CAPACITIVE LONG-RANGE POSITION SENSOR FOR MICROACTUATORS

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ABSTRACT

Design, fabrication and measurements for a capacitive long-range position sensor for microactuators are presented. The sensor consists of two periodic geometries (period $\approx 8\text{-}16\mu\text{m}$) on resp. a slider and a sense-structure with minimal gap-distance of $\sim 1\mu\text{m}$. A relative displacement between the two results in a periodic change in capacitance. In open-loop operation the change in capacitance vs. slider displacement is measured using synchronous detection. Adjusting the minimal gap-distance with additional sense-actuators increases the capacitance. In closed-loop operation the position of the sense-structure is controlled to keep the sensor-capacitance at a larger constant value. Our results indicate that the position precision is increased to 18 nm in closed-loop operation compared to 70 nm in open-loop operation.

Keywords: capacitive position sensor, displacement transducer, microactuator, nano-position control.

1. INTRODUCTION

Accurate positioning is of paramount importance for many applications of micro-systems. Microactuators for example have a high potential in probe-microscopy and future probe memory applications [1] provided that nm position accuracy can be obtained over 10^3 's of μm displacement range. In many cases such accuracies cannot be obtained using open loop control and, thus, position sensing is required. In order to make such systems both economically viable as well as compact, on chip position sensing appears to be a requirement.

Pedrocchi et al [2] have demonstrated a PC board 10x model for a long-range micromachined capacitive position sensor with an optimized electrode pitch-to-spacing ratio. Measurement results were limited by Johnson noise to 63 nm sensitivity. Because of the geometry of the capacitance this concept suffers from out-of-plane forces. Cheung et al [3] and Legtenberg [4] have used micromachined comb-sensors to detect displacements. Cheung was able to measure lateral positions with 0.01 μm estimation error using Kalman state-variable feedback. Legtenberg measured a linear change $\Delta C/\Delta x \approx 2.67$ [fF/ μm] with initial capacitance $C_{\text{comb}} \approx 300$ fF ($\Delta C_{\text{max}} \approx 80$ fF) over a deflection range of 30 μm . Kung et al have reported an air-gap-capacitor pressure sensor with integrated NMOS circuits where a 100 fF air-gap-capacitor could be measured with a resolution of less than 30 aF [5].

In the broader context of this work we investigate a capacitive position sensor integrated with a micromachined electrostatic microactuator to facilitate nano-position control. The aim is to develop a position sensor with nanometer accuracy over a

displacement range of 50-100 micrometers. To achieve this while keeping the demands on the dynamic sensing range of the sensor modest, a combination of discrete (counting) and analog measurement techniques is investigated.

Capacitive metrology systems and capacitive displacement transducers using phase read-out with mm-scale electrode plates are known to be able to achieve nm-accuracy or better with large dynamic range [6,7,8]. For micro-scaled MEMS devices a capacitive position sensor becomes a challenge because of small sensor capacitances with relative large influence of parasitics and noise-sources (e.g. kT/C).

2. MEASUREMENT CONCEPT

The concept for a surface-micromachined capacitive position sensor presented in this article is given in Fig. 1 and an example of a realized device is given in Fig. 2. The sensor consists of a slider driven in x-direction by two electrostatic comb-drive actuators in push-pull configuration [9] and sliding along sense-structures, which are fixed in x-direction only. Both slider and sense-structures have opposing periodic patterns. In open-loop operation, the capacitance between slider and sense-structure changes periodically as the slider-beam moves (x-direction). By counting the number of periods as well as measuring the change in capacitance within one period, one will in principle be able to obtain a (infinitely) long-range position measurement with high resolution and high accuracy i.e. an incremental position sensor. Additional sense-actuators (comb-drives) are used to make the design-gap between slider and sense-structure smaller, thus, increasing the capacitance C_s and capacitance variation ΔC_s .

