Analysis of a Surface Acoustic Wave Motor

P. J. Feenstra, P. C. Breedveld
Control Engineering Laboratory, Drebbel Institute for Mechatronics and Faculty of EEMCS,
University of Twente, P.O. Box 217, 7500 AE Enschede, Netherlands
{p.j.feenstra, p.c.breedveld}@utwente.nl

Abstract – Based on first principles a dynamical contact model of a Surface Acoustic Wave motor is built. Besides slider behavior also contact point behavior is obtained, which is hard to acquire experimentally. The contact point behavior is used to explain slider behavior like threshold amplitude and like oscillations that are observed in experimental set-ups.

I. Introduction

The use of Surface Acoustic Waves (SAW) for actuation has some inherent advantages and that give it some potential for high precision applications. It is shown [3] that it is possible to generate steps as small as (2nm) i.e. high resolutions. Furthermore, no lubrication is required, which makes it suitable for vacuum applications. An experiment showed that the motor is able to operate at a pressure of less than $3\ 10^{-2}$ mbar. Moreover, the motion will be blocked in absence of waves. A SAW motor is capable of operating in single and multiple degrees of freedom (DOF), e.g. planar motions [4] and rotational motions. Multiple DOF allows a compact and structural simple construction, which does not require guiding.

The principle of operation of a SAW motor is based on the elliptical motion of surface particles of a substrate (called stator); see figure 1. An object (called slider) is pressed with a sufficient preload force against the stator and due to the frictional contact a linear motion of the slider is generated. The slider is equipped with multiple contact points to prevent an air film.

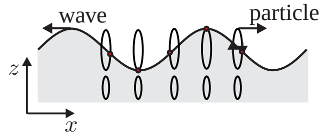


Fig. 1. Elliptical motion of surface particles

Quite a number of experiments were performed to determine the particular features of a SAW motor. The observable features include the threshold amplitude of the drive signal and the difference in falling and rising slopes of a step response. Besides the behavior of the slider, the behavior of the contact points is of interest, e.g. the stick-slip behavior that underlies the actuation. The latter cannot be observed straightforwardly.

The objective is to explain previously mentioned slider behavior by analyzing the contact point behavior, as not all observed phenomena are fully understood yet. To this end a hybrid, non-linear impact model is constructed based on first principles. The model considers a slider with one spherical contact point. The use of one contact point gives the same qualitative behavior as a multipoint slider due to the relatively large time constant of the slider motion with respect to the SAW frequency.

First a brief description of the basic components of a SAW motor will be given in section II. Section III describes the contact model. Some results obtained by simulation are discussed in section IV. Finally some conclusion are given in section V.

II. Setup

This section describes briefly the experimental setup. The setup exist of a block shaped stator ($35mm \cdot 160mm \cdot 5mm$) made of hard PZT equipped with four interdigital transducers (IDT) at the top surface (two at each side). Each IDT has 10 finger pairs, an aperture of $20mm$ and generates SAW at a frequency of $2.2MHz$.

For simulation an experimental slider consisting of an aluminium triangular shaped plate ($18mm{\cdot}1.5mm$) with 3 steel balls with $1mm$ radius glued at the bottom is chosen. The mass is $0.267g$ and there is no additional preload other than the gravity force.

III. MODEL

A hybrid, non-linear impact model is developed based on first principles in order to study slider and contact point behavior simultaneously. The model considers a slider with one spherical contact point. Hybrid refers to the switching between the *stick* and *slip* states involved with static friction. Secondly it refers to the switching of structure which appears due to the sinusoidal motion of a wave in normal direction, i.e. there is an intermittent contact between wave and slider when the wave amplitude exceeds a certain *release* amplitude. This release amplitude is discussed in next section.

The normal motion is considered first. The wave is approximated by a plane because its curvature is small relative to the curvature of a contact point. The normal stiffness of a *plane-sphere* contact can be found by literature [1]. According to Hertz, the normal force P as function of the total deformation z of both surfaces in normal direction is

$$P = \frac{4}{3} E \sqrt{R} z^{3/2} \Big|_{x=0} \quad (1)$$

where R is the radius of the sphere and E depends on the elastic properties of sphere and plane. Furthermore, the tangent force Q of a *plane - sphere* contact at a constant normal force P is given by

$$Q = \mu P \left(1 - \left(1 - \frac{16xaG}{3\mu P} \right)^{3/2} \right) \Bigg|_{P=const} \quad (2)$$

where μ is the Coulomb friction coefficient, $a = \left(\frac{3PR}{4E}\right)^{1/3}$ the contact radius, x the tangent deformation and G depends again on the elastic properties of sphere and plane [1]. See figure 2. Equations 1 and 2 should be combined to find a two port storage element, i.e. a relation that describes the interaction between normal and tangent deformation. However, the state of contact between two bodies subjected to variations in normal and tangential load depends on the history [1]. To simplify the problem we assume that the tangent stiffness is pure elastic, i.e. no dissipation due to micro slip. Consequently, equation 2 is relaxed to $Q = Q(P, x)$. Furthermore, it can be shown that the influence of tangent motion on the normal motion is small and therefore negligible hence $P = P(z)$. The normal motion can therefore be treated independently of the tangent motion.

