High speed, high resolution ultrasonic linear motor using V-shape two bolt-clamped Langevin-type transducers

Kazumasa Asumi\textsuperscript{1,2}, Ryouichi Fukunaga\textsuperscript{1}, Takeshi Fujimura\textsuperscript{1} and Minoru Kuribayashi Kurosawa\textsuperscript{2}

\textsuperscript{1}Taiheiyo-Cement Corporation, Akedori 3–24–1, Izumi-ku, Sendai, 981–3206 Japan
\textsuperscript{2}Tokyo Institute of Technology, Nagatsuta 4259, Midori-ku, Yokohama, 226–8502 Japan

(Received 9 July 2008, Accepted for publication 2 October 2008)

Abstract: An ultrasonic motor using two bolt-clamped Langevin-type transducers was described. A rigorous optimization of the motor’s structure was conducted and its results are reported in regard to various motor parameters. Based on FEM analysis and experimental results it was established that symmetric and anti-symmetric resonance frequencies could be matched by adjusting the mass of the tip of the motor’s head block. The driving voltage of the motor was reduced by using stacked multi-layered piezo-elements. The velocity of the motor fabricated in this study was more than 1.5 m/s and 25 N in a condition. However, a velocity of less than 100 mm/s could not be achieved using conventional resonance driving. In the case of a velocity lower than 1 mm/s, driving was achieved by “inertial driving.” 1.5 nm resolution was observed using DC driving.

Keywords: Ultrasonic motor, Langevin-type transducer, Resolution, Speed

PACS number: 43.38.Fx  [doi:10.1250/ast.30.180]

1. INTRODUCTION

In semiconductor manufacturing using such techniques as Critical Dimension SEM or Electron Beam Lithography, electromagnetic noise should be prevented in order to maintain or improve performance. In furthering the remarkable progress in the 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 speed and nanometer-order resolution. On the other hand, a light and compact driving system can be realized by using an ultrasonic motor instead of an electromagnetic motor, due to its lower speed and higher thrust or torque [1–4]. However, linear ultrasonic motors have a limitation in that they cannot provide high thrust. Yun reported an ultrasonic motor design that could achieve a speed of 0.5 m/s and a thrust of more than 100 N [5]. 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 position-setting time is relatively longer and its static stability is lower. A complex holding system has been proposed using two Langevin-type transducers that vibrates at the same frequency as the motor and is attached to the end of the motor [6]. Kurosawa proposed a V-shape two bolt-clamped Langevin-type transducer ultrasonic linear motor (VSM) having a speed of 3.5 m/s and thrust of 51 N [7]. There are two nodal vibration points in this motor design. 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 efficiency of this motor was reported to be more than 50% [8], and is driven by two degenerated vibration modes whose degeneration parameter is based on the length of the nuts. However, a change in nut length affects the position of the nodal point on the motor. Thus, another parameter not related to the position of the nodal points is necessary to degenerate the motor’s proper vibrations. For practical use, the realization of a lower driving voltage was also a challenge.

In this paper, some solutions regarding the motor’s practical design are presented. A more suitable optimization parameter to degenerate the motor’s proper vibrations is proposed, and multi-layered piezo stacks were applied in an attempt to decrease driving voltage.
2. PRINCIPLE AND DESIGN OF THE VSM

Figure 1 shows the configuration of the VSM. Two bolt-clamped Langevin transducers are arranged in an orthogonal geometry. The head block and holding block are made of duralumin; the bolts and nuts are made of stainless steel. The head block has a horn structure which is designed to enhance the displacement of the vibration. The piezo-element consists of a multi-layer stack of 12 disks of piezo-ceramics called “NA” manufactured by NIHON CERATEC Corp. (Japan). “NA” is a hard piezoelectric material having the following parameters: $d_{33} \sim 290 \times 10^{-12} \text{m/V}$, $\tan \delta < 0.5\%$, and mechanical quality factor ($Q_m$) $\sim 1,500$. Phosphor bronze plates are used as electrodes. A friction material is attached at the tip of the head block.

2.1. Vibration Mode Analysis by FEM

The VSM has two vibration modes [7,8]. One is a symmetric mode in which two Langevin-type transducers vibrate in phase, as shown in Fig. 2(1) and the other is an anti-symmetric mode in which two transducers vibrate in opposite phase as shown in Fig. 2(2). If a suitable design is chosen, these two resonance frequencies can be matched, resulting in the degeneration of these vibrations. At the degenerating frequency, the tip of the VSM is activated to vibrate in an elliptical motion by applying a 90-degree phase-shifted two-phase voltage. Initially, we used FEM analysis to optimize the design intended to degenerate the vibrations.

