Ultrasonic Linear Motor Using Surface Acoustic Waves

Minoru Kurosawa, *Member, IEEE,* Masakazu Takahashi, and Toshiro Higuchi, *Member, IEEE*

Abstract—**The first success in the operation of an ultrasonic linear motor at HF band driving frequency using the Rayleigh wave is described. The substrate material is a 127.8° Y-cut LiNbO$_3$ wafer whose diameter is three inches. Four interdigital transducers (IDT's) are arranged to excite x- and y-propagation waves in both directions. The dimensions of the IDT are 25 mm aperture size, 400 μm pitch, 100 μm strip width, and 10 pairs. The operation area is about 25 mm square. The driving frequency is about 9.6 MHz in the x direction and about 9.1 MHz in the y direction. The most important point of the success is the shape of the contact surface and slider materials. For the contact materials, small balls about 1 mm in diameter are introduced to obtain sufficient contact pressure around 100 MPa. The use of ruby balls, steel balls, and tungsten carbide balls is investigated. Each slider has three balls to enable stable contact at three points. The maximum transfer speed is about 20 cm/s. The transfer speed is controllable by changing the driving voltage.**

I. INTRODUCTION

RAPID positioning devices with accuracies on the order of nanometers are being used in the production of semiconductors [1]. Ultrasonic motors are expected for a micro-actuator which can make the slider move to a precise position because of a high output force and direct drive. For the miniaturization of ultrasonic motors, the stator transducer should be small, so that the wavelength becomes short and the driving frequency rises. Therefore, the friction drive condition has to be examined at high frequency and small vibration amplitude. For this purpose, a surface acoustic wave motor is suitable. Moreover, the surface acoustic wave motor itself would be a small linear actuator. A rigid mounting at the bottom of the substrate will also be an advantage of this motor.

Many types of ultrasonic motors have been developed and reported [1]–[5]. However, nobody has reported using the HF band (from 3 to 30 MHz) surface acoustic wave due to high frequency. There has been only one report about a high-frequency ultrasonic motor which used 4-MHz Lamb wave. However, it only showed that polysilicon blocks moved in the direction of the wave propagation [6]. It was not a direct frictional drive, but a fluid coupled radiation force drive. Hence the linear motion velocity was at the low speed of 2 cm/s. In consequence, the high-frequency drive, such as 10 MHz of the ultrasonic motor, was believed to be impossible except for a fluid coupling drive [6], [7].

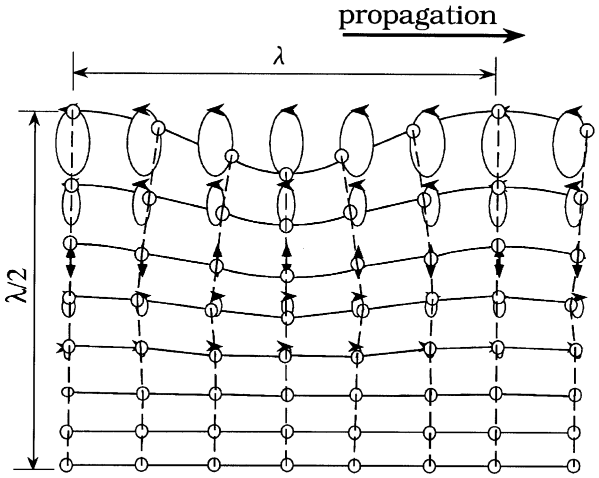


Fig. 1. Motion of the Rayleigh wave which propagates in semi-infinite elastic medium; the upper surface is free boundary and the others are continuous elastic medium.

From reports of ultrasonic motors, the contact pressure is usually around 20 MPa [8], [9]. When a fluid such as oil exists at the boundary between a stator and a rotor, a rather high pressure is required to make the motor work well. In the case of a miniaturized ultrasonic motor with high-frequency small amplitude operation, the influence of adhesive contaminants or air may become significant. Therefore, it is expected that a high contact pressure is required for the friction drive.

In this study, the feasibility of the HF band ultrasonic motor operating at 10 MHz was investigated by using a high contact pressure slider and a surface acoustic wave stator transducer. The motor worked successfully and a small X–Y linear stage was achieved.

