SURFACE ACOUSTIC WAVE LINEAR MOTOR USING SILICON SLIDER

N. OSAKABE¹, M. KUROSAWA¹, T. HIGUCHI¹, and O. SHINOURA²

¹ Dept. of Precision Machinery Engineering, Graduate School of Engineering,
The University of Tokyo

7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN

Phone; +81 3 3812 2111 ext. 6466, FAX; +81 3 5800 6968

² TDK Co, R&D Center, Ichikawa, Chiba 272, JAPAN

ABSTRACT

Using a silicon fabricated slider, the output force and the maximum traverse velocity of a surface acoustic wave motor has been improved up to 12 times larger force and twice faster speed than the previous motor which used a multi contact points slider. To obtain the high output force, large contact area between the slider and the stator transducer is required. Therefore a silicon slider was developed and tested. As a result, the maximum output force of 3.5 N and the maximum traverse velocity of 0.65 m/s were obtained. The maximum output force of 3.5 N was 90 times of the transducer weight. Such a high output force performance is produced by high power density of surface acoustic wave devices and friction drive.

INTRODUCTION

A surface acoustic wave motor has a lot of merits such as high output force, high speed, long stroke up to centimeter order, high energy density, easy holding, high resolution positioning, and applicable to smaller actuator for MEMS. The operation of a friction drive surface acoustic wave motor has been demonstrated [1]. For friction drive at high frequency vibration, high contact pressure such as several hundreds MPa is required. The operation conditions and the basic performances have been investigated in experiments [2]. From our recent researches, to obtain the large output force, there were two important points [2],[3]. First, pressing force, namely, pre-load should be adjusted that the elastic deformation of slider and stator was the half of the vibration displacement. Second, the contact area of the slider and the stator should be enlarged to make good use of the large thrust density.

To enlarge the contact area, a multi contact points slider had been made on trial and the output force became 0.3N [4]. Using a multi contact points slider, even though,

the whole contact area of the slider was only $2.5 \times 10^{-3} \text{ mm}^2$, namely about 1/10000 of the slider area. In this study, to enlarge the contact area further more, the silicon slider was made on trial. By testing various types of silicon slider, it was discussed that which types of slider was optimum to obtain the high output force.

To discuss a possibility that the surface acoustic wave motor which uses the silicon slider is available as a precise positioning device, the minute step driving was performed.

SETUP OF A SURFACE ACOUSTIC WAVE LINEAR MOTOR

Experimental setup

The schema of a surface acoustic wave linear motor is shown in Fig. 1. The Rayleigh wave, a surface acoustic wave is generated by an interdigital transducer. The mechanical power of the traveling Rayleigh wave is converted to the traverse motion of the slider by frictional force[2][5]. Two types of experimental setup were prepared, namely a swing arm type and a linear guide type which are shown in Fig. 2 and Fig. 3. Using the swing arm type, the linear motion of the slider was changed to the swing motion of the beam. The swing angle of the beam was measured using a rotary encoder.

Fig. 1 The schema of a surface acoustic wave linear motor.

Fig. 2 Swing arm type.

Fig. 3 Linear guide type

The slider was pressed by a coil spring placed in the spring housing. The other type has a linear guide and the pre-load mechanism using the plate spring. The slider displacement and velocity was measured using a laser Doppler displacement meter and a laser Doppler velocity meter.

The material of the transducer was LiNbO_3 . The dimensions of the both transducers were $15 \times 60 \times 1 \text{ mm}^3$. The driving frequency was 9.6 MHz.

Silicon sliders

In order to obtain the large contact area, a flat contact surface slider on a flat surface substrate is quite common. From a tribological point of view, however, it is almost impossible to make the flat surface slider contact to the stator due to the squeeze film pressure. Therefore the texture of the slider contact surface is an important point.

Silicon sliders which have many projections for the contact surface were made on trial. These sliders, whose dimensions were $4 \times 4 \times 0.3 \text{ mm}^3$, were made of silicon. These were fabricated by usual etching process as shown in Fig. 4. Six types of silicon sliders were prepared as shown in Table 1. The projection diameters or the projection consistencies were different between each silicon slider. The diameters and consistency of the projections were designed based on the previous investigations[3][6][7]. The contact area of the silicon sliders was about 50 to 1000 times larger than that of the multi contact points slider.

Fig. 4 SEM photograph of the silicon slider contact surface

Table 1 Six types of silicon sliders and a multi contact points slider

Slider type	Projection diameter [μm]	Projection consistency [projections/ mm^2]	Slider contact area [mm^2]
type1	50	90	2.84
type2	30	90	1.02
type3	20	90	0.45
type4	10	90	0.11
type5	20	380	1.91
type6	20	20	0.10
A multi contact points slider	2.52	14	0.0025

EXPERIMENT USING SILICON SLIDERS

Transient response

The driving frequency was 9.6 MHz and the pre-load was 1.4 N. The transient response of the type1 slider was measured using the linear guide type with the change of the driving voltage as shown in Fig. 5. The slider traverse velocity is variable by changing driving voltage. The maximum traverse velocity of 0.65 m/s was obtained when the driving voltage was $120 V_{0-p}$.

