Development of a Surface Acoustic Wave Planar Motor under Closed Loop Control

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ABSTRACT

This paper describes the development of a Surface Acoustic Wave (SAW) planar motor under closed loop control, which can be applied as an ultra precision multi-axis manipulator. In papers presented so far on this topic, a SAW motor is driven in open loop. The slider is manipulated by inducing a repetitive small number of wave periods. In this way a slow slider motion can be generated, which however, is not constant during the cycle time. Although very small steps have been reported for SAW actuators operating in open loop (in the order of 2 nm), the reproducibility of such open loop steering is low in an environment with disturbances. Therefore, one of our focus points is *closed loop control* of the SAW actuator. To investigate the open- and closed-loop behaviour, two linear SAW motor demonstrators have been developed. Measurements have shown that for conventional actuation a dead band appears in the response of the input signal to the speed of the motor. To overcome this phenomenon, a different way of continuous actuation is presented in this paper, on which a patent has been filed. As a result of the investigations of the linear demonstrators, a closed loop controlled *planar* SAW motor has been designed, which is under construction and is scheduled to be operational in the spring of 2002. This planar motor concept features a simple and compact construction with low moving mass, since the drive- and guiding-systems are combined, without the need for external bearings, transmissions or guiding systems. Compared to stacked linear systems, a high stiffness and good dynamic behaviour can be achieved. Further experiments are planned to establish the potential benefits of a planar SAW motor in applications of precision engineering and nanotechnology.

Introduction

Current solutions of multi-axis manipulators are often based on a stacked construction of linear systems consisting of an electromechanical motor, a transmission and a linear guiding system. Such concept results in a relatively large size and a reduced stiffness due to the series connection of components, and hence loss of accuracy and dynamic performance. Furthermore, each component contributes to the total mass, compliance and price of the drive unit. For this reason, a drive-system consisting of fewer components would be favourable. To reduce the number of components, a direct drive electromechanical system may be applied, thereby eliminating the transmission. In that case, the drive system has no self-jamming properties, so the adjusted position will be lost when the power is switched off. For this reason a brake system can be provided. Another solution may be to continuously apply power to the motor, which implies additional power-dissipation. In some cases flexures are used as guiding system due to their compact design, lack of hysteresis and vacuum compatibility. On the other hand, the travel range is limited (some mm), and a force has to be applied to overcome the stiffness of these elements. Many of the characteristics described above can be overcome by a different concept of a planar manipulator, like a design based on SAWs, that is described in this paper.

SAW actuation principle

The actuation principle of a SAW motor is based on moving a slider across an elastic solid medium, called stator, through the surface of which Rayleigh waves are propagating [1]. The waves are generated by applying an AC voltage (in this case with a frequency of 2.3 MHz) to so-called Inter Digital Transducers (IDTs), finger shaped galvanic patterns applied at a locally polarised stator surface. Our stator is made of PXE43, a homogeneous polycrystal. Considering the speed of Rayleigh waves in our stator ($2.2 \cdot 10^3$ m/s) and their frequency of 2.3 MHz, the wavelength, determined by the distance between two IDT-fingers with the same polarity, becomes 0.95 mm. At this frequency, the wave amplitude is in the range of 20 to 40 nm (depending on the applied voltage), demanding a surface roughness of about 20 nm. By ELID grinding a surface roughness of 10 to 15 nm has been attained. In order to generate sufficient traction force to move the slider and to prevent a squeeze airfilm between slider and stator, the contact surface of the slider (1 cm^2) consists of many ball-segments, closely packed, made by lithographic etching of silicon [1]. To avoid high contact pressure at the ball segments, a large radius of curvature has been applied. Depending on the number of ball-segments per cm^2 slider surface, a certain preload force has to be applied to provide maximum traction force. For this purpose, the weight of the slider itself is insufficient (approx. 0.4 N). In our case the applied preload force amounts to 40 N/cm^2, resulting in a traction force of 4 N. Depending on the application, several force generating principles can be applied, e.g. a vacuum- or magnetic-force, etc.

Linear demonstrator

In our first demonstrator the preload concept consisted of two sliders moving simultaneously at opposite sides of the stator and preloading each other by a spring, as shown in Figure 1. The required preload force between one of the sliders and the stator is identical to the force between the other slider and the stator and is generated by the spring. Consequently, an external guiding system –required to avoid slider motion in y-direction– is not loaded by the preload force, so the friction is limited. In addition, the preload force does not cause a bending load to the stator in this construction.