II. STATOR TRANSDUCER

The motion of the Rayleigh wave, a kind of surface acoustic wave, is illustrated in Fig. 1. Each surface point in the elastic medium moves along an elliptical locus, because the Rayleigh wave is a coupled wave of the longitudinal wave and the shear wave which has normal displacement component to a boundary. The motion of the surface is similar to the flexural wave, therefore the Rayleigh wave is suitable for an ultrasonic motor. Conveniently, the wave motion is attenuated in the thickness direction, hence permitting rigid mounting at the bottom of the substrate.

In the case of the Rayleigh wave, a tiny vibration displacement due to high frequency is a problem for friction drive. For example, when the driving frequency is 10 MHz and

---

Manuscript received August 15, 1995; revised April 5, 1996. This work was supported by a Grant-in-Aid for General Scientific Research from The Ministry of Education, Science, Sports and Culture.

The authors are with the Department of Precision Machinery Engineering, Graduate School of Engineering, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113 Japan (e-mail: mkur@pe.u-tokyo.ac.jp).

Publisher Item Identifier S 0885-3010(96)06328-9.

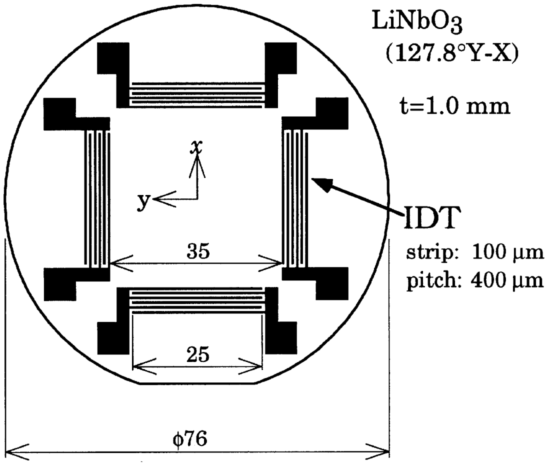


Fig. 2. Schematic of the stator transducers for surface acoustic wave motor. Dimensions are in millimeters.

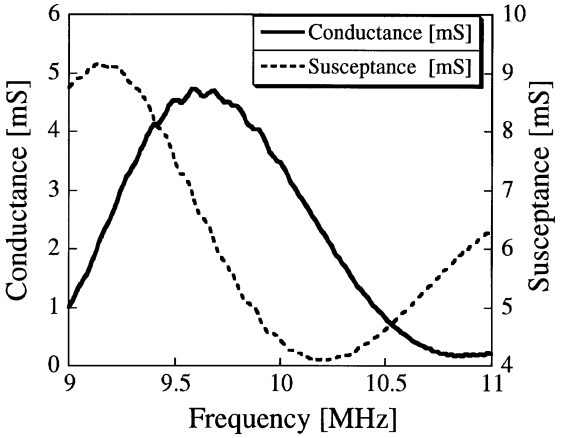


Fig. 3. Conductance of a stator transducer on which water is put.

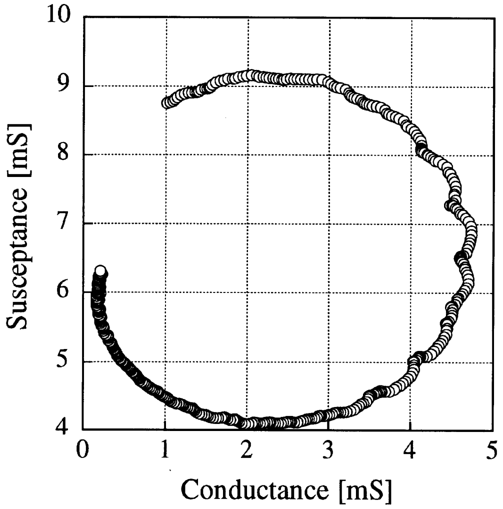


Fig. 4. Admittance loop of an x-direction stator IDT on which water is put.

