Control of a Surface Acoustic Wave Motor Using PID Controller

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Abstract A surface acoustic wave (SAW) motor has been investigated as a small to micro linear motor by authors. It has been already shown that the SAW motor has high speed, large thrust and high resolution specific. Hence, the novel actuator is expected to make a system compact and functional. We have successfully controlled the motion of a SAW motor using PID controller including nonlinear function.

Keywords: Linear motor, Surface Acoustic Wave, PID control, nonlinear control

1. Introduction

We have investigated a Surface Acoustic Wave (SAW) motor. In the past research it has been showed that the SAW motor has high speed, large thrust and high resolution specific (1) in spite of its small size.

But as is the case with any other ultrasonic motor (USM), the SAW motor also have a nonlinearity because the motor’s output force is caused by a frictional force between a stator and a slider.

In order to counteract its nonlinear response of the USM, there are supposed some very complicated control system by many authors.

Hence, the novel actuator is expected to make a system compact and functional. If we can use a simple control system, a high speed and a high resolution actuator controller using simple and compact hardware circuit will be achieved.

We designed a very simple PID feedback control system and introduced a nonlinear function in the feedback control system to modify its nonlinearity. The PID parameters in this approximated LTI (Linear time-invariant) system was decided by ultimate sensitivity method using simulation (Matlab/Simlink). The designed system was implemented in a digital control system using a DSP board installed in PC. We controlled the driving voltages of the motor using AM modulation thorough the DSP’s analog output. The speed and the position of the motor which were measured by Laser Doppler Vibrometer (LDV) and an incremental encoder.

We tested the sinusoidal 3Hz at 0.15 m/sec speed motion of the motor at first so that the motor can move smoothly and continuously. And the 1 mm up-down step response of the position of the motor was also operated and estimated. Experimental result showed that the SAW motor was successfully controlled using this simply control system.

2. Principle

2.1 A principle of the SAW motor

The SAW motor is a traveling wave type ultrasonic motor using Rayleigh wave (2). The Rayleigh wave is excited on a stator by interdigital transducers as illustrated in Fig. 1. The stator was made of 128 degree rotated y-rotated x-propagation LiNbO₃; piezoelectric crystal substrate. The slider was made of silicon which had a lot of micro projections and it was designed to avoid an influence of the squeeze film and get a flat stress by the pre-load. Fig. 2 shows an frictional force generated at a contact region between the stator and the slider. The particle movement of the stator is elliptical vibration. The stator is forced to the opposite direction of the traveling wave by the frictional force. The SAW motor obtains this frictional force as thrust. Because the Rayleigh wave power is concentrated around its surface, it enable to make the small and high power actuator. It is already shown the motor has more than 1.5 m/s high speed, over 10 N high thrust, and subnanometer high resolution (1).

2.2 Structure of the energy circulation type SAW motor

We recently proposed a circulation type SAW motor (3) as shown in Fig. 3. This structure can excite a Rayleigh wave more efficiently and raise the efficiency of
the motor. The traveling Rayleigh wave is excited the
two driving IDT's. The two IDT was applied the RF
voltage; its frequency was 14.3MHz and 90 degree phase
difference. The Rayleigh wave is once converted to the
electrical power at the circulation IDT and emitted an-
other circulation IDT.

Hence another circulation IDT emits the Rayleigh
wave to both direction, the reflector IDT reflect the wave
so that it is treated as the unidirectional IDT. The cir-
culation power overlap the input power and go round
again. This is the principle of the circulation structure.

We defined the Rayleigh wave move left to right as shown
in Fig. 3 as forward, and right to left as backward.

3. Characteristics of the SAW motor
3.1 Transient response of the motor

As is the case with any other USM, the SAW motor
also has the dropping characteristics between its thrust
and speed as shown Fig. 4 shows a transient response
of the speed of the SAW motor at each input power.

The motor’s motion equation shows below

\[ m \frac{dv}{dt} = F \]

\( m \) is defined mass of the SAW motor, \( v \) is the speed,
and \( F \) is the output force. The dropping characteristic
is expressed as below.

\[ v = v_0 \left( 1 - \frac{F}{F_0} \right) \]

Then motor’s output speed has a transient response as
below.

\[ v = v_0 \left( 1 - e^{-\frac{t}{\tau}} \right) \]

The transfer function can be expressed as below.

\[ G(s) = \frac{1}{1 + sT} \]

3.2 the dead-zone of the motor

It is only the case which the amplitude of the
Rayleigh wave is enough large in order to move the SAW
motor. We need to consider the case the input power is
not enough to move the motor.