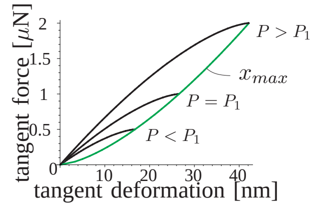
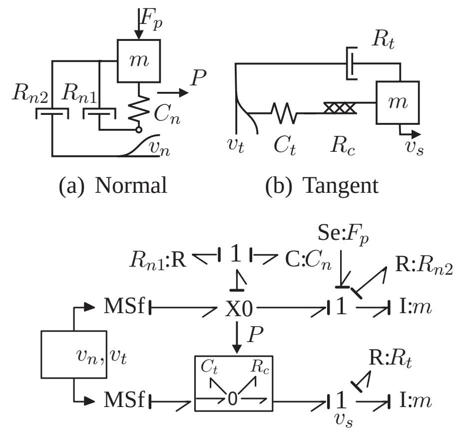


Fig. 2. Tangent stiffness as function of the normal force P



(c) Tangent and normal motion (bond-graph)

Fig. 3. Model of contact mechanism

Figure 3(a) shows the model of the normal motion. C_n is given by eq. 1. The open circle indicates a switched junction. A switched junction is used to the detect the moment of contact and switches between the *contact* and *no-contact* states. Element m represents the inertia, F_p denotes the preload force, which is the sum of the gravity force and an additional applied external force. R_{n2} represent viscous air damping and R_{n1} models losses as result of contact point deformation (non linear viscous damping). The normal motion of the wave is modeled by a velocity source v_n. The normal force P is used as input variable for the tangent model.

There is switching involved due to friction as pointed out at the beginning of this section. Friction is conceptual modeled by two elements. A (tangent) stiffness, eq. 2, that models the deformation (not the elasticity of asperities) and a dry friction element that models the dissipation. In case of **stick** there is no dissipation, because the velocity of wave and slider is equal at the point they touch. The deformation x and accordingly the force Q is calculated by the velocity difference between wave v_t and slider v_s, i.e. $x = \int(v_t - v_s)dt \rightarrow Q(x, P)$.

The transition from stick to slip occurs when the tangent stiffness reaches its maximal displacement $x_{max}(P)$ or equivalently when $Q = \mu P$. See figure 2. The displacement $x_{max}(P)$ can be found by substituting $Q = \mu P$ in equation 2. Note that the maximal displacement only depends on the normal force P. In case of **slip** there is dissipation (dry friction). The velocity v_f belonging to the dry friction element is given by

$$v_f \quad = \quad v_t - \dot{x}_{max}(P) - v_s \tag{3}$$

where v_t is the tangent wave velocity, $\dot{x}_{max}(P)$ the velocity change of the stiffness due to a change in normal force P and v_s the slider velocity, see figure 4. The causality for dry friction is given and fixed in case $v_f \neq 0$, i.e. $F_f = F_f(v_f)$. Therefore a causality change takes place, *viz.* the force is calculated by the dry friction and the velocity due to the tangent stiffness $\dot{x}_{max}$ is found by differentiation.

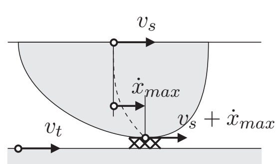


Fig. 4. Velocities in tangent direction ($\dot{x}_{max}$ is actually due to contact point and stator deformation)

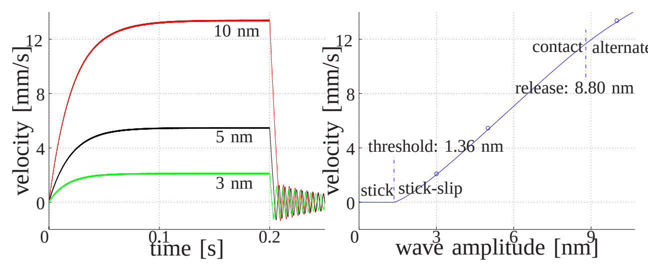
The contact remains in its slip state until the velocity difference v_f approximates zero. This implemented by defining an infinitesimal neighborhood DV around $v_f = 0$ [2]. The contact switches from slip to stick if $|v_f| < DV$.

The model of tangent motion is shown in figure 3(b), where R_t represents viscous air damping, C_t is given by eq. 2 and m is the inertia. The total model is implemented as bond-graph model in 20-Sim, see figure 3(c). Here $X0$ represents the switched junction and the MSf elements generate the wave velocities. The remaining elements are in conformance with the iconic diagram. C_t and R_c are implemented as one submodel.

IV. Results

This section presents some simulation results obtained with the model discussed in previous section. The parameters used in the simulation are derived from the slider and stator discussed in section II. Only one contact point is considered instead of 3, therefore some parameters are changed accordingly. The parameters E, G and μ are respectively 64 GPa, 12 GPa and 0.08 and the damping parameters are chosen arbitrary.