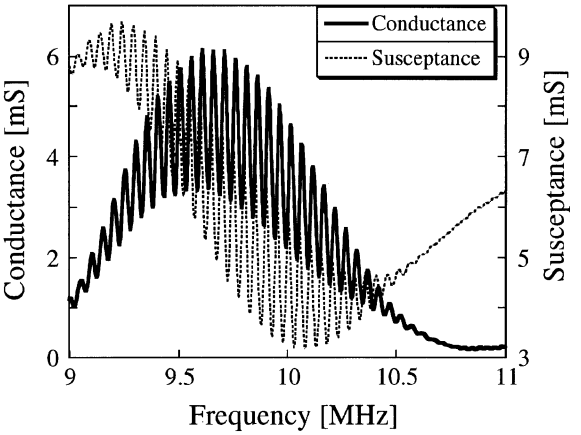


Fig. 5. Conductance of the stator transducer without water.

the particle velocity at the surface is 0.3 m/s, the vibration amplitude becomes about 5 nm. In some cases, the amplitude is smaller than the roughness of the surface. From the limits of the aperture size of a driving transducer and the substrate thickness, it is not practical to lower the driving frequency below several MHz. Therefore, it was decided that the driving frequency should be around 10 MHz.

We used a 127.8° y-rotated x-propagating $LiNbO_3$ substrate for the Rayleigh wave propagation. On the surface of the 3-in substrate, four interdigital transducers (IDT's) were arranged as shown in Fig. 2. The wave propagation velocity in the x direction is 3960 m/s, so that the IDT pitches are 400 μm. The dimensions of the IDT are a 100-μm strip width and 25-mm aperture size. Each IDT has 10 strip electrode pairs. To prevent a standing wave excitation, silicone grease was pasted between the IDT's and the wafer edge.

For absorption of the reflecting wave from the opposite electrode, water was put on the stator transducer. The resonance frequency was measured at this condition with an impedance analyzer. The typical susceptance and the conductance are shown in Fig. 3. As can be seen from these results, the x-direction resonance frequency was 9.56 MHz and the y-direction resonance frequency was 9.11 MHz. The resonance frequencies were not the same, due to anisotropy of the substrate material. The stator transducer was driven at these resonance frequencies. The typical admittance loop for an x direction is shown in Fig. 4.

After removing the water on the stator, the admittance was measured again. This admittance was the actual admittance for the motor operation. There were a lot of peaks in the admittance spectrum as shown in Fig. 5. These were caused by the reflection from the other side of the IDT. It meant that not only the traveling wave but also the standing wave was excited. Only the traveling wave is required for the ultrasonic motor operation, however, the pure traveling wave was not obtained. The standing wave ratio was about 1.3 from the measurement of the vibration distribution. For excitation of the pure traveling wave, the impedance matching condition at the opposite side electrode should be examined.

The vibration amplitude of the normal direction to the surface was measured directly using a laser Doppler vibrometer. The amplitude was on the order of nanometers as shown in Figs. 6 and 7. From these measurements, the normal vibration velocity component was estimated to be about 31 cm/s at 50 V_{peak} in the x direction and 12 cm/s at 50 V_{peak} in the y direction. The vibration velocity in the tangential direction was

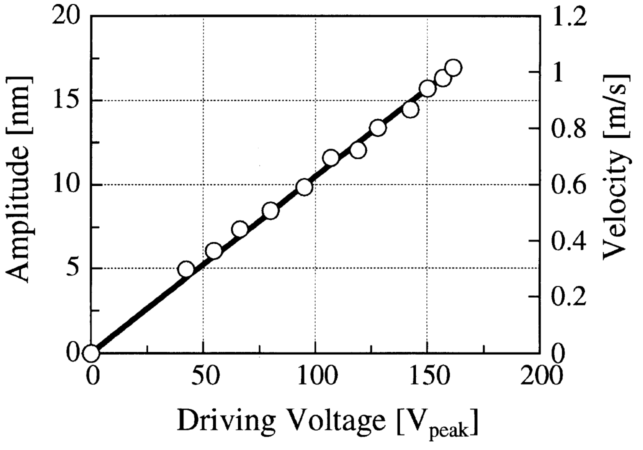


Fig. 6. Normal vibration amplitude and vibration velocity of x propagation.