Figure 6 shows the vibrating velocity of the stator transducer tangential direction and the slider traverse velocity with the change of the driving voltage. At each driving voltage, the slider velocity was about 0.2 m/s slower than the vibrating velocity of the stator transducer tangential direction. If the frictional force between the slider and the linear guide decreased, the slider traverse velocity would become nearly as fast as the vibrating velocity of the stator transducer tangential direction. So the maximum traverse velocity of a surface acoustic wave motor would become 1 m/s or more.

Measurement of the output force

Using the swing arm type, the output force was estimated from the transient response. The driving voltage was $100 V_{0-p}$. The pre-load was changed from 1.4 N to 17 N. Figure 7 shows the type1, type2, type3, and type4 slider output force. The projection consistency of each slider was equal, namely 90 projections/ mm^2 , and the projection diameters were different. The type1,

Fig. 5 The transient response of the type1 slider with the change of the driving voltage.

Fig. 6 The vibrating velocity of the stator transducer tangential direction and the slider traverse velocity.

type2, type3, and type4 slider projection diameters were $50 \mu\text{m}$, $30 \mu\text{m}$, $20 \mu\text{m}$, and $10 \mu\text{m}$. From Fig. 7, it is found that the type2 slider output force was the largest, the type1 slider output force was the second largest, and the type4 slider output force was the smallest. The optimum projection diameter which gave the highest output force would exist around $30 \mu\text{m}$. It would be in vain that the projection diameters were large over $50 \mu\text{m}$ to enlarge the contact area. Each type of slider, the output force increased, up to the pre-load of 17 N. The increase rate of the output force, however, was low. So a certain pre-load which would give the highest output

Fig. 7 The output force against the pre-load about type1, type2, type3, and type4.

Fig. 8 The output force against the pre-load about type3, type5, and type6.

force would exist. Figure 8 shows the type3, type5, and type6 slider output force. The projection diameter of each slider was equal, namely $20\ \mu\text{m}$, and the projection consistencies were different. The type3, type5, and type6 slider projection consistencies were 90, 380, and 20 projections/ mm^2 . In Fig. 8, it is shown that the type5 slider output force was the largest and the type6 slider output force was the smallest. The higher the projection consistency, the larger the output force, up to projection consistency was 380 projections/ mm^2 . The type6 slider output force became small over the pre-load of 10 N, and other two types of slider output force would also become small over a certain pre-load.

A certain pre-load which would give the highest output

Fig. 9 The type2 slider output force against the pre-load about four kinds of driving voltage.

force, namely the optimum force for the high output force, should be decided by the elastic deformation of the stator transducer and the stator transducer vibration amplitude, like the case of the multi contact points slider[5][8]. The difference of the slider texture should make the different elastic deformation of the stator transducer. From Fig. 7 and Fig. 8, the difference of the slider texture influenced the optimum pre-load for high output force. Therefore the elastic deformation of the stator transducer should influence the optimum pre-load for high output force.

In order to investigate the effect of the stator transducer vibration amplitude on output force, the slider output force was measured at four kinds of driving voltage, $40\ \text{V}_{0-p}$, $50\ \text{V}_{0-p}$, $70\ \text{V}_{0-p}$, and $100\ \text{V}_{0-p}$. A different driving voltage generates a different stator transducer vibration amplitude. Figure 9 shows the type2 slider output force with changing the pre-load from 4.2 N to 28 N. Owing to the high pre-load such as 28 N, the maximum output force of 3.5 N was obtained. When the driving voltage became high, namely the stator transducer vibration amplitude became large, the slider output force also increased. When the driving voltage were $40\ \text{V}_{0-p}$ and $50\ \text{V}_{0-p}$, the optimum pre-load for high output force appeared at 15 N and 25 N. When the driving voltage was $70\ \text{V}_{0-p}$, and $100\ \text{V}_{0-p}$, the optimum pre-load seemed to be beyond 28 N. Therefore the stator transducer vibration amplitude influence the optimum pre-load for high output force. From the above

mentioned, consequently, the optimum pre-load for high output force should be decided by the elastic deformation of the stator transducer and the stator transducer vibration amplitude like the case of the multi contact points slider.

From the results of the six types slider output force, as shown in Fig. 10, it was calculated that the relationship between the slider contact area and the slider output force per the slider contact area at the pre-load of 6.6 N, 12 N, and 17 N. The slider output force per the slider contact area came to low, when the slider contact area came to large. As this reason, two reasons were considered. First, when the slider contact area was large, a surface acoustic wave would be attenuated or distorted at a certain part of contact area. By this attenuated or distorted surface acoustic wave, the slider would not get enough driving force from surface acoustic wave at another part of contact area. Second, when the slider projection area was large, the effect of the squeeze film pressure came to large. So we have to consider not only enlarging the slider contact area but texture of the silicon slider for high output force. For example, the type4 and type6 slider output force curves are shown in Fig. 11. About these two types of sliders, the slider contact areas were almost same. The output force over the pre-load of 10 N, however, was different. Moreover, the optimum pre-load for high output force was also different. The type4 slider output force was higher than that of the type6 slider. The projection consistency of type4 was higher than that of type6 and the projection diameter of type6 was larger than that of type 4. Therefore, for high output force, making the high projection consistency might be more important than enlarging the projection diameter. There was only one example, however, it should be examined for another examples.

