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Actuation methods for a Surface Acoustic Wave Moto

P. J. Feenstra, P. C. Breedveld, J. Van Amerongen
Control Laboratory, University of Twente, PO Box 7500 AE, Enschede, NETHERLAN

Abstract: A surface acoustic wave motor has a (varying) dead zone in the relation be control input and motor velocity. From a control point of view it is beneficial to elimina dead zone. Therefore, four actuation methods are compared to examine their ability to de this problem. This examination shows that pulse width modulation (PWM) eliminates th zone. without the risk of overcompensation and without a large decrease in efficiency. fore, this method is recommended for SAW motor control, in particular closed-loop cont

Keywords: surface acoustic wave motor, control, actuation, pulse width modulation

1. Introduction

A surface acoustic wave (SAW) motor is an ultrasonic motor that utilizes Rayleigh wa generate motion. Raleigh waves can propagate at the surface of an elastic half-space (stat fundamental Raleigh wave feature is the elliptical motion of the surface particles. Due wave motion a friction force is exerted on a slider that is pressed against the wave tops re in a motion of the slider (figure 1). To prevent a squeeze air film between slider and stat slider surface is covered with small hemispheres called projections (not shown in the figu so-called Interdigital Transducer (IDT) can generate Rayleigh waves. Two IDT's are requ obtain a one degree of freedom motion, *i.e.*, one IDT to generate a wave in positive directi one IDT to generate a wave in the opposite direction (figure 2). The actuation block cal both actuation signals (u_{min} and u_{plus}) as a function of the control input u. Subsequently, frequency f_c (MHz) carrier signal multiplies the signals to obtain an amplitude modulated signal. The AM signals drive the IDT's of the SAW motor.

Some features of a SAW motor are: a high driving force per unit weight, absence of ma fields, no lubricant requirements and a large blocking force when not actuated. However, control point of view, the use of friction drive has some inherent drawbacks. One drawbac existence of a (varying) dead zone in the relation between control input and motor velo dead zone with a time-variant and position depending threshold amplitude is not beneficia a control point of view. Therefore, four actuation methods are compared in order to ex their ability to deal with this problem. In section 2, we examine the origin of the dead zo

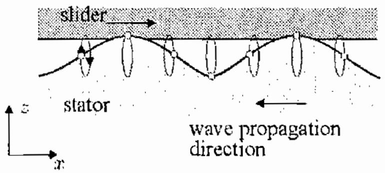

Figure 1: Principle of actuation of a SAW motor.

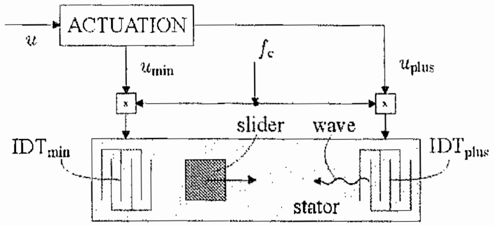

Figure 2: SAW motor setup.

the causes of the variation. The four actuation methods are examined in section 3. Finally, some conclusions are given in section 4.

2. Analysis of the dead zone

In [2] we have derived a contact model of a SAW motor. Figure 3 shows the iconic representation of this model. The model considers a slider with one projection and accounts for the normal and tangential nonlinear compliance of both slider and stator. The friction between slider and stator is modeled by dry (Coulomb's) friction. Figure 4 shows the no-force slider velocity $\dot{x}_s$ as a function of the normal wave amplitude $\hat{u}_z$ obtained by numerical simulation. Three regions can be distinguished, which are separated by the 'threshold' and 'release' amplitude. We will explain these three regions in terms of the contact behavior.

1. **Dead zone** There is no resulting slider motion if the wave amplitude is smaller than the threshold wave amplitude $\hat{u}_{z,\mathrm{th}}$, because wave and slider stick continuously.
2. **Continuous** The slider starts to move if the wave amplitude exceeds $\hat{u}_{z,\mathrm{th}}$. In this region,

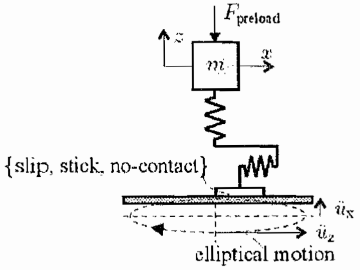

Figure 3: Iconic representation of a SAW contact model.