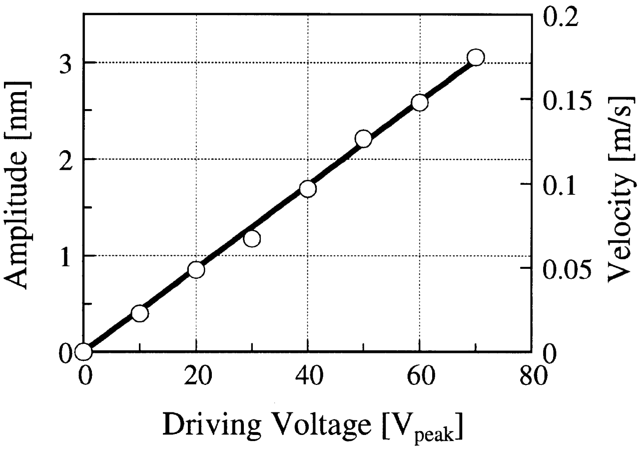


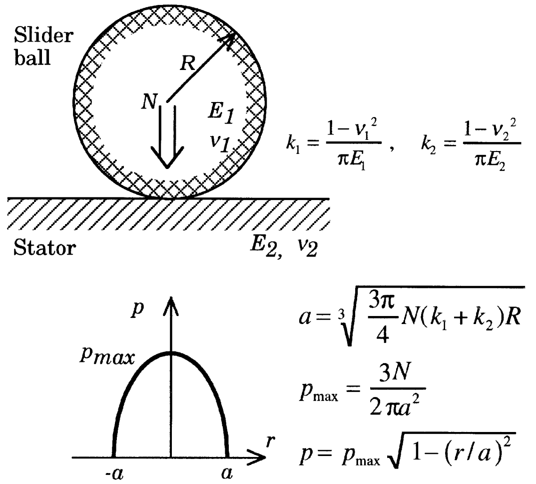
Fig. 7. Normal vibration amplitude and vibration velocity of y propagation.

estimated to be about 19 cm/s at 50 V_{peak} in the x direction and 7 cm/s at 50 V_{peak} in the y direction from the calculated elliptic shape. It is certain that the vibration velocities are sufficient for ultrasonic motors, however, the normal amplitude seems to be small for friction force control.

The surface roughness, R_y, of the stator was measured with an instrument which uses a precision stylus. The surface roughness R_y refers to the difference between the top of the mountain and the bottom of the valley of the traced surface. In the case of a new stator transducer, R_y for the x direction measured 8.1 nm and that for the y direction measured 14 nm over a measuring distance of 0.8 mm. In the case of a stator transducer which was used several times, R_y for the x direction was 15 nm and that for the y direction was 20 nm. These surface roughnesses were of the same order as the vibrating amplitude. It was found that the surface roughness became worse after driving the motor.

III. SLIDER GEOMETRY AND MATERIAL

To realize the friction drive of the ultrasonic motor, the lubrication condition should be controlled. As is well known, if the contact pressure is rather low, some kind of fluid exists between the two materials. In such a case, the two materials do not contact each other, so that the traction force can not transfer from one material to the other. In the case of small driving amplitudes, contaminants and air would likely have a significant effect on the lubrication condition.



$$k_1 = \frac{1-\nu_1^2}{\pi E_1}, \quad k_2 = \frac{1-\nu_2^2}{\pi E_2}$$

$$a = \sqrt[3]{\frac{3\pi}{4}N(k_1+k_2)R}$$

$$p_{\max} = \frac{3N}{2\pi a^2}$$

$$p = p_{\max}\sqrt{1-(r/a)^2}$$

Fig. 8. Hertz contact.

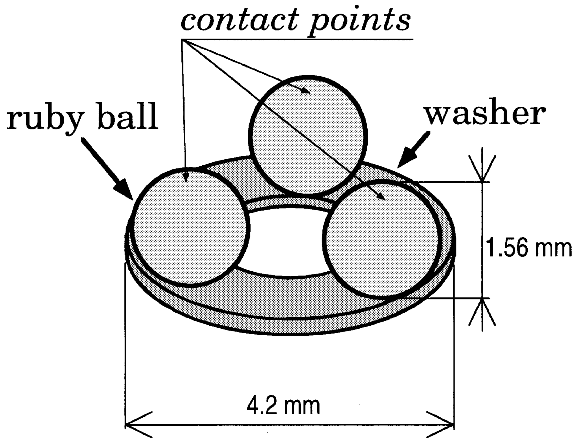
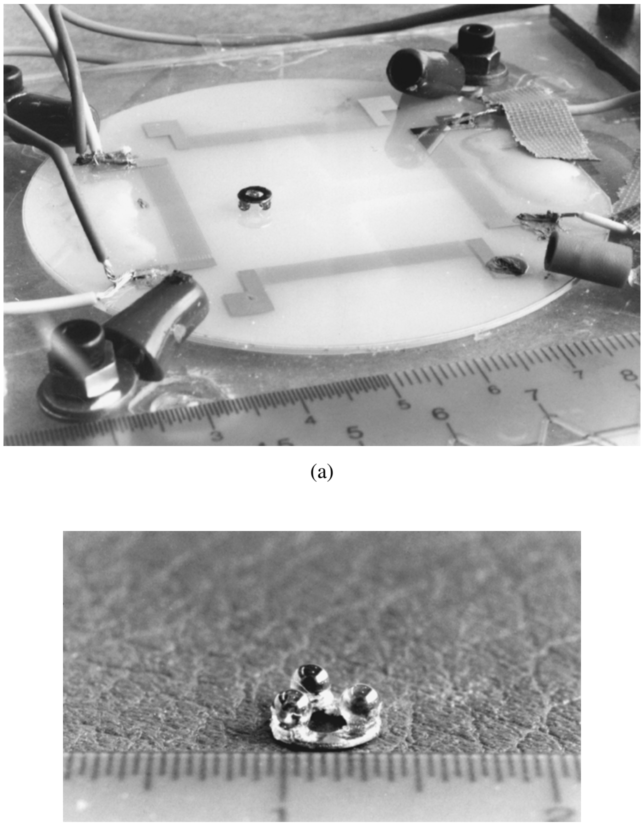


