a V-Shape Transducer Ultrasonic Motor

Figure 1 shows the configuration of the ultrasonic linear motor using V-shape two sandwich-type transducers (VSM) before we attempted to miniaturize it. The VSM has one duraluminum head block, two multi-layered piezoelectric elements, one duraluminum angled block, and two end nuts. The piezoelectric elements and the angled block were bolt clamped between the head block and the nut. The piezoelectric elements were 0.6-mm-thick seven-layer cofired elements to reduce the driving voltage. The diameter of the piezoelectric elements and the nuts was 20 mm. An alumina ceramic was glued as a friction material at the front end of the head block. The dimensions of the transducer was 122 × 67 × 20 mm3. The driving frequency was approximately 31 kHz. With a preload mechanism, the depth of the motor was approximately 130 mm. In this study, we tried to miniaturize the VSM without making the piezoelectric elements smaller, so that we were able to maintain the high power. The target size of the new VSM was two-thirds of the size of the original VSM in depth.

The VSM has two resonance modes, symmetric and asymmetric. The resonance frequencies of these two modes are required to be matched, and these frequencies can be matched by adjustment of the weight of the friction material at the front end of the head block of the VSM.

The angled block was placed around the mid position of each Langevin type transducer for fixing without inhibiting vibration. Since nut length was in inverse proportion to the acoustic velocity of the nut to maintain the nodal point of the transducer, we chose lower-acoustic-velocity material for miniaturization.

2.1 Shape of the head block

Figures 2(a) and 3 show the new trial design of the head block and VSM using the new head block, respectively. Several motors with three different nut lengths were fabricated by way of trial. Figure 4 shows the frequency difference between the symmetric mode and the asymmetric mode by adding some weight to the friction material. Two resonance modes could not be matched by changing the weight of the friction material; the weight of the front of the head block was required to be reduced to approximately 1 g.

Next, we scraped away as much of the front of the head block as possible while maintaining the thickness of the internal thread to preserve the strength of the internal thread for bolt clamping. Figure 2(b) shows the second trial design of the head block. Resonance frequency matching was examined again after nut length was adjusted.
2.2 Nut length
Phosphor bronze was chosen for the nuts instead of stainless steel, because of its high mechanical quality factor, non-magnetic characteristic, and high strength, in addition to its lower sound speed.

Figure 5 shows resonance frequencies of the three VSMs obtained by changing nut length. The dispersions of each set of resonance frequencies were not over 0.5 kHz. There were spurious vibration modes. When the nuts were 19 mm long, the spurious mode and the asymmetric mode were coupled. Nut lengths of 17 or 21 mm were suitable for avoiding the spurious mode.

Figure 6 shows the energy consumptions of several VSMs with 17-, 19-, 21-, and 23-mm nuts. The VSMs were installed on a 15 kg stage. Energy consumption was measured while the stage was driven at 200 mm/s with a feedback control system. Considering the dispersion of this measurement, the energy consumptions were not markedly different from each other. However, when the nut length was 21 mm, the energy consumption was slightly lower than that for other nut lengths. On the basis of this result, 21 mm was chosen as the nut length. Figure 7 shows the new design of the VSM.

Next, symmetric and asymmetric resonance frequencies were matched within 300 Hz with dispersion by changing the...
weight of the friction material. The final design of the VSM was $92 \times 52 \times 20 \text{mm}^3$, which was 58% of the volume of the original VSM. The driving frequency was approximately 39 kHz.

3. Characteristics of the Miniaturized VSM

The VSM has three operation modes, a fast motion mode driven by a single-phase resonance frequency, a nanometer motion mode driven by DC voltage and an inertial driving mode using low-frequency saw wave voltage for unlimited stroke motion in DC driving.\(^1^7,^1^8\)

3.1 Speed and thrust

The speed and the thrust of the VSM were estimated from the measurement of transient response by using the linear stage shown in Fig. 8. The moving part of the stage was 1 kg, the driving voltage was 100 Vrms, and the preload was 120 N. The no-load speed of the miniaturized VSM was 1.6 m/s, and the zero-speed thrust was about 40 N using one VSM, as shown in Fig. 9. The no-load speed of the original VSM was $\geq 2.0 \text{m/s}$, and the zero-speed thrust was approximately 30 N. The speed of the new VSM was lower than that of the original VSM, but might be sufficient for the precision stage.