Figure 5 shows the *slider* behavior for a fixed preload F_p. Figure 5(a) shows the step (a burst of waves) response for different wave amplitudes. After a certain time the slider converges to a steady state velocity. The steady state velocity as function of the amplitude is shown in figure 5(b).

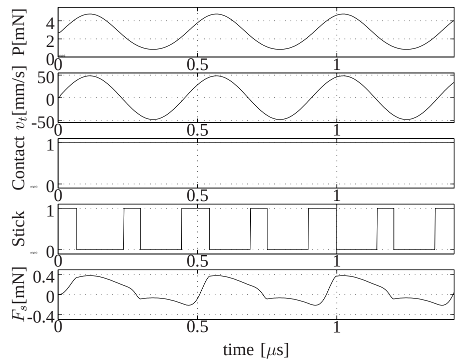


(a) Step responses for different wave amplitudes

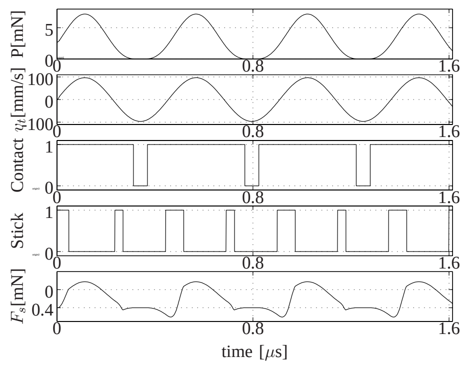
(b) Steady state velocity

Fig. 5. Slider behavior

First the steady state behavior will be discussed. Three regions can be distinguished, which are separated by the *threshold* and *release* amplitude. *(i)* There is no effective slider motion when the wave amplitude is smaller then the threshold amplitude. In this situation there is continuously stick between wave and slider. *(ii)* The slider starts to move when the wave amplitude exceeds the threshold amplitude, i.e. when slip occurs. Figure 6(a) shows the contact point behavior at acceleration. The time corresponds to figure 5(a). There is always contact between wave and slider when the wave amplitude is below the release amplitude. In this region, the normal force P reaches a maximum when the wave velocity v_t is positive and a minimum when the velocity is negative. Therefore, the average friction force, which drives the slider, becomes positive. Consequently, the steady state velocity will differ from zero. *(iii)* Within region 3, the wave amplitude exceeds the release amplitude. Therefore, the contact between a slider-contact point and the wave is intermittent. Accordingly, contact-no contact switching is present besides stick-slip switching. See figure 6(b).



(a) Constant contact: wave amplitude $= 3nm$



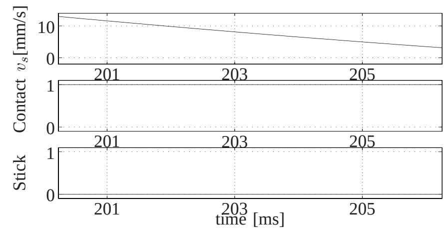
(b) Intermittent contact: wave amplitude $= 10nm$

Fig. 6. Contact point behavior: during burst

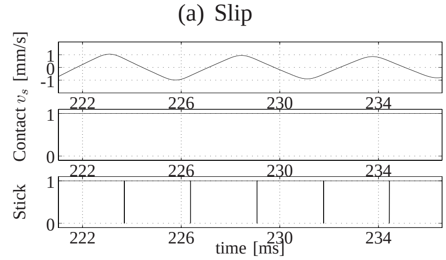
Secondly, consider the step response of figure 5(a). Two interesting phenomena occur when the burst ends. At the time instant where the burst ends there is a velocity difference between wave (=0) and slider v_s, see figure 7(a). Therefore only slip will be present and accordingly the applied slider force F_s equals approximately (ignoring dampers) $\mu P sign(v_s)$. Furthermore the normal force P is approximately constant. Therefore the acceleration $a = F_s/m$ is constant and the velocity v_s linear with time. The friction switches to stick when the velocity v_f becomes zero (within DV), see figure 7(b). A damped oscillation will occur due to the combination of tangent stiffness, mass and damper.

V. Conclusions

The model predicts the threshold amplitude in a qualitative way. This phenomenon is explained at contact point level, i.e. below the threshold amplitude the contact between slider and wave remains in stick-mode and accordingly no effective motion of the



(a) Slip



(b) Oscillation

Fig. 7. Contact point behavior: after burst

slider occurs. A step response of a SAW motor shows a difference between its rising slope and its falling slope. The rising slope has a curved shape, which at the contact points level is explained by stick-slip behavior between slider and wave. By contrast, the falling slope is linear with time due to dry friction (slip mode). Oscillation occurs after the linear slope. During the oscillation the contact is in stick mode and there is exchange of power between the slider mass and the stiffness of the contact points. The conclusion is that a study of the contact point behavior by means of simulation of a dynamic model enhances the insight into the SAW motor behavior. Quantitative validation of the model and obtaining design parameters will be addressed in future work.

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