Fig. 9. Sketch of a slider.

For control of the contact pressure, the geometry of the contact material should be arranged. For this purpose, a spherical shape is suitable. From the Hertz contact theory [10], the maximum contact pressure and the contact area can be estimated as shown in Fig. 8. E_1 and E_2 are the coefficients of elasticity of the stator and the slider, and ν_1 and ν_2 are Poisson's ratios. The radius of the ball is indicated by R. When we give the pressing force N in the normal direction, the pressure, maximum pressure, and the contact radius are $p, p_{\max}$, and a as indicated in Fig. 8.

Three kinds of miniature balls were used for the contact material. The materials were tungsten carbide (diameter: 1.56 mm), ruby (diameter: 1.56 mm), and steel (diameter: 1 mm) because they were easy to obtain. The geometry of the slider should be arranged so that there is a suitable contact condition at each point. For this purpose, the number of contact positions should be three. The sliders are shown in Fig. 9. The slider's weights of tungsten carbide, ruby, and steel ball were 123, 55, and 28 mg, respectively, and from the calculation, each maximum contact pressure was 110, 80, and 140 MPa.



(a)

(b)

Fig. 10. The stator transducer (a) and the slider (b).

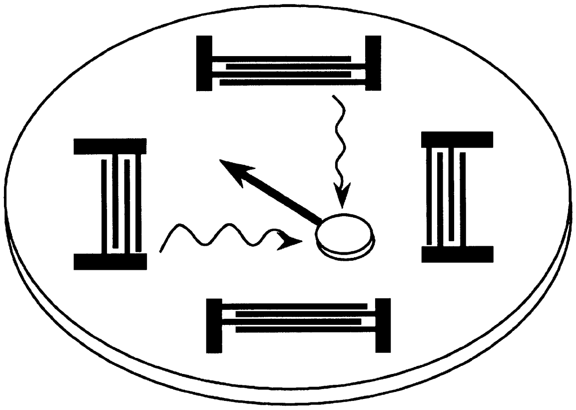


Fig. 11. Two-dimensional driving.

IV. Motor Operation

To obtain good operation condition of the friction drive, the contact surface should be kept clean. Because contaminants such as oil and other adhesives disturb the friction drive, the stator transducer surface and the slider contact part were wiped with acetone to remove any contaminants present. Photographs of the transducers and the slider are shown in Fig. 10.

When both x- and y-direction IDT's were driven at the same time, the slider moved diagonally as shown in Fig. 11. The angular direction was changeable by modifying the amplitude of the driving voltages of both directions. This shows that the motor is also suitable for two-dimensional actuation. However, the y-direction motion was not stable. Therefore, only x-direction operation characteristics were measured in detail.