A silicon element that has a lot of micro projections
on its stator increases the frictional force \((4)\); the pre-load
was around 10 N. Depending on the pre-load, the mo-
tor has dead zone as shown in Fig. 5. The dead zone
causes the nonlinearity of the motor response; that is
no motion against small driving voltage caused by the
frictional drive.

In addition, Fig. 5 also shows that there is some differ-
cence between forward or backward motion of the SAW
motor. This is because the performance of the circu-
lation type stator. We used a 37 mm very long stroke
stator this time so that we could test some various op-
eration. But it was difficult for this long stator to circle
the power efficiently because there were so many factors
of the SAW motor, we operated the input voltage using AM modulation so that we could not apply the voltage more the 100 % AM modulation. The parameter was decided as far as both we can really operate and control system was stable. The estimated parameter is shown in Table. 1.

### Table 1. Parameters of the controller

<table>
<thead>
<tr>
<th>Speed</th>
<th>Position</th>
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<tbody>
<tr>
<td>Speed</td>
<td>9.6</td>
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<tr>
<td>Position</td>
<td>380</td>
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</table>

4. Control system

4.1 Feedback control system using nonlinear function

As described in Introduction, it has already proposed some useful control system by many authors to control such a nonlinear plant. But some many system are complicated and need to high performance hardware. Providing simple and compact actuator controller, we introduced a simple nonlinear inverse function to counteract the nonlinear response of the SAW motor in a PID feedback control system as shown in Fig. 6.

A position feedback control system is also shown in Fig. 7. The speed feedback block was inserted to raise the control performance.

In order to estimate the PID parameter, we use the ultimate sensitivity method at the simulation. Matlab/Simlink was used as the simulation environment. Considering about the implementation, we assumed approximated LTI system as the discrete time LTI system; sampling frequency 10kHz. Transfer function of the PID controller can be expressed as below.

\[ P_s = K_P \left( 1 + \frac{1}{T_I s} + T_D s \right). \]

Because the ultimate sensitivity method guarantees the stability of the system, designed speed control system was stable. According to the position control, it was required to carefully consider the open loop performance
bit. The position resolution of the incremental linear encoder was 1 μm.

AM 100% modulation of input voltage was set to 70 V_{0-p} and its maxmam speed was 0.43 m/sec at forward, and 0.3 m/sec at backward when the motor was moved by the open loop control.

The driving frequency of the applied voltage at the stator was set to 14.33 MHz. And we use the silicon slider whose projections were 5 μm diameter and its each interval was 15 μm.

5. Experimental result

Fig. 9 shows sinusoidal wave response of the speed of the SAW motor. The frequency of the motion was set to 3Hz, and the amplitude of the speed was 0.15 m/sec. Experimental result shows that the PID controller including nonlinear function successfully controlled the SAW motor that had dead zone. The error of the response was about 5 mm/sec (3.3%).

Fig. 10 shows step response of the position of the motor. Step time interval was set to 1.0 sec and step range was 1 mm. Position control system had also worked successfully both up and down steps. The setting time was about 70 msec and the position error was about 20 μm (2 %).

Hence the experimental result shows the availability of the designed system, some problem had also become clear. At first the output speed response was quite different from the case which the motor’s acceleration are increasing or decreasing. This was because the stick-slip condition at the contact region between the stator and the slider was different for the increasing and decreasing. It will be needed to design the sliding mode system so as to get much more control performance. Secondly, the position error of 20 μm were not much more decreasing if we set the smaller step. And this error was periodic and its frequency was about 200Hz. It was thought that this is because of the influence of the electrical noise inner the feedback or the mechanical resonance of the actuator but that’s not certain.

6. Conclusions

Using the nonlinear function to compensate the non-linearity of the SAW motor, a simply PID feedback control system was designed and implemented. Experimental result showed that nonlinear function had worked successfully and a PID feedback system could perform whether sinusoidal speed control or position step control.

In future we are going to improve the control system considering the behavior of the motor’s acceleration increasing and decreasing so as to get higher control performance as possible as very simple control system. And we will also clear the inner loop noise source and the mechanical resonance of the actuator so that we could get much more high precision position control.

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References