Fig. 1: Concept of the capacitive long-range incremental position sensor.

In closed-loop operation the sense-actuators are controlled in order to keep the capacitance C_s constant (i.e. $C_s = C_0$, $\Delta C_s = 0$). As a result the sense-structures will move in y-direction, closely following the pattern on the slider. The required sense-actuator voltage (i.e. the control voltage U_{control}) will have the same period as the periodic geometry and becomes a measure for the slider displacement. This way of control can give a better Signal-to-Noise Ratio (SNR), because for all position points within

a period the sensor-capacitance is kept at a larger constant value than is possible with open-loop operation.

To our knowledge the combination of long-range, high accuracy and micromachined devices as presented in this work has not been addressed before. Previously, various geometry combinations were investigated numerically with respect to maximum performance (i.e. large capacitance and large capacitance changes) [10]. Our first experimental results using an impedance analyzer indicated that simulation results were in the same order as the measured capacitance values [11]. In this paper we describe the experimental results for two measurement concepts using a synchronous detection technique: i) Open-loop operation, ii) Closed-loop operation. These concepts are independent of their application in micro-scale devices but the realization raises particular challenges including capacitance measurement.

Fig. 2: Micromachined periodic capacitive position sensor. As the slider beam moves, the capacitance between opposing periodic patterns on the slider and the sense structure changes.

Design and fabrication

An example of a realized device is given in Fig. 2. It is fabricated in a one-mask surface micromachining process as described by Legtenberg [12]. All structural parts are in a 5 μm -thick Boron-doped poly-Silicon layer. In this symmetric design electrostatic forces on the slider are balanced. Fabrication is relatively easy because sensor and actuator are in the same layer and made with the same technology, using only one lithographic mask. The symmetric periodic electrode patterns inherently cause ambiguities in position detection and a periodic sensitivity. Hence, in our design we intend to use quadrature detection combined with two geometrically shifted sense-structures so that a minimum in sensitivity for one sense-structure is balanced by a maximum in sensitivity of the other (see Fig. 3).

3. EXPERIMENTAL RESULTS

Fig. 4 gives a schematic view of the applied capacitance measurement technique. An ac-voltage with amplitude U_s and frequency f_s is probed to the sensor capacitance C_s and the result-

ing current is converted by the charge-amp to a voltage (inverted) which is mixed and filtered in the synchronous detector. The dc-output voltage is proportional to the ac-current going through C_s and therefore it is also proportional to C_s . The output voltage is measured with an HP34401A multimeter. The capacitance values are determined by calibrating the output voltage of the synchronous detector with the use of fixed smd capacitors and an HP impedance analyzer.

Fig. 3: Two sense structures with rectangular fingers opposing a triangular pattern (period of 16 μm) on the slider can be used in a quadrature detection technique if they are shifted a quarter period.

Fig. 4: Schematic view of the applied capacitance measurement technique. The changing sensor capacitance can be measured using a charge-amplifier and synchronous detection.

The Low-Pass-Filter (LPF) of the synchronous detector has a bandwidth (BW) of 100 Hz. The multimeter has an LPF set to 3Hz and a measurement resolution set to slow-6-digits. This means 100 Power Line Cycles are used for averaging i.e. $\text{BW}=0.5$ Hz. The device is connected through probe-needles for both actuation and sensing. The charge-amp and synchronous detector are specially designed on small-scale pcb-design and positioned as close as possible to the device. All measurements are carried out without reference capacitance (Fig. 4).

Results for Open-loop operation

Fig. 5 shows the various periodic geometries that were included in both 2D-FE simulations [10] and the measurements presented here. Fig. 6 shows the measured change in capacitance vs. slider displacement for different geometry combinations. Here, the

minimal gap-distance was determined by the standard available lithography process and the distance was not electronically altered. By carefully designing the lithography mask it was possible for larger periods to achieve a design gap-distance g_d lower than the normally obtainable distance of $\approx 2 \mu\text{m}$. The curves in Fig. 6 are sections of the measured mean capacitance after 10 cycles of slider displacement. In each cycle the displacement of the slider has been $x=0, \approx 17, \approx 17, 0 \mu\text{m}$ in steps of $\sim 150 \text{ nm}$.

