Study on Modeling of Surface Acoustic Wave Motor

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Abstract—An equivalent modeling of a surface acoustic wave (SAW) motor is proposed. The equivalent model has an advantage to simulate the motor operating conditions such as speed and output force that is required for design of a servo system. From an investigation for measurements of the motor operation in detail the modeling was carried out. The output force of the motor was measured precisely including a dead zone i.e. no response area at lower driving voltage. The output force and damping coefficient dependences on the driving voltage were introduced into the model with a first lag term due to a slider mass. The motor response at falling down to stop was also introduced. Then the motor model was built fully taking care of the nonlinear characteristics. Simulation results using the motor model concurred well with the measurement results; the model represented the mechanical property of the motor including the nonlinearity.

I. Introduction

High speed, high resolution positioning and quick response surface acoustic wave motors have been investigating [1]-[13]. The components of the surface acoustic wave motors are fabricated by surface micro machining process that is well known as MEMS fabrication process. The fine process results excellent and reproducible devices. Each component, a stator and a slider, thickness is 1 mm or less. Thin and simple device construction are advantages for advanced system design. The other some groups have also reported interesting research results [14], [15].

Success of the extremely high frequency drive of surface acoustic wave device, one hundred or one thousand times higher than that of usual ultrasonic motors, is high contact pressure at tiny contact points [1]-[4]. To obtain higher output force of motor, contact points of sliders were increased [5]. By introducing silicon micro machining process [6]-[8], the contact points of the slider increased to a hundred thousand or more. The diameter and the amount of the contact projections were investigated in the viewpoints of the speed and the thrust of the motor.

For commercialize this actuator, the efficiency from electric power to mechanical output should be improved. An energy circulation driving method have been developed to solve this problem [9], [10]. Excitation of the traveling wave and the motor operation have been reported already. However, the energy circulation ratio seemed to be still low. The electrode design of the transducer should be improved to reduce the driving power.

In this paper, motor model including nonlinearly of the motor driving characteristic is reported. The motor model simulation was performed well. The model represented the mechanical property of the motor including the nonlinearity.

II. Principle

A. Friction Drive

The SAW motor consists of stator made of a piezoelectric material and slider as shown in Figure 1. Two RF electrical power sources $E_1$ and $E_2$ in which the phase difference is 90 degrees are applied to two interdigital transducers (IDTs). IDTs generate the Rayleigh wave by the piezoelectric effect. The Rayleigh wave propagates to a right side on the stator; each particles of the stator move elliptical locus as shown in

![Fig. 1. Schematic view of an energy circulation type SAW motor.](image1)

![Fig. 2. Friction drive mechanism using traveling Rayleigh wave.](image2)
Fig. 2. The contact with the particles slider that is pushed to the stator, the frictional force is generated between the Rayleigh wave and the slider. The frictional force thrusts the slider, thereby, the SAW motor operates.

If the phase of $E_1$ and $E_2$ is switched from +90 degrees to -90 degrees, the slider moving traveling direction is reversed.

B. Energy Circulation Type

In order to improve the efficiency of the SAW motor, an energy circulation drive has proposed and being studied [1]. After the Rayleigh wave pass through beneath the slider of an experimental motor setup as shown in Fig. 3, the Rayleigh wave that has arrived at a unidirectional IDTs is transduced to RF electrical power. Then, the electrical power is transduced into the Rayleigh wave at the other unidirectional IDTs again. In this way, the energy is circulated, so that the driving power is saved.

III. Experimental Setup

In parameters of experimental specification, mass of moving part was 53 g, pre-load was 9 N and the driving frequency for Rayleigh wave propagation was 14.34 MHz.

Input voltage $V$ is converted driving voltage of $E_1$ and $E_2$ through function generators and RF amplifiers as shown in Fig. 3. Input voltage $V$ is amplitude modulated by the function generators that generated two-phase signals that have 90 degrees phase difference; carrier frequency was 14.34 MHz. Amplitude modulation signals were amplified by the RF amplifiers, then $E_1$ and $E_2$ were used applied to the motor.

The motor speed was measured a linear scale along with a second-order speed observer [2]. The second-order speed observer was used to calculate the speed based on the position signal obtained by the linear scale. The second-order speed observer is as follows:

$$ v = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} u $$

The observed speed $v$ from the linear scale displacement $u$ has advantageous compared with the $v$ directly measured speed by the laser Doppler velocimeter (LDV). Fig. 4 shows the comparison between observed speed and the LDV speed when the motor was step responding. From Fig. 4, it is shown that noise level of the observed speed signal was lower than that of the LDV signal. The LDV speed signal had a difficulty that it didn’t conform to 0 m/s after motor stopping due to influence of a low pass filter in the LDV. The observed speed, on the other hand, showed accurate null after stopping. In experiment, the observed speed by second-order speed observer was used.