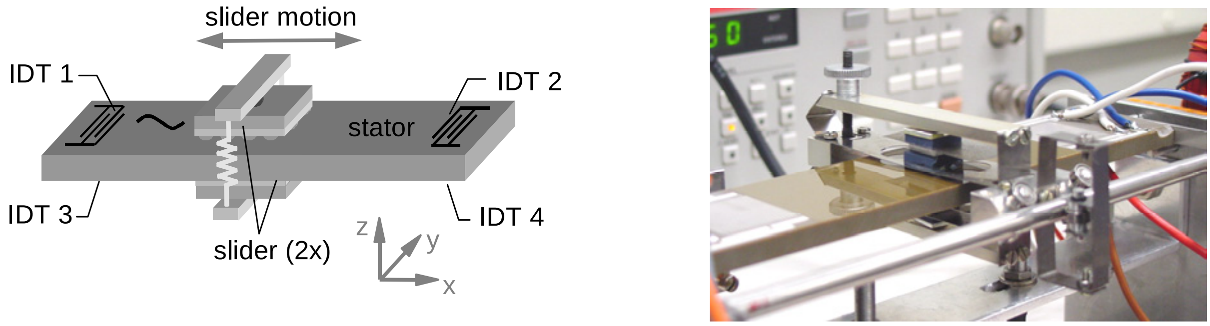

Figure 1 a) and b): Linear SAW motor with two sliders, preloading each other.

Modelling for control

In papers presented so far, small steps of 2 nm have been reported [2] for SAW actuators operating in open loop. In an industrial environment, disturbances will harm the reproducibility of this kind of open loop steering. Therefore, one of our focus points is to achieve closed loop control of the SAW actuator. Our first experiments with the linear motor involved stepresponses. Figure 2 shows the response of a square wave input, alternately positive and negative, resulting in backward and forward motion.

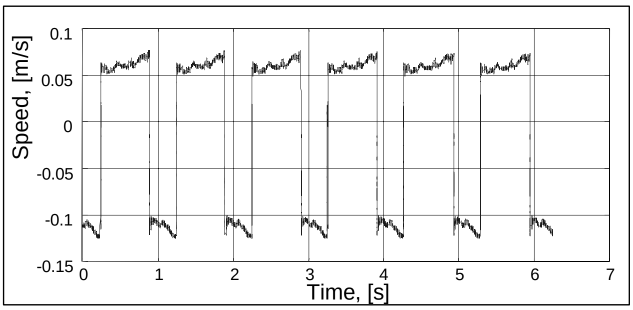

Figure 2: Slider response due to square wave input.

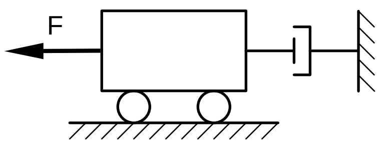

Figure 3: Simple model of linear SAW motor

This measurement learns that the achieved speed is quite reproducible for a number of alternating motions. However the speed-amplitude is different for motion backward and forward due to differences in electronic matching (not optimised yet). Furthermore, the speed varies with the position of the slider. This is caused by internal material damping and divergence of the wave during propagation through the stator. By applying closed loop control, this position-dependent behaviour can be overcome.

Considering a stepresponse, the actual speed of the slider builds up as an exponential function, thus suggesting first order behaviour, that can be represented by the simple first order model, given in Figure 3. This model consists of a mass and a damper, loaded by an external force F. The response of the input signal to the speed closely resembles the response of a voltage driven DC actuator. For that type of actuator, having an internal resistance and negligible self-inductance, the damper in the model can be physically explained by a back EMF: for increasing speed, the induced voltage rises.

For the SAW motor, the physical explanation of the damper lies in the *'running-in and -out'* of fresh material in the contact between stator and slider. Assuming elastic deformation of the material involved, the continuously running in and -out causes that the macroscopic observed behaviour is that of damping instead of stiffness, as the deformation is not allowed full restitution of the energy when the external force is lost. In daily life, this kind of phenomenon is encountered when driving a car in the presence of cross wind. For a car that is standing still, a constant cross wind leads to a constant displacement of the car due to lateral elastic deformation of the tires (stiffness). But when the car is moving (material is running in and out of the contact between tire and road), a cross wind leads to lateral displacement that is increasing at a constant pace. So although the stiffness in the contact is still providing the counter force, its macroscopic behaviour is that of a damper (constant force leads to a constant speed).