Fig. 5: Various opposing periodic geometries were included in the measurements.

Fig. 6: Measured change in capacitance ΔC up to one period for different geometries and design gaps g_d .

Fig. 6 shows the measured change in capacitance as a function of position for different periodic geometry combinations. The combinations a, b, c, show a larger periodic capacitance change due to a smaller design-gap. A smaller gap also allows for a smaller period of the electrodes, which improves the position accuracy. The fabricated devices show a maximum sensitivity in the order of $4 \text{ fF}/\mu\text{m}$. The accuracy of these particular capacitance measurements, based on the calculated (maximum/minimum) standard deviation, is between 14 aF and 0.5 fF and is limited by temperature and humidity variations of the surrounding air and small particles that occasionally were found to obstruct a proper motion of the slider [11] and cause hysteresis. Thus, using two sensing structures shifted by a quarter period, a position-accuracy of 125 nm or better is obtained.

The correspondence between the measured capacitance and

the capacitance obtained by 2D finite element simulations is satisfactory. The 2D-FE modeling proves to be a useful tool to predict the capacitance as a function of displacement for different periodic geometries.

Fig. 7 gives the measured capacitance vs. slider displacement for a device with a sinus pattern on the slider and rectangular 'fingers' on the sense-structures with a period of $10 \mu\text{m}$ (Fig. 5). The displacement values of the slider are determined by calibrating the applied actuation voltages of the driving actuators with the known distance between 2 points of maximum (minimum) capacitance i.e. the design period P_x . With 14 Vdc (II) applied to the additional sense-actuators, the gap is considerably smaller than the design-gap of $1.5 \mu\text{m}$ and the change in capacitance is clearly increased. The maximum sensitivity has increased from app. $2.4 \text{ fF } \mu\text{m}^{-1}$ (I) to $4 \text{ fF } \mu\text{m}^{-1}$ (II).

Fig. 7: Two measured curves using synchronous detection. Applying a voltage (II) to the sense-actuators decreases the gap between slider and sensing structures and increases $\Delta C(x)$.

The curves in Fig. 7 show that the measured change in capacitance after 1 cycle has much less hysteresis caused by small particles, changing temperature and humidity of the environment, than reported in [11]. For both curves the mean difference $(\text{Err})_{\text{mean}}$ between up- and down sweep is calculated. $\text{Err}(I) \approx 98.6 \mu\text{V}$, $\text{Err}(II) \approx 236 \mu\text{V}$. Taking the ratio with the measured amplitude $|\Delta u|_{\text{max}}$ per $5 \mu\text{m}$ this error corresponds with a displacement error. The maximum amplitude $|\Delta u|_{\text{max}}(I) \approx 10.6 \text{ mV}$ ($|\Delta C|_{\text{max}} \approx 12 \text{ fF}$) and $|\Delta u|_{\text{max}}(II) \approx 16.7 \text{ mV}$ ($|\Delta C|_{\text{max}} \approx 20 \text{ fF}$). The estimated displacement uncertainties are $\Delta x_x(I) = 46 \text{ nm}$ and $\Delta x_x(II) = 70 \text{ nm}$.

The (unwanted) slope in the curves is probably caused by the cross-talk of the (changing) capacitance of the driving comb-actuators.