![Fig. 3 Photograph of the experimental setup.](image)

![Fig. 4 Driving and measurement system for the SAW motor.](image)

![Fig. 5 The SAW motor speed at step response.](image)
IV. Characteristic of the dead zone

We started with the modeling of the SAW motor. The scope of the modeling was from input voltage to output slider speed. The SAW motor has strong non-linearly relation to the input voltage and output speed i.e. a dead zone. The dead zone becomes a serious problem at beginning the motor movement. So as to examining the dead zone in detail, a relation between input voltage and output speed was measured by sinusoidal motion (60Vpp, 5Hz) as indicated in Fig. 6. The minus speed represented motor driving of backward. Due to the stator characteristic of the SAW motor, the forward speed was faster than the backward speed. A trajectory between the input
voltage and the output speed is depicted in Fig. 7. First, the motor was moved forward. The motor was applied driving voltage from 0Vpp; the motor began to move from 32Vpp (point A in Fig. 7). The motor motion drew counterclockwise rotation trajectory and stopped at 12Vpp (point B). Next, the motor moved similarly backward. The motor started to move from -45Vpp (point A') and stopped at -19Vpp (point B'). As can be seen from Fig. 6, a threshold of dead zone was different in starting voltage (point A) and stopping voltage (point B).

The voltage differences seem to be caused by the delay of the motor response due to the inertia. In order to make clear influence of inertia, the dead zone was measured when driving frequency of the motor was changed (3Hz, 5Hz and 8Hz). As illustrated in Fig. 8, threshold voltages of the dead zone were plotted while the motor was reciprocating sinusoidal drive at each driving frequency. When the driving frequency was higher, the difference between the starting voltage (point A) and the stopping voltage (point B) became higher. If the driving frequency was 0Hz, we expected that the threshold voltage between the starting voltage and the stopping voltage was equal voltage. As shown in Fig. 8, the threshold voltages were not equal voltage. And each starting voltage at A and at A' varied in each frequency. The threshold voltage changing seems to be due to the cause other than inertia.

V. Modeling and Simulation

There are two stages to driving the SAW motor: input voltage \( V \) generate the force \( F \) by friction driving; the force \( F \) is then converted to the motor speed \( v \). Where the input voltage \( V \) is converted into the force \( F \), there is dead zone. The relation between the force \( F \) and the motor speed \( v \) is first order lag
The first order lag system has a mass \( M \) part and a damping \( D \) part. To know the motor model, the damping part must be identified. The damping part was measured in two cases of acceleration and deceleration.

### A. Acceleration

The damping part was measured using step responses as shown in Fig. 9. The step responses were changed force-speed curves at raising the motor speed as shown in Fig. 10. The lines of force-speed curves stand for each input voltages. A reciprocal of the force-speed curves inclination means damping coefficient \( D \). The inclination increased with the input voltage, thereby, the force-speed curves were changed by input voltage.

### B. Deceleration

The damping part of deceleration was measured using two stage step responses as indicated in Fig. 11. The first stage of region G in Fig. 11 is each voltage step responses from 0 sec to 0.02 sec: the second stage of region H is 30 V step responses from 0.02 sec to 0.06 sec. At this time, the force-speed curves are illustrated in Fig. 12. The three lines coincided with line C of deceleration part. The force-speed curves inclination of the deceleration part was measured similarly at 25V. The force-speed curves inclination, which was measured at both acceleration part and deceleration part, increased linear with input voltage as shown in Fig. 13. The inclination of force-speed curves is expressed as

\[
\frac{1}{D} = aV + b
\]

The damping coefficient \( D \) is equal to reciprocal of the force-speed curves inclination.

### C. Modeling

When the input voltage was 0V, the damping coefficient was inferred \( 1/b \). The damping coefficient is

\[
D = \frac{1}{aV + b} = \frac{D_0}{aV + 1}
\]

where \( a = a/b \) and \( D_0 = 1/b \). The varying damping coefficient depending on the input voltage was identified as indicated in Fig. 14.

A maximum dynamical friction force that was calculated from the maximum accelerated speed at step responses was measured 2.03 N. The maximum dynamical friction is the maximum force of the SAW motor that does friction drive. The SAW motor force has limit by the dynamical friction force. Through the examination of damping coefficient and dynamical friction force, the motor model was depicted in Fig. 15.

### D. Simulation

Using the motor model, the step responses were simulated. A simulating motor speed was compared to the measured motor speed at step responses as shown in Fig. 16. Each acceleration curve at speed rising up, the sloops of the model simulation agreed well with the actual motor. It should be mentioned specially, in addition, that the speed falling down slops by the model simulation perfectly coincided with the motor behavior.

On the force-speed plane, the motor responses are indicated in Fig. 17. The right hand of the null point of the force is the ordinary relationship between the speed and mechanical load, namely, output force of the motor. The left hand of the null point is the motor response when the speed is falling down. All the region, the simulation curves from the equivalent block diagram indicated in Fig. 15 agreed very well with the actual motor. From Fig. 16 and Fig. 17, it can be seen that the model performed well through acceleration and deceleration. The model represented the mechanical property of the motor including the nonlinearity.

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![Fig. 15. The block diagram of the SAW motor model.](image-url)
VI. Conclusion

The driving characteristic and the driving model of the SAW motor was investigated. The motor has dead zone and varying damping coefficient depending on the driving voltage, i.e., the motors shows highly nonlinear characteristics. Then, the motor model was built fully taking account of the nonlinear characteristics. Simulation results using the motor model concurred well with the measurement results; the model represented the mechanical property of the motor including the nonlinearly.

Acknowledgments

This work was supported by the Ministry of Education, Culture, Sports, Science and Technology, Grant-in-Aid for Science Research; Kakenhi.

References