Experiments

The model proposed above suggests a linear system. However, measurements have shown that for Rayleigh waves that have an amplitude below a certain threshold, no movement of the slider results (see Figure 4a). So in the relation between wave amplitude and (steady state) speed, there is a dead band. The dead band appears for low inputs, since in that case, the wave amplitudes in transversal direction become smaller than the surface roughness of the stator. Furthermore, at the transition from standstill to motion, stick-slip occurs. These phenomena hamper good control of the SAW motor.

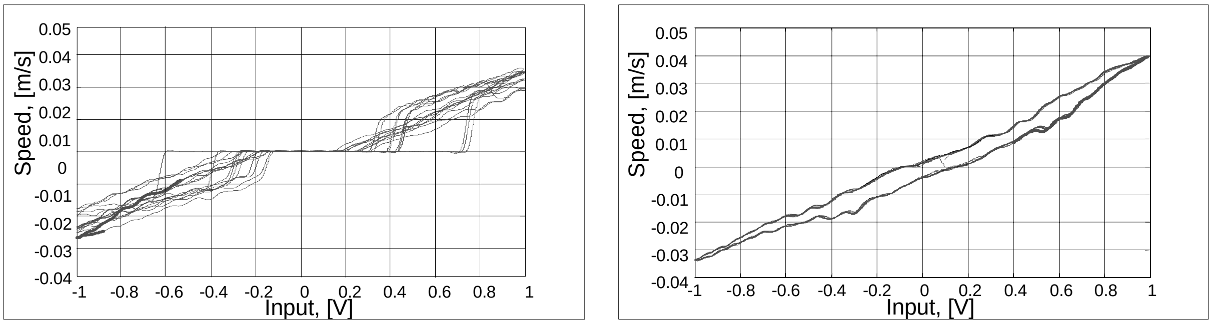

Figure 4: Measured open loop speed against input, a) dead band present, b) dead band solved.

In this paper a different way of continuous actuation is presented. To avoid the dead band, the slider is manipulated by generating simultaneous SAWs from opposite sides with slightly different amplitudes, which we call 'dual side actuation'. Experiments have shown that in this way, the dead band has been eliminated, see Figure 4b. In addition, the reproducibility of the system is high: Figure 4b shows ten backward and forward motions. In this way, a significant reduction of the smallest possible slider movement is envisaged with respect to single side continuous actuation. As a result, a high range to resolution ratio and a significant reduction of the minimum slider velocity are to be expected. Since we believe that high performance in closed loop can only be achieved when this dead band is eliminated, patent requests on the achieved solutions have been filed. Using this solution, the SAW actuator may now be considered as a linear system. So we can characterise it by a frequency response function (FRF), see Figure 5. Indeed, the mass-damper model can be recognised in the FRF, along with dynamics that have been identified as rigid body modes of the slider on its guiding due to a mismatch in position between applied traction force and centre of gravity.

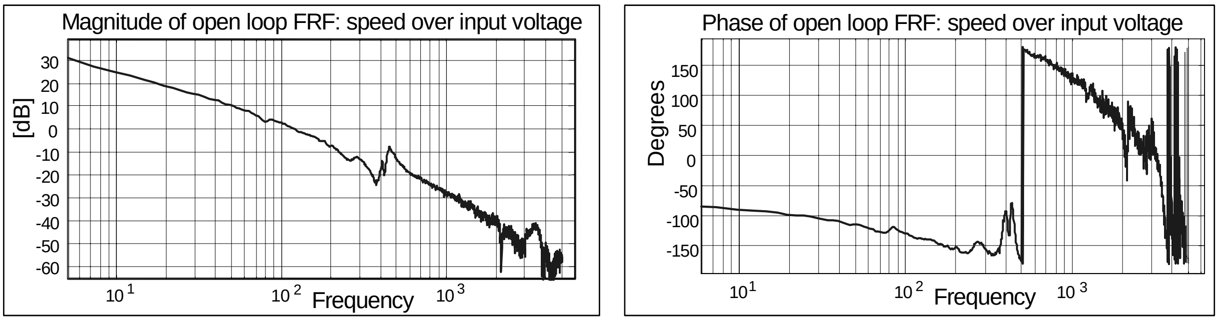

Figure 5: Open loop FRF of the linear SAW actuator.