The length of “Nut (A),” the thickness of “Holding block (B),” and the length of the front edge of “Head block (C)” were chosen as the analysis parameters as defined in Fig. 1. Figures 3–5 show the results obtained from this analysis. One surface of the holding block marked by triangle in Fig. 1 was fixed as a boundary condition for this analysis. Symmetric and anti-symmetric modes were found close to the frequency of 30 kHz and the frequencies of both modes were changed by modifying the nut length. From the view point that the nodal points of the VSM should be at the holding block, the length of the nuts were

---

**Fig. 1** Configuration of the VSM.

**Fig. 2** Resonance modes of the VSM.

**Fig. 3** Nut length effect.

**Fig. 4** Holding block thickness effect.
fixed to 37 mm. From the Fig. 2, holding block looks deformed. Ideally, the vibration of a Langevin transducer in the VSM is only longitudinal mode. However, bending vibration was generated by the other Langevin transducer conjoined. Although the holding block was deformed since its bending vibration, the motion of the holding block was smallest when the nut length was 37 mm. The holding block thickness had no effect on symmetric and anti-symmetric resonance frequencies. However, by changing the length of the front edge of the head block, only the anti-symmetric resonance frequency was found to be changed while the symmetrical resonance frequency was not influenced. From the FEM analysis it was also found that the shape of the front edge of the head block did not deform, which indicated that the length of the edge of the head block can be taken as equivalent to the weight of the front edge of the head block. Thus, a suitable weight of the friction material would be almost 0 g. Moreover, the resonance frequencies were found to be insensitive to a shape of the tip of the head block. Next, the results of the FEM analysis were confirmed experimentally by changing the weight of the friction material attached to the front edge of the head block.

2.2. Resonance Frequencies Adjustment

The relation between the weight of the friction material and the symmetric and anti-symmetric resonance frequencies measured using an impedance analyzer are shown in Fig. 6. In this test, the weight of the friction material was changed by changing its size. Only the anti-symmetric resonance frequency was found to decrease by increasing the weight of the tip, which is in agreement with the results of the FEM analysis as indicated in Fig. 5. The data shown in Fig. 6 clearly indicate that the resonance frequencies can be adjusted by changing the weight of the friction material. The suitable weight of the friction material would be 0.3 g.

The dimensions of the motor determined based on FEM analysis are shown in Fig. 1. Based on the results of this experiment, 0.3 g was chosen as the weight of the friction material. Configurations of the friction materials in this paper were wagon-head with radius 2 mm and the thicknesses were changed depending on the density of the friction materials.

3. MOTOR CHARACTERISTICS

3.1. Speed

The speed of the VSM was measured using a linear stage. The weight of the moving part of the stage was 2.1 kg and the stroke was 450 mm. The slider was made of alumina. The speed was measured at the end of the stage by applying a specific voltage. The phase shift of two electric sources was 90 degrees. A friction material made from polyimide was used to keep the surface of the slider in a consistent condition. The friction coefficient was approximately 0.3 to 0.4. Ceramic is the material most commonly used for the tip of an ultrasonic motor. However, severe wear may often occur in an open-loop control. Since polyimide tip is deformable compared to ceramics in this test, tip was required appropriate exchange. A preload was applied through a coil spring. Figure 7 shows the variation of speed as a function of preload. The preload and applied voltages were changed from 29.4 N to 176.4 N and 20 V\text{rms} to 100 V\text{rms}, respectively. The speed was over 1.5 m/s at 60 V\text{rms} and over 2.0 m/s at 80 V\text{rms}. The speed of the
former VSM was around 1.5 m/s at 400 V\textsubscript{rms} when the preload was 110 N \cite{7}. The driving voltage was reduced to around 1/7 by using the multilayer piezo elements compared to the result of the former VSM.

3.2. Low Speed Characteristics

The speed of the VSM having a zirconia friction tip was evaluated. The friction coefficient was approximately 0.2 to 0.3. The result is shown in Fig. 8. In this measurement, the preload was 74 N, the driving frequency was 30.9 kHz, and the phase shift was 90 degrees. The VSM couldn’t be driven under 15 V\textsubscript{rms} and started to move at 20 V\textsubscript{rms} when the speed was more than 500 mm/s. This result shows the difficulty of lower speed controllability by using voltage control. In this section, the driving method or principle is investigated and explained.