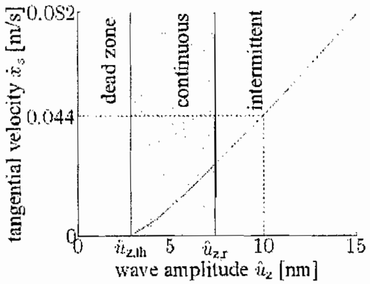

Figure 4: Tangential slider velocity versus wave amplitude.

there is always contact between wave and slider. The contact between wa sticks and slips.

3. **Intermittent** The wave amplitude is greater than the 'release' amplitude. T contact between wave and slider is intermittent. The 'modes' during operat slip and no-contact.

Because of the constant ratio between wave amplitude $\hat{u}_z$ and actuation signal (figure 2), there is also a dead zone in the relation between these actuation signals velocity. In the remainder of this paper we refer to this dead zone and the associa amplitude.

In practice, the (actuation) threshold amplitude varies. For example due to the the wave amplitude along the stator length. Two important causes of this variat attenuation and diffraction [3]. Furthermore, the contact conditions between slic influence the value of the threshold amplitude. Consequently, a variation of the pre a function of the slider displacement changes the threshold amplitude as well. A r disturbance is the variation of the coefficient of friction. This coefficient is affecte

1. slider and stator conditions (contamination, scratches, wear);
2. ambient conditions (humidity, temperature, etc.);
3. Rayleigh wave (amplitude, shape of wave envelope, etc).

The first two contributions are rather obvious. The third contribution is predomi the increase of the coefficient of static friction μ_{st} with time [1], *i.e.*, the value μ the history of the contact.

3. Actuation

This section considers the actuation of a SAW motor, *i.e.*, the relations between the u and the two actuation signals u_{min} and u_{plus} (figure 2). The four strategies that ar are qualified by their relative efficiency and their ability to eliminate the dead zon

3.1 Single-sided actuation

The simplest way to achieve two actuation signals is by using the sign of u for swi u_{plus} is u if the sign of $u > 0$ and *vice versa*. Figure 5 shows an experiment pe this so-called Single-Sided Actuation (SSA). It demonstrates that both the dead variation remain. In order to define the relative efficiency, we approximate the rel the no-force velocity $\dot{x}_s$ and the control input u where $0 \leq u \leq 1$ (figure 5) by:

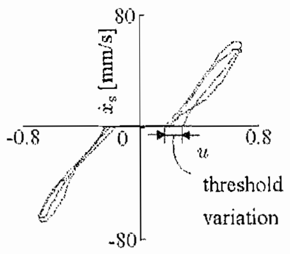

Figure 5: The no-force slider velocity $\dot{x}_s$ as function of the input u for Single-Sided Actuation (SSA).

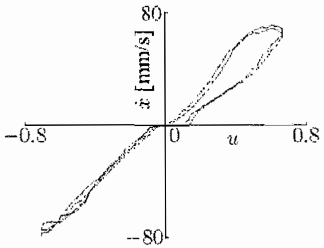

Figure 6: The no-force slider velocity $\dot{x}_s$ as function of the input u for Compensated Single-Sided Actuation (CSSA).

$$\dot{x}_s = \begin{cases} \frac{\dot{x}_{s,\max}}{1-u_{th}}(u-u_{th}) & \text{for} \quad u > u_{th} \\ 0 & \text{for} \quad 0 \le u \le u_{th} \end{cases} \tag{1}$$

where u_{th} is the threshold control input and $\dot{x}_{s,\max}$ is the slider velocity for $u = 1$. By rewriting equation 1 we can find $u = u(\dot{x}_r)$ for $0 \le \dot{x}_r \le 1$, where $\dot{x}_r = \dot{x}_s/\dot{x}_{s,\max}$ is the normalized slider velocity. Accordingly, the wave power can be written as a function of $\dot{x}_r$.

$$P_{ssa} = P_{ssa,\max}\left(u_{plus}^2 + u_{min}^2\right) = P_{ssa,\max}(\dot{x}_r - \dot{x}_r u_{th} + u_{th})^2 \quad \text{for} \quad 0 \le \dot{x}_r \le 1 \tag{2}$$

where $P_{ssa,\max}$ is the wave power for $|u| = 1$. Now, we can define the relative efficiency as the wave power of other actuation methods α (to be discussed next) with respect to SSA:

$$\eta_{rel} = \frac{P_{ssa}}{P_\alpha} \tag{3}$$

3.2 Compensated single-sided actuation

It is possible to eliminate the dead zone if the threshold amplitude u_{th} is known; a value corresponding to the (smallest) threshold amplitude is added to the steering signal u. Note that overcompensation occurs when the compensation is larger than the actual dead zone. Velocities near zero are not reachable in case of overcompensation. Figure 6 shows results of an open-loop experiment performed with compensated single-sided actuation (CSSA). It demonstrates the intended decrease of the dead zone. However, the dead zone is not completely eliminated, as could be expected. The relative efficiency η_{rel} is 100 %, because the relation between $\dot{x}_s$ and u_{plus} or u_{min} is identical to SSA.