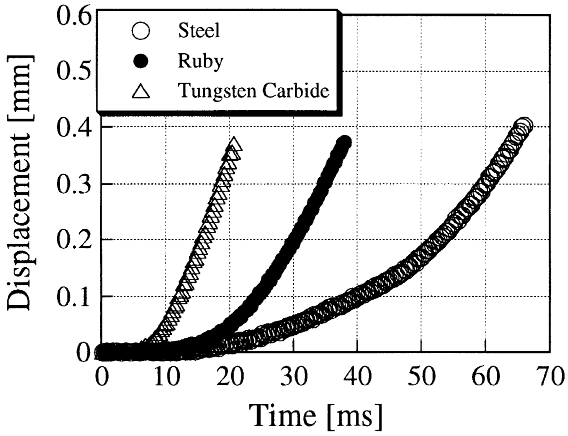


Fig. 12. Effect of the slider material on the transient response of the motion.

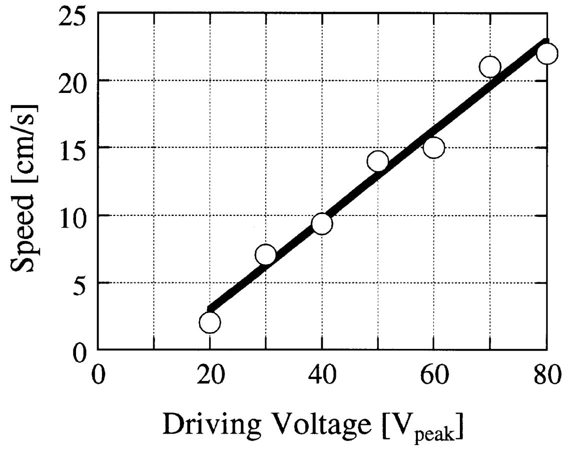


Fig. 13. Speed of the motor as a function of the driving voltage for x-direction drive.

The different transient responses of the slider materials were examined. The transient motion of the sliders was measured by using an Opto-Follow which is an optical displacement measuring instrument. The transient responses of the three balls are shown in Fig. 12. According to these measurements, the tungsten carbide was superior and the ruby was the next best. We measured the frictional coefficient by inclining the stator transducer on which the sliders were placed without ultrasonic vibration. The frictional coefficients of the tungsten carbide, the ruby, and the steel against $LiNbO_3$ were 0.8–4.2, 0.66, and 0.47, respectively. For reference, it is reported that the frictional coefficient of steel and aluminum against steel are 0.46 and 0.54 [11]. From the point of view of quick response, the tungsten carbide was superior. However, the motion of the tungsten carbide was not stable, hence we used the ruby ball slider for other experiments.

The traverse speed of the slider is variable in accordance with the driving voltage as indicated in Fig. 13. This characteristic is the same as other major ultrasonic motors [12]–[14]. In a low vibration amplitude range up to about 20 V_{peak} driving voltage, the slider did not move. From this value, the speed increased linearly with increasing driving voltage. In

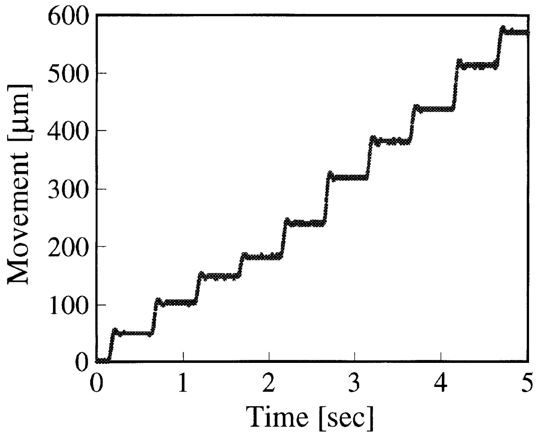


Fig. 14. Motion of the slider by burst drive for x-direction drive.

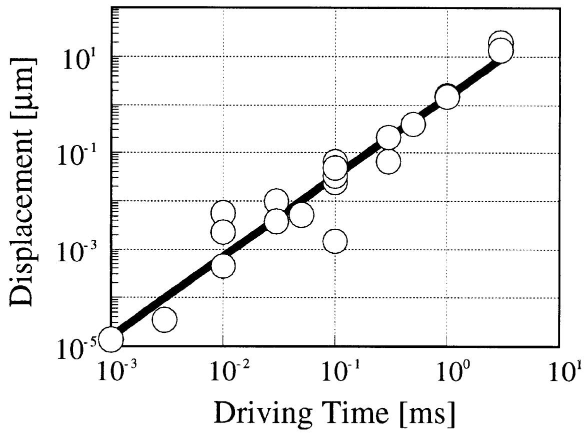


Fig. 15. Change of average traveling distance for x-direction drive.

this measurement, the maximum speed was 22 cm/s. Due to high driving voltage over a long time, the stator transducer generated heat. For continuous drive, therefore, the driving voltage was limited below 80 V_{peak}. However, a higher driving voltage could be momentarily applied, allowing a higher maximum speed.

