Micromachined capacitive long-range displacement sensor

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Summary: *First measurement results are presented for a surface-micromachined long-range (50– 100 μm) periodic capacitive position sensor. The sensor consists of two periodic geometries (period = 10 μm) sliding along each other with minimum spacing of about 1.5 μm. The relative displacement between the two, results in a periodic change in capacitance. An electrostatic comb-drive actuator is employed to generate displacements. Measured maximum capacitance change ΔC=0.72 fF corresponds to simulation results but needs better shielding from external noise sources. The results show this sensorconcept can potentially lead towards long-range nano-positioning control of microactuator systems.*

Keywords: *periodic capacitive position sensor, displacement transducer, periodic geometry, surface-micromachining, MEMS, comb-drive, microactuator, nano positioning,*
Category: *1 (General, theoretical and modeling) & 10 (Applications)*

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's of μm displacement range. In many cases such accuracies cannot be obtained using open loop operation 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.

In 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 nm-range 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.

2 Measurement concept

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 [2,3,4]. 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).

The concept for the surface-micromachined capacitive position sensor presented in this article is given in Figure 1. The sensor consists of a slider driven by two electrostatic comb-drive actuators and sliding along a fixed sense-structure. Both slider and sense-structure have opposing periodic patterns. As the slider-beam moves (x-direction) the capacitance between slider and sense-structure changes periodically. 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 long-range position measurement with high resolution and high accuracy.

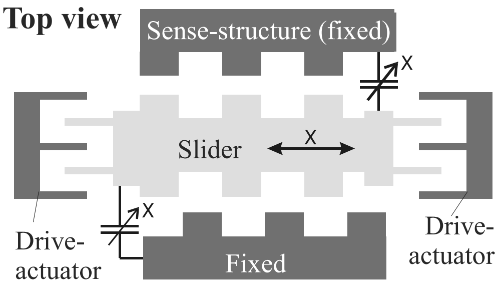

Figure 1: Concept of a capacitive long-range position sensor. Dark parts are fixed, light part moves.

Pedrocchi et al [5] 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 [6] and Legtenberg [7] 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 $C_{comb} \approx 300$ fF ($\Delta C_{max} \approx 80$ fF) over a deflection range of 30 μm. Kung et al [8] 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. These figures indicate that measurement of the capacitance-changes of the periodic capacitive sensor and micromachined devices is feasible. 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 pattern combinations were investigated numerically with respect to maximum performance (i.e. large capacitance and large capacitance changes) [9]. In this paper we describe the first experimental results.

3 Design and experimental

An example of a realized device is given in Figure 2. It is fabricated in a one-mask surface micromaching process as described by Legtenberg [10]. In this symmetric design electrostatic forces on the slider are balanced. The symmetric periodic electrode patterns we use 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 Figure 2).

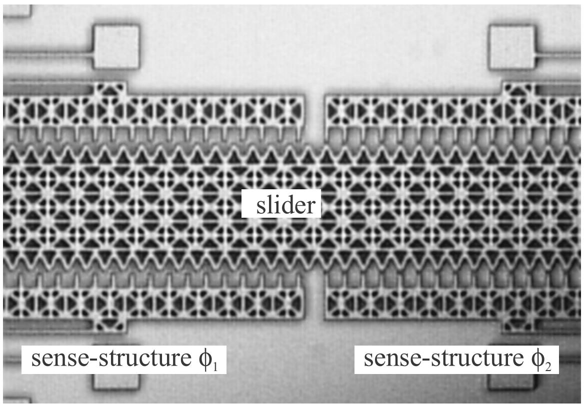

Figure 2: Photograph of a micromachined long-range capacitive position sensor with a slider beam with sinusoidal 10 µm-period and 2 pairs of sense-structures with rectangular 'fingers'. Minimum gap is 1.5 µm.