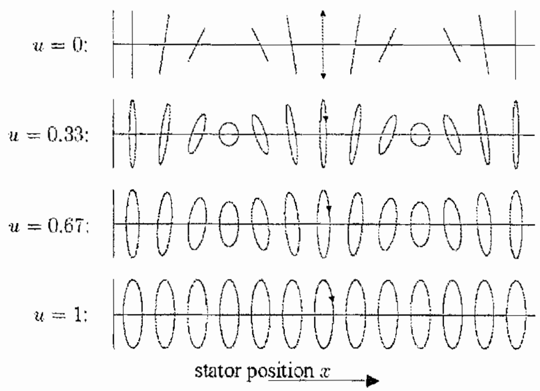

Figure 7: The particle motions due to DSA at the surface of a stator.

3.3 Dual-sided actuation

A third strategy is proposed in [4]. They assumed that the stator roughness causes th rather than the stick behavior. Nevertheless, this method implicitly tackles the stick and consequently eliminates the dead zone. Since both IDT's are actuated simultai method is called Dual-Sided Actuation (DSA). For example, if DSA for $u = 1$ coı SSA (only one wave) the actuation signals are

$$u_{plus} = \frac{1+u}{2} \qquad u_{min} = \frac{1-u}{2}$$

The principle of slider motion is explained by the surface particle displacement sl ure 7. For equal wave amplitudes ($u = 0$), the motions are symmetric (a stan Consequently, the slider does not move. For unequal wave amplitudes, the surface tion is elliptical and may generate slider motion. The dead zone disappears when wave amplitude is such that constant stick behavior between slider and stator is ov a smaller wave amplitude, the threshold amplitude only reduces. Overcompensatioı sible. Figure 8 shows the results of an experiment performed with this strategy, whi this actuation method almost eliminates the dead band.

However, figure 7 shows that the particle displacement amplitudes depend on the This dependency causes an additional position dependent disturbance. Apart from dependent disturbance, this method has another drawback: the relative efficiency i

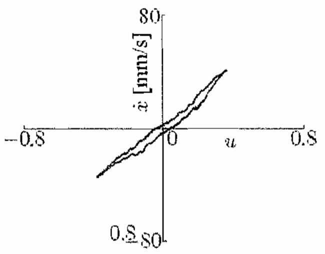

Figure 8: The no-force slider velocity $\dot{x}_s$ as function of the input u for DSA. Experiment is taken from [4].

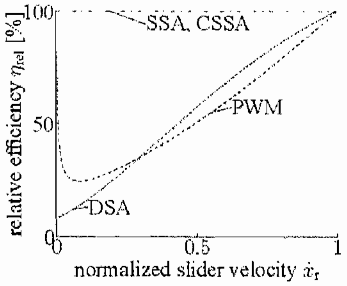

Figure 9: The relative efficiency of the four actuation methods.

Consider equation 4 and suppose $u = \dot{x}_r$. Then, the input power for DSA is

$$P_{\rm dsa} \;=\; P_{\rm ssa,max}\left(u_{\rm plus}^2 + u_{\rm min}^2\right) \;=\; P_{\rm ssa,max}\frac{1+\dot{x}_r^2}{2} \quad \text{for} \quad 0 \le \dot{x}_r \le 1 \tag{5}$$

Hence, 50 % of the maximal power is dissipated for a zero slider velocity. Figure 9 shows $\eta_{\rm rel}$ for $u_{\rm th} = 0.2$. The relative efficiency of DSA is 100 % for $\dot{x}_r = 1$ and only 8 % for $\dot{x}_r = 0$.

3.4 Pulse width modulation

The fourth actuation method consists of the application of a pulse train of constant amplitude but variable pulse width, therefore, this method is called pulse width modulation (PWM). The dead zone disappears if the applied amplitude exceeds the threshold amplitude. Figure 10 illustrates the principle of operation. In order to visualize the behavior, the PWM frequency is chosen rather small. The top plot shows the PWM signal for a duty cycle (*dc*) of 0.5 (dashed) and 0.25 (solid). The second subplot shows a step response and two PWM signals with $dc = 0.5$ (dashed) and $dc = 0.25$ (solid). The bottom plot shows the slider displacement, which contains a small ripple. This ripple decreases with an increasing PWM frequency.