For the control of the traverse distance, the relation between the driving time and each displacement distance was examined. For example, we measured the displacements when the motor was driven with 30 000 cycles of waves every 0.5 s as shown in Fig. 14 at the voltage of 40 V_{peak}. The step motion of the slider was measured with the Opto-Follow. The slider repeated traveling and standstill. Thirty thousand cycles of waves are equal to 2.87 ms of drive. The mean distance of the displacements was about 60 μm. However, the individual displacements were not identical.

We also measured the mean displacement produced by the single burst drive by changing the driving duration from 1 μs to 3 ms at the driving voltage of 40 V_{peak}. The step motion of the slider was measured with a videotape recording from 1 μs to 1 ms drive and the Opto-Follow from 1 to 3 ms drive. The results are shown in Fig. 15. From this measurement, it was found that the minimum mean step displacement was about 10 pm for 1 μs driving, namely, 10 periods of wave trains. Due to the instability of the motor operation, the step displacement varied widely. If the displacement distance error from the mean value became small, we would be able to use this driving method for precise open-loop positioning. The possibility of using this motor as a precise positioning device which is applicable to a long stroke actuator with an appropriate position sensor is shown.

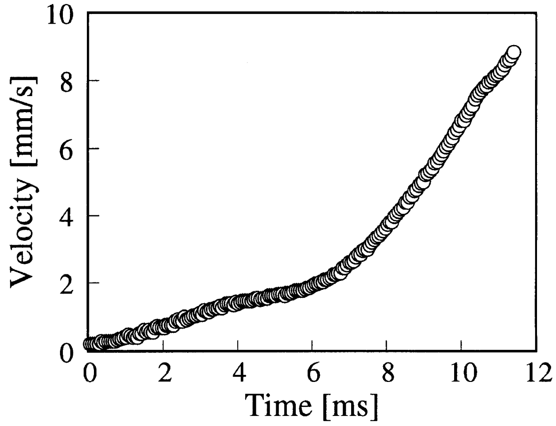


Fig. 16. Transient response of the slider for x-direction drive.

The transient response of the slider is shown in Fig. 16. The acceleration increased with higher transfer speed. Usually, an ultrasonic motor has the property that when the transfer speed increases, the acceleration decreases. It appeared that a bad contact condition was caused at the start of the motion. If the contact condition is improved, the transient response of the slider may be more like that of the usual ultrasonic motor.

V. CONCLUSIONS

We have proved that the HF band ultrasonic motor is feasible and the Rayleigh wave is applicable to the motor. Until now, this surface acoustic motor operates at the highest reported driving frequency. The difficulty of the friction drive at high frequency has been overcome by the control of the contact pressure. For this purpose, the spherical contact parts were introduced to allow enough pressure of about 100 MPa.

To realize a superior ultrasonic motor, the friction drive should be examined from the tribological view point. Material, lubrication condition, and operation pressure are important factors. These kinds of problems have not been fully examined yet. Research from the tribological perspective could improve the performance of these ultrasonic motors.

The surface acoustic wave motor could be a miniature linear motor. The operation length is changeable from mm-order to several cm, and the cross section could be less than 1 cm square. This small linear motor could have high resolution, such as 100 or 10 pm. We showed the possibility of the use of this motor as a precise positioning device with a long stroke.

ACKNOWLEDGMENT

The authors would like to thank Y. Ohtsuka of Nippon-dennso Co., Ltd., for his cooperation in fabricating the surface acoustic wave transducers.

REFERENCES

[1] S. Ueha and Y. Tomikawa, *Ultrasonic Motors—Theory and Applications*. Oxford: Clarendon, 1993.

[2] K. Ragulskis, R. Bansevicius, R. Baraaskas, and G. Kulvietis, *Vibromotors for Precision Microrobots*. New York: Hemisphere, 1988.

[3] J. F. Manceau and F. Bastien, "Production of a quasitraveling wave in a silicon rectangular plate using single phase drive," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 42, no. 1, pp. 59–65, 1995.