Results for Closed-loop operation

In closed-loop control operation the sense-structures are actuated by sense-actuators to keep the output voltage of the synchronous detector ($U_{\text{out_det}}$) at a certain value i.e. the setpoint-value U_{setpoint} . This setpoint value corresponds to a certain capacitance and thus corresponds to keeping the sensor-capacitance constant (i.e. $\Delta C_s = 0$). The implementation of the control for the following experiments consists of a PC-implemented PID control program (HPVEE). When the sliderbeam is at a certain position where the measured output voltage $U_{\text{out_det}}$ dif-

fers from the setpoint U_{setpoint} , the PID controller calculates the necessary control voltage for the sense-actuators to make the error zero. When the error is below a certain limit (e.g. Error-limit=25 μV) for 4 successive measured values, the slider jumps to a new position. A typical result is given in Fig. 8 for two setpoint values. Setpoint 2 (SP2= -0.554V, corresponds with a larger sensor capacitance value than setpoint 1 (SP1= -0.553V) and results in a larger amplitude of the control voltage. However, the pid-control voltage has been limited to 28V in Fig. 8 because of possible side-pull-in of the sense-actuators for higher voltages.

Fig. 8: The measured control voltage for the sense-actuators in closed-loop operation for two different setpoints. The sensor-capacitance value for setpoint 2 is larger than for setpoint 1.

The average differential change dV/dx in control voltage $U_{\text{control}} \approx 2\text{V } \mu\text{m}^{-1}$ and $|dV/dx|_{\text{max}} = 3.8\text{V } \mu\text{m}^{-1}$ around $x=0$. With the same procedure as for open-loop the mean difference between up- and down sweep (1 cycle) is $\text{Err}_{\text{mean}}(1) \approx 78.5\text{ mV}$, $\text{Err}_{\text{mean}}(2) \approx 37\text{ mV}$ and corresponds to estimated displacement uncertainties $\Delta e_x(1) = 40\text{ nm}$ and $\Delta e_x(2) = 18\text{ nm}$.

4. DISCUSSION

The values for sensitivity ($4\text{ fF } \mu\text{m}^{-1}$) and accuracy ($<0.5\text{ fF}$) for the open-loop measurements of capacitance versus slider displacement correspond to values reported in literature. The results in Fig. 6 can be seen as the result of open-loop capacitance measurement without sense-actuators. The change in capacitance vs. displacement is determined by the choice of design gap-distance and periodic geometry and limited by the available standard lithography. With the additional sense-actuators the gap can be made smaller than designed and Fig. 7 shows, the change in capacitance is increased. In principle the larger capacitance would mean a larger Signal-to-Noise Ratio SNR based on kT/C . However, we see that the calculated displacement error $\Delta e_x(II)$ is larger than $\Delta e_x(I)$. We think the cause may be additional noise from the voltage-supply and humidity and temperature changes. The influence of the last two effects is expected to diminish with the use of a reference capacitance (Fig. 4).

Closed-loop operation can give a better SNR, because for all

position points within a period the sensor-capacitance is kept at a larger value than obtainable with open-loop and stays at that value. For closed-loop operation the calculated displacement uncertainty of 18 nm is indeed lower than for open-loop and clearly shows its potential. Though, an external characterization setup is needed to specify the achieved accuracy more clearly.

5. CONCLUSIONS

Design, fabrication and measurements for a capacitive long-range position sensor for microactuators are presented. Two different concepts, open-loop operation and closed-loop operation, are discussed. The sensor consists of two periodic geometries (period $\approx 8\text{--}16\mu\text{m}$) with minimal gap-distance of ca. $1\mu\text{m}$. A relative displacement between the two, results in a periodic change in capacitance, which is measured using synchronous detection. In open-loop operation, the change in capacitance vs. slider displacement can be increased by decreasing the minimal gap-distance with additional sense-actuators. A maximum sensitivity of $4\text{ fF } \mu\text{m}^{-1}$ and a calculated uncertainty of 70 nm are found. Closed-loop operation does potentially increase the Signal-to-Noise Ratio (SNR) and shows an uncertainty of 18 nm.

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Acknowledgements

This research is financed by the Dutch technology foundation STW. The MESA+ laboratory staff is much acknowledged