At this point it can be concluded that, once the dead band between wave amplitude and response has been eliminated, *closed loop control* of the SAW actuator resembles controlling a voltage driven DC actuator, which implies applying straightforward control strategies. In line with common experience, the application of standard PID controllers to this kind of system (maybe with some extra filters) together with mass- and damping-feedforward, results in high accuracies. In closed loop control, the positioning accuracy attained for this demonstrator is a few increments (i.h.c. 0.15 μm) of the applied measuring system. The bandwidth of the SAW motor is limited by the wave propagation time and the sample time of the digital controller. Further experiments are planned to establish the potential benefits of the SAW motor under closed loop control.

Planar SAW motor

Using the knowledge obtained from the experiments with the linear demonstrators, the motor concept described above can be extended to a planar SAW motor (shown in Figure 6, size: 250x250x60 mm). Planar motion of a carrier is performed by controlling three degrees of freedom: two translations (x and y) and one rotation Rz. For this purpose the carrier has three sliders that can be driven individually in x- and y-direction across their accompanying stators. In this way, a rotation Rz can be generated by driving sliders 1 and 2 in opposite y-directions and slider 3 in the accompanying x-direction. Preload of each slider is performed by (adjustable) magnetic attraction between magnets connected to the carrier and a steel plate under the PXE-stator plates, resulting in a small structural loop of the preload force. A complementary function of the steel plate is to improve ambient heat transfer from the piezo-actuators. The position of the slider is measured by a planar measuring system, consisting of a grid plate that is connected to the bottom side of the carrier, and a readhead which is adjustable with respect to the frame. Hence, no moving cables or hoses –that could disturb motion– are connected to the carrier. The control strategy of the *planar* SAW actuator is based on principles described above, along with a decoupling strategy in both measurement and actuation. Figure 7 shows a picture of the mechanics of the planar motor which is under construction at the moment.

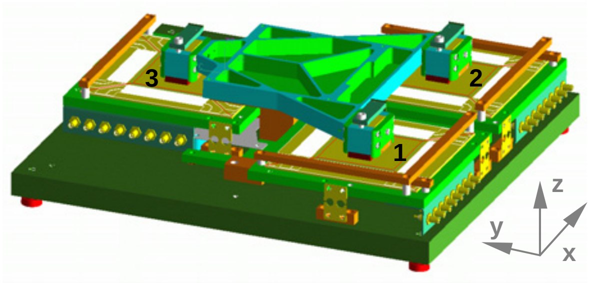

Figure 6: Design Planar SAW motor

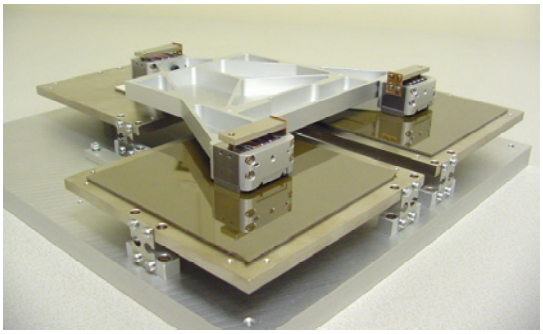

Figure 7: Mechanics of planar SAW motor

The planar SAW motor features a simple and compact construction with low moving mass, since the drive- and guiding-systems are combined, and without need for external bearings, transmissions or guiding systems. As stiffness is present after switching off power, no additional brake system is required, thereby reducing complexity and increasing accuracy. Due to the planar shape of the motor instead of stacked linear systems, a high stiffness and natural frequency are combined with a compact construction. Due to the absence of flexures, a large travel range results, and no parasitic flexure-forces have to be overcome.

Conclusions

In this paper the development of a SAW planar motor under closed loop control is described. To investigate the open- and closed-loop behaviour, two linear demonstrators have been developed. A different way of continuous actuation has been found and patented, to overcome a dead band in the response of a conventionally driven SAW motor. A planar SAW motor, featuring a simple and compact construction, is under construction and will be realised in the first half of 2002. Further experiments are planned to establish the potential benefits of the SAW planar motor in applications of precision engineering and nanotechnology.

References

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