[4] T. Maeno, T. Tsukimoto, and A. Miyake, "Finite-element analysis of the rotor/stator contact in a ring-type ultrasonic motor," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 39, no. 6, pp. 668–674, 1992.

[5] M. Kurosawa and S. Ueha, "Hybrid transducer type ultrasonic motor," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 38, no. 2, pp. 89–92, 1992.

[6] R. M. Moroney, R. M. White, and R. T. Howe, "Ultrasonic micromotors," in *Proc. IEEE Ultrason. Symp.*, 1989, pp. 745–748.

[7] K. Nakamura, T. Ito, M. Kurosawa, and S. Ueha, "A trial construction of an ultrasonic motor with fluid coupling," *Jpn. J. Appl. Phys.*, vol. 29, no. 1, pp. 160–161, 1990.

[8] M. Kurosawa, K. Nakamura, and S. Ueha, "Numerical analysis of the property of a hybrid transducer type ultrasonic motor," in *Proc. IEEE Ultrason. Symp.*, pp. 1187–1990.

[9] T. Maeno and D. B. Bogy, "Effect of the hydrodynamic bearing on rotor/stator contact in a ring-type ultrasonic motor," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 39, no. 6, pp. 675–682, 1992.

[10] S. P. Timoshenko and J. N. Goodier, *Theory of Elasticity*, 3rd ed. New York: McGraw-Hill, 1970, pp. 409–414.

[11] Y. Kimura and H. Okabe, *An Introduction to Tribology (Toraiborogii Gairon)*. Tokyo: Youkendou, 1984, ch. 3 (in Japanese).

[12] T. Takano, Y. Tomikawa, T. Ogasawara, S. Sugawara, and M. Konno, "Ultrasonic motors using piezoelectric ceramic multimode vibrators," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 37, no. 2, pp. 224–229, 1990.

[13] P. Muralt, M. Kohli, T. Maeder, A. Kholkin, K. Brooks, N. Setter, and R. Luthier, "Fabrication and characterization of PZT thin-film vibrators for micromotors," *Sensors Actuators, A*, vol. 48, pp. 157–165, 1995.

[14] K. Nakamura, M. Kurosawa, and S. Ueha, "Characteristics of a hybrid transducer type ultrasonic motor," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 38, no. 3, pp. 188–193, 1991.

Minoru Kurosawa (formerly Kuribayashi) (M'95) 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 the Tokyo Institute of Technology, Tokyo, in 1982, 1984, and 1990, respectively.

Beginning in 1984 he was a Research Associate with the Precision and Intelligence Laboratory, Tokyo Institute of Technology, Yokohama, Japan. Since 1992, he has been an Associate Professor at the Graduate School of Engineering, the University of Tokyo, Tokyo, Japan. His current research interests include ultrasonic motor, micro actuator, PZT thin film, SAW sensor and actuator, and single-bit digital control system.

Dr. Kurosawa is a member of the Institute of Electronics, Information, and Communication Engineers, the Acoustical Society of Japan, and the Japan Society for Precision Engineering. Currently, he is a member of the editorial board of the *Journal of the Acoustical Society of Japan*.

Masakazu Takahashi was born in Tokyo, Japan on March 11, 1972. He received the B.Eng. degree in precision machinery engineering from the University of Tokyo, Tokyo, Japan, in 1994.

Since 1994, he has been with the Graduate School of Engineering, the University of Tokyo, Tokyo, Japan.

Mr. Takahashi is a student member of the Japan Society for Precision Engineering.

Toshiro Higuchi (M'87) was born in Ehime, Japan on February 26, 1950. He received B.E., M.S., and Ph.D. degrees in precision machinery engineering from the University of Tokyo, Tokyo, Japan, in 1972, 1974, and 1977, respectively.

In 1977, he was a Lecturer at the Institute of Industrial Science, the University of Tokyo and since 1978, has been an Associate Professsor in the same institute. Since 1991, he has been a Professor at the Graduate School of Engineering, the University of Tokyo. He has also been a Leader of the Higuchi "Ultimate Mechatronics Project" at the Kanagawa Academy of Science and Technology since 1992. His present interests include mechatronics, magnetic bearings, stepping motors, electrostatic motors, robotics, and manufacturing.

Dr. Higuchi is a member of the Japan Society for Precision Engineering, the Japan Society of Mechanical Engineers, and the Society of Instrument and Control Engineers.