The silicon slider step driving

To discuss a possibility that the surface acoustic wave motor which uses the silicon slider is available as a precise positioning device, the minute step driving was performed. The driving voltage was $100V_{0-p}$. Figure 12 shows an example of the step driving of the type1 slider. Each driving period was $7\ \mu s$, then the displacement of each step was about 60 nm. The laser Doppler displacement meter resolution was 4 nm. According to the previous results of a multi contact points slider, the displacement could be decreased to several nanometers by short driving time such as $1\ \mu s$ [4]. So the silicon slider displacement is also expected

Fig. 10 The relationship between the slider contact area and the slider output force per the slider contact area.

Fig. 11 The output force against the pre-load about type4 and type6.

to be several nanometers. By getting shorter the driving time or lower driving voltage, the silicon slider displacement could be more minute displacement such as sub-nanometer or several tens of picometers. Therefore there is a possibility that the surface acoustic wave motor is available as a precise positioning device.

CONCLUSION

To enlarge the contact area, a multi contact points slider had been made on trial and the output force became 0.3N. Using a multi contact points slider, even though, the whole contact area of the slider was only 2.5×10^{-3}

Fig. 12 The step driving of type1 slider.

mm², namely about 1/10000 of the slider area. In this study, to enlarge the contact area further more, six types of silicon sliders which had many projections at the contact surface were made on trial. The contact area of the silicon slider was about 50 to 1000 times larger than that of the multi contact points slider.

Using the silicon slider, the output force of the motor was estimated from the transient response of the slider with changing the pre-load. As a result, the maximum traverse velocity of 0.65 m/s was obtained when the driving voltage was 120 V_{0-p}. The maximum output force of 3.5 N was obtained when the pre-load was 28 N. Due to the frictional force between the slider and the linear guide, the stationary traverse velocity decreased about 0.2 m/s. The maximum traverse velocity will be 1 m/s or more by reducing the frictional force and increasing the vibration amplitude. Each silicon slider have the optimum pre-load. It was turned out that the optimum pre-load for high output force should be decided from the elastic deformation of the slider and the stator transducer and the stator transducer vibration amplitude like the case of the multi contact points slider.

To discuss a possibility that the surface acoustic wave motor which uses the silicon slider is available as a precise positioning device, the minute step driving was performed. As a result, it was succeeded to perform the step driving of 60 nm. If the driving time become short or driving voltage become low, the silicon slider displacement could be more minute displacement such as sub-nanometer or several tens of picometers.

Therefore the surface acoustic wave motor is available as a precise positioning device.

Now the stator transducer whose resonance frequency was 9.6 MHz was used. This transducer size is 15 x 60 x 1 mm³. If the resonance frequency of the stator transducer is 50 MHz, it will be possible to make the smaller transducer such as 3 x 30 x 0.5 mm³.

ACKNOWLEDGMENT

This work was supported by the Grant-in-aid for general scientific research of the Ministry of Education, Science, Sports and Culture, and the Foundation for Promotion of advanced Automation Technology.

REFERENCES

- [1] M.Kurosawa, M.Takahashi, and T.Higuchi; "An Ultrasonic X-Y Stage Using 10MHz Surface Acoustic Wave", Proc. of IEEE Ultrasonics Symp., Cannes, pp.535-538, 1994.
- [2] M.Kurosawa, M.Takahashi, and T.Higuchi; "Ultrasonic Linear Motor Using Surface Acoustic Waves", IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control, Vol.43(5), pp.901-906, September 1996.
- [3] M.Kurosawa, M.Chiba, and T.Higuchi; "Multi Contact Points Slider for a Surface Acoustic Wave Motor", Trans of Inst. Electrical Engineers of Jpn. E, vol.117E, no.8, pp.430-431, 1997.
- [4] N.Osakabe, M.Chiba, M.Kurosawa, T.Higuchi; "Experimental Estimation of Surface Acoustic Wave Linear Motor", Proc. of the International Conference on MIPE, Tokyo, Japan, pp.265-268(1997),
- [5] M. Kurosawa, M. Takahashi, and T. Higuchi, "Optimum Pre-Load of Surface Acoustic Wave Motor", Proc. of IEEE International Ultrasonics Symp. '96, San Antonio, Texas, pp.369-372 (Nov. 3-6, 1996).
- [6] M.Kurosawa, M.Chiba, and T.Higuchi; "Evaluation of a surface acoustic wave motor using multi-contact-point slider", Smart Materials and Structures (in printing).
- [7] M.Kurosawa, M.Takahashi, and T.Higuchi; "Elastic Contact Conditions to Optimize Friction Drive of Surface Acoustic Wave Motor", submitted to IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control.
- [8] M. Chiba, M. Takahashi, M. Kurosawa, and T. Higuchi, "Evaluation of a surface acoustic wave motor output force", Proc. of IEEE Workshop on MEMS, Nagoya, Japan, pp.250-255(1997).