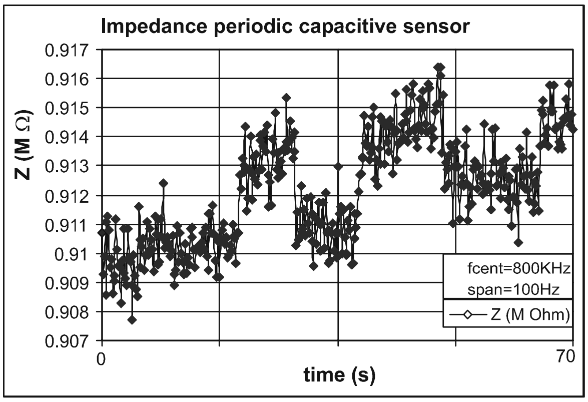

Figure 3: Impedance of 1 sense-structure as measured with the HP4194A impedance analyzer for the structure of Figure 2. The impedance is measured while the slider is step-wise displaced.

We performed measurements with a HP4194A impedance analyzer and compared results with 2D-Finite-Element simulations [9] for various periodic geometries. Measurement results for the micro-machined device in Figure 2 are presented. The impedance of one sense-structure at f=800 kHz was measured, while the slider is driven by a comb-drive microactuator between a position of minimum capacitance (sense-structure bottom-left) and a position of maximum capacitance (bottom-right). The sliderbeam has a sinusoidal pattern and the sense-structures have rectangular-fingers by design but are rounded by the micromaching processes. The period of the pattern is $P_x = 10\mu m$ and the minimum gap is $g=1.5\mu m$. Each point in the graph was obtained by averaging 8 measurements, each obtained using an integration time set to 'medium'.

The steps in impedance in Figure 3 correspond to a change in capacitance $\Delta C \approx 0.72$ fF around a nominal capacitance value of $C_{nom} \approx 218$ fF. FE-simulations of the capacitance between a 10µm-period sinus-pattern and rectangular fingers on slider and sense-structure respectively, show a $\Delta C_{max} = 2.4$ fF for a minimum gap of 1 µm and $\Delta C_{max} = 0.7$ fF for 2 µm gap. This is a clear indication that the measured changes in capacitance are indeed due to the displacements. Figure 3 also shows that the measurement set-up needs further improvement to decrease external disturbances and noise sources. Naturally, the first next step is to measure with all 4 sense-structures and implement proper shielding. Future work will also encompass different measurement techniques.

4 Conclusions

We have shown first experimental results for micromachined capacitive long-range displacement sensors based on electrode patterns with periodic geometry. Measurements clearly show the potential of this method.

References

1 P.Vettiger, M.Despont, U.Drechsler et al., The "Millipede" - More than one thousand tips for future AFM data storage, IBM J RES DEV 44 (3): 323-340 MAY 2000

[2] L.K.Baxter et al., Capacitive Sensors: design and applications, IEEE Press, New York, 1997.

[3] P.D.Atherton, T.R.Hicks, The Nano-positioning book, Queensgate Instruments, Berkshire, 2000.

[4] K.B.Klaassen, C.L.van Peppen, Linear capacitive microdisplacement transduction using phase read-out, Sensors & Actuators, **3**, (1982), 209-220.

[5] A.Pedrocchi, S.Hoen *et al*, Perspectives on MEMS in Bioengineering: A novel Capacitive Position Micro-sensor, IEEE Trans. On Biomedical Eng., **47**-1, (2000), 8-11.

[6] P.Cheung, R.Horowitz, Design, Fabrication, Position Sensing and Control of an Electrostatically-driven Polysilicon Microactuator, IEEE trans. Magnetics, **32**-1, (1996), 122-128.

[7] R.Legtenberg, A.W.Groeneveld *et al*, Towards Position control of electrostatic comb drives, *Proc. 6th Workshop on Micromachining Micromechanics and Microsystems (MME'95)*, Copenhagen, Denmark, 3-5 Sept.,1995.

[8] J.T.Kung, H.S.Lee, An integrated Air-Gap-Capacitor Pressure sensor and digital readout with sub-100 attofarad resolution, J. of Microelectromechanical systems, **1**, no.3, 121-128, 1992.

[9] A. A. Kuijpers et al. 2D-Finite-Element simulations for long range capacitive position sensor, invited for publication in J. Micromech. Microeng, July 2003.

[10] R.Legtenberg et al., Comb-drive actuators for large displacements, J.Micromech. Microeng., **6**, (1996), 320-329.