3.2.1. Phase shift

In general, the ultrasonic motor has a dead zone, meaning that a specific voltage is essential for the motor’s activation. In order to activate the motor, a specific displacement magnitude is necessary to climb over the asperity of the contacting surface \cite{9}. If a two-phase voltage is applied (in phase or opposite phase) the symmetric or the anti-symmetric vibrations is excited. If the phase shift is between 0 and 180 degrees, both symmetric and anti-symmetric vibrations are excited. When the phase shift is closer to 0 degrees, symmetric vibrations are dominant while when the phase shift is closer to 180 degrees, anti-symmetric vibrations are dominant. Therefore, a phase shift closer to 0 degrees is required to obtain the displacement required for climbing over the asperity of the contacting surface.

Figure 9 shows the variation of the speed obtained by changing the phase shift of the applied voltage. The speed was highest at a 100 degree phase shift corresponding to 1,000 mm/s. However, the motor couldn’t be driven at a 20 degree phase shift. Thus, the minimum speed is still more than 300 mm/s.

3.2.2. Driving frequency

The variation in speed as a function of driving frequency is shown in Fig. 10. When the driving frequency was changed from the resonance frequency of the VSM to a higher frequency, the speed was found to decrease gradually. The magnitude of the speed was 130 mm/s at 32.3 kHz which decreased to 10 mm/s at 32.4 kHz. Control of the motor can be achieved more effectively by means of changing the frequency than by changing the phase shift or voltage. However, the speed was changed 120 mm/s by a small change in the frequency of 0.1 kHz and thus only frequency is not sufficient to control the speed of the VSM.

3.3. Slow Feeding

The low speed controllability of the VSM was not obtained by ordinary AC driving near the resonance frequency. Thus, investigations were carried out to discover another driving principle. Higuchi \textit{et al.} described another driving method that uses inertia and friction \cite{10,11}. In their method, a piezo actuator was attached to
a mass with a counter weight. The mass was held by friction. In the forward cycle, when the piezo actuator expands rapidly, the mass slips. On the reverse cycle, the actuator shrinks at a certain speed necessary to produce a non-slip condition to move the center of gravity. The piezo actuator moves by going over these two cycles. The VSM also can be driven using inertia and friction as below. If the right side and the left side of the piezo-elements of the VSM are exposed to plus and minus DC voltage, respectively, the tip of the VSM moves in the driving direction. If the one-way motion is quicker to slip from a slider (or a stage) while the other is slow to forward a slider (or a stage), the VSM will be able to forward a slider unlimitedly. Hereafter, this principle is referred to as “inertial driving.”

Figure 11 shows the motion of the stage obtained by inertial driving at frequencies of 1 Hz. The weight of the stage’s moving part was 2.1 kg. Pre-load was 88.2 N. The friction material of the VSM was zirconia. The applied voltage was $320 \mathrm{V}_{\text{pp}}$. When the tip of the VSM moved slowly, the stage moved forward roughly 0.5 to 0.6 µm, and when the tip moved rapidly the stage was pulled back quickly around 0.1 µm regardless of the frequency. Each forward motion can be fitted by a parabolic curve. The displacements of the VSM’s tip calculated by using a piezoelectric constant were around 0.8 µm at $320 \mathrm{V}_{\text{pp}}$. The experimental displacement was slightly smaller than the calculated value, which may be caused by forward slip.

Figure 12 shows the variation of the speed achieved by inertial driving at $320 \mathrm{V}_{\text{pp}}$ as a function of the driving frequency from 0.2 Hz to 500 Hz. The velocities were proportional to the frequencies.

3.4. Positioning

One of the unique features of the VSM is a small displacement obtained by applying DC voltage. Resolution was measured using a capacitance-type gap sensor on the linear stage. We used an ADE 3401-RA2 as the gap sensor and a NIHON CERATECH MT-3200 as a feedback controller which is exclusive to a piezo actuator. The reference position and the experimental position for 1.5 nm step motions are shown in Fig. 13, respectively. The gray lines indicate the reference position while the black lines indicate the experimental position. These results show that the resolution was at least 1.5 nm.