Depending on the sign of u the signals $u_{\rm min}$ and $u_{\rm plus}$ are zero or equal to the generated PWM signal. Furthermore, to obtain a linear relation between $\dot{x}_r$ and u, the duty cycle of the PWM signal is $dc = \sqrt{|u|}$. Hence, the PWM wave power for a constant amplitude $\hat{u} = 1$ is

$$P_{\rm pwm} \;=\; P_{\rm ssa,max}\hat{u}^2 dc \;=\; P_{\rm ssa,max}\sqrt{\dot{x}_r} \quad \text{for} \quad 0 \le \dot{x}_r \le 1 \tag{6}$$

Hence, the input power is zero for a zero slider velocity. Figure 9 shows $\eta_{\rm rel}$ for PWM actuation. The efficiency is 100 % for $dc = 1$ and $dc = 0$. The minimum efficiency is 25 %. A drawback of this method is the requirement of extra hardware. Figure 11 shows the result of

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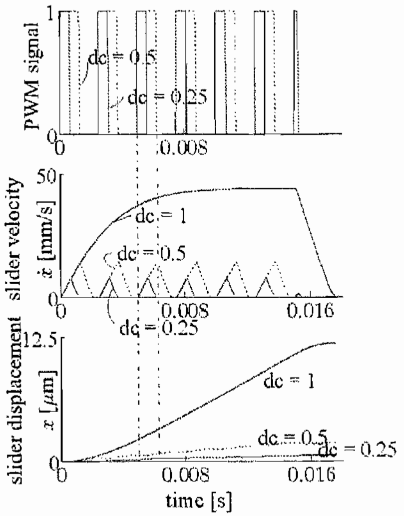

Figure 10: Slider behavior with pulse width modulation (simulation).

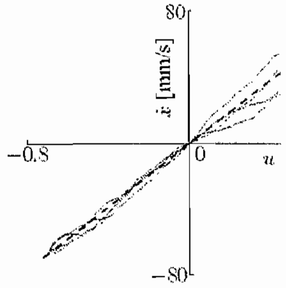

Figure 11: Experiment perform width modulation.

with a PWM frequency of 20 kHz that demonstrates the elimination of the dead the variation of the dead zone.

3.5 Overview of actuation methods

Table 1 contains an overview of the four discussed actuation methods. By com cussed methods it follows that the best results are obtained for PWM actuation the dead zone and its efficiency can be qualified as good. Furthermore, other ex demonstrated the closed-loop applicability of PWM. Therefore, actuation by me to be preferred.

method	eliminates dead zone	relative efficiency
SSA	no	best
SSA + compensation	partly	best
DSA	yes	low
PWM	yes	good

Table 1: Actuation methods.

4. Conclusions

We have demonstrated the existence of a varying dead zone between the control input and the no-force slider velocity of a SAW motor. The dead zone is caused by stick and the variation is, among others, due to variation of the wave amplitude, the preload and the coefficient of friction. By adding a constant value with a proper sign the dead zone only partly disappears (CSSA). Furthermore, CSSA allows overcompensation. The use of two opposite propagating waves (DSA) eliminates the dead zone without the risk of overcompensation. However, the input power for a zero slider velocity is large. Finally, this examination has shown that pulse width modulation (PWM) also eliminates the dead zone, also without the risk of overcompensation, but with considerably smaller input power compared to DSA in case of small slider velocities. Therefore, this method is recommended for SAW motor control, in particular closed-loop control.

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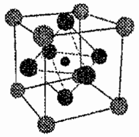

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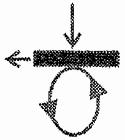

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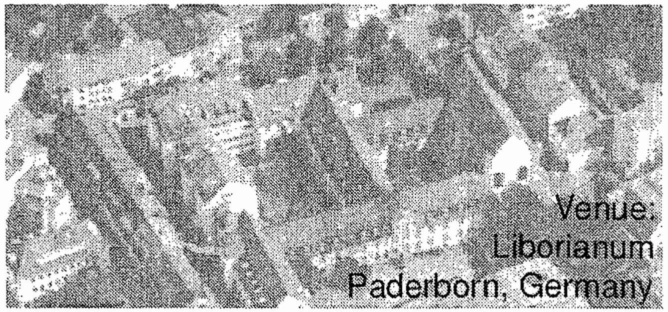

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