3.2 Resolution

For precise positioning, DC driving was used. A stepping motion was observed with the feedback control system using a 10 kg ceramic stage, as shown in Fig. 10. The scale resolution was 0.2 nm. Figure 11 shows an experimental result of a 10 nm stepping motion every 1 s within 1 nm deviation. The resolution of the original VSM was also 1 nm,\(^1^7\) and thus the resolution of the new VSM was equal to that of the original VSM. The stroke of the new VSM by DC driving applied from $-150 \text{V}$ to $+150 \text{V}$ was approximately 800 nm. The sensitivity of the displacement was about 2.5 nm/V. The stroke and the sensitivity of the new VSM were also equal to those of the original VSM.

3.3 Settling characteristics of a massive stage

For the measurement of the settling characteristics, we built a sole-use feedback control system that could operate the VSM automatically, selecting the driving mode depending on the required speed and/or preciseness at an instance.\(^1^7\) A 10 kg ceramic stage was driven using the new VSM with the feedback control system. The moving part of the stage was 10 kg. The motion of the stage is shown in Fig. 12. The upper graph shows the observed position and velocity, and the lower graph shows dynamic position deviation from when the motion started to settling. For a traveling distance of 20 mm, the stage motion was controlled successfully, under control conditions of 200 mm/s maximum speed, $3 \text{m/s}^2$ acceleration, and $90 \text{m/s}^3$ acceleration differential from 0 to 228 ms in the fast motion mode. After testing under those conditions, the stage was settled using the nanometer motion mode and inertial driving mode. The precise positioning of 1 nm was carried out within 350 ms.

4. Discussion

The miniaturized VSM has a spurious mode near the driving frequency. From finite element method (FEM) analysis, we observed that in this spurious mode, the head block vibrates vertically compared with the vibration direction in the asymmetric mode. The results of FEM analysis, when the nut length was 19 mm, are shown in Fig. 13.
Assuming that each Langevin transducer is in fundamental longitudinal vibration, a nodal point can be calculated using longitudinal wave velocity and resonance frequency. From the results shown in Fig. 5, if the resonance frequencies of the VSM with 17-, 19-, 21-, and 23-mm nuts are 43, 42, 39, and 37 kHz, respectively, and the longitudinal wave velocities of duralumin and phosphor bronze are 5050, and 3450 m/s, respectively, then the positions of the nodal points can be calculated to be at 4.5, 2.2, 1.6, and 0.5 mm from the boundary between the nut and angle block, respectively. The thickness of the angle block is 5 mm. Therefore, a 19-mm nut is the most suitable length for our desired purposes. On the other hand, from the result in Fig. 6, we see that the energy consumption of the VSM with 21-mm nuts was lower than that of VSM with nuts of other lengths. If the angled block is placed closer to the mid position of each Langevin-type transducer, the energy loss due to vibration of the angle block may be smaller. However, the consumption result of the VSM with 19-mm nuts included a loss of spurious vibration. If there is another method to shift the spurious vibration frequency, another optimum nut length might be found.

The speed of the miniaturized VSM is lower than that of the original VSM. Vibration velocity is a product of displacement and frequency, and displacement and resonance frequency are in proportion and inverse proportional to the length of a vibrating body. Therefore, vibration velocities should reach almost the same value. However, the shape of the head block was changed through miniaturization. The head block has a horn structure, which enhanced the vibration displacement. This may be one of the reasons for the difference in the speed between the new and original VSMs.

The sensitivity of the displacement of the new VSM was about 2.5 nm/V, as mentioned above. Any output noise of a driver for the VSM can be suppressed under 10 mV. Without environmental disturbance, the resolution of the VSM might be finer.

5. Conclusions

The miniaturization of the VSM was carried out. The head block design and nut length were optimized to match resonance frequencies without coupling asymmetric and spurious vibrations. The volume of the miniaturized VSM was 58% of that of the original VSM. The speed, thrust, and resolution of the miniaturized VSM compared favorably with those of the original VSM. Using the sole-use feedback control system, we were able to drive a massive ceramics linear stage using the new VSM. For a traveling distance of 20 mm, the stage motion was controlled to the target position plus or minus 1 nm within 350 ms.