3.5. Efficiency

Figure 14 shows the speed and the efficiency of the VSM. Since wear toughness of Si$_3$O$_4$ is better than ZrO$_2$ and polyimide is impractical because of its deformable characteristics, Si$_3$N$_4$ was chosen as a friction tip in this test. The friction coefficient was approximately 0.25 to 0.35. In this measurement, the preload was 79 N and the driving voltage was $80 \mathrm{V}_{\text{rms}}$. Thrust was calculated based on the acceleration and weight of the stage. The weight of the moving part of the stage was 1.0 kg. Input voltage and
current were stored using a data logger. Electric power was calculated as the averages of the products of voltage and current every 200 ns. The speed was more than 1,500 mm/s when the thrust was 10 N, and the thrust was around 27 N when the speed was 55 mm/s. Because of the limitation of the travel distance of the stage, the saturated speed couldn’t be observed. When the speed was lower than 50 mm/s, the thrust was smaller than maximum. The friction force between the tip and the slider was not over 30 N, since the preload multiply friction coefficient was less than 30 N. Consequently, slip happened the starting up of the transient motion of the test to evaluate the speed-thrust characteristics of the motor. Because of the slip, the thrust when the speed less than 50 mm/s was considered to be smaller than maximum. The efficiency when the thrust was 10 N to 15 N was maximum and was around 6%. The efficiency of the former VSM was more than 10% [7]. The efficiency of the motor was lower than Kurosawa’s result [8], which may be explained by the preload not being optimized for this motor in this test.

4. DISCUSSION

The VSM’s low speed controllability was a problem since a feedback control system cannot be used to drive it. This problem resulted from the aspect ratio of the elliptic motion of the VSM’s tip being quite large. When the vibration amplitude is sufficient to climb over the roughness of the contacting surface, the amplitude of the feeding direction vibration is quite large. In order to drive the VSM using feedback control, only the vibration amplitude perpendicular to the slider’s surface should be enhanced. By adjusting the phase shift of two electric sources or the driving frequency, the vibration amplitude perpendicular to the slider’s surface could not be obtained.

5. CONCLUSION

An ultrasonic linear motor using two bolt-clamped, Langevin-type transducers was investigated in terms of its structural parameters. Symmetric and anti-symmetric resonance frequencies can be matched by adjusting the weight of the friction material at the tip of the VSM’s head block. The driving voltage was decreased by using multilayer piezo disks. The speed of the motor fabricated in this study was 1.5 m/s at 60 V_{rms} and 2 m/s at 80 V_{rms}. Low speed controllability under 100 mm/s was not achieved by conventional AC driving near the resonance frequency. A speed of less than 1 mm/s was achieved by “inertial driving.” Nanometer positioning can be obtained by DC driving using a feedback control system with a resolution of 1.5 nm.

REFERENCES


Kazumasa Asumi received his M.E. degree from Tokyo Institute of Technology in 1990. He is currently a chief research scientist at Taiheiyo-cement Corp. His research topics are piezoelectric materials and their applications. He is also a doctoral student in the Department of Information Processing, Interdisciplinary Graduate School of Engineering, Tokyo Institute of Technology.

Ryouichi Fukunaga was born in Kochi, Japan in 1972. He received his M.S. degree from Osaka University in 1998. He worked at Taiheiyo Cement Corporation. His research interests are ultrasonic motor, such as a rectangular plate type ultrasonic motor using a double mode piezoelectric vibration of first longitudinal and second bending modes.

Takeshi Fujimura graduated from Department of Electrical Engineering, Nagaoka University of Technology in 1988 and received a M. Eng. degree from Department of Electrical Engineering, Nagaoka University of Technology in 1990. He is currently a chief research scientist at Taiheiyo-cement Corp. His research topics are electronic circuit design and motion control software.

Minoru Kuribayashi Kurosawa (formerly Kuribayashi) was born in Nagano, Japan, on April 24, 1959. He received the B. Eng. Degree in electrical and electronic engineering, and the M. Eng. and D. Eng. degrees from Tokyo Institute of Technology, Tokyo, in 1982, 1984, and 1990, respectively. Beginning in 1984, he was a research associate at the Precision and Intelligence Laboratory, Tokyo Institute of Technology, Yokohama, Japan. From 1992, he was an associate professor at the Department of Precision Machinery Engineering, Graduate School of Engineering, The University of Tokyo, Tokyo, Japan. Since 1999, he has been an associate professor in the Department of Advanced Applied Electronics, then Department of Information Processing, Interdisciplinary Graduate School of Engineering, Tokyo Institute of Technology, Yokohama, Japan. His current research interests include ultrasonic motors, micro actuators, PZT film and its application to ultrasonic transducers, SAW actuators, and single bit digital signal processing and its application. Dr. Kurosawa is a member of the Institute of Electronics Information and Communication Engineers, the Acoustical Society of Japan, IEEE, Material Research Society, the Institute of Electrical Engineers of Japan, and the Japan Society for Precision Engineering.