

Measurements for a capacitive incremental position sensor for microactuators

Toon A.A.Kuijpers*, Gijs J.M.Krijnen, Remco J.Wiegerink, Theo S.J.Lammerink, Miko C.Elwenspoek
Transducer Science & Technology group, MESA⁺ Research Institute, University of Twente

*Email: a.a.kuijpers@utwente.nl

Abstract— Integrated high accuracy long-range position sensing will be of paramount importance for high potential applications like future probe memories [1, 2] and probe-microscopy scanners provided that nm position accuracy can be obtained over 10's of μm displacement range. In this work design, fabrication and measurements of an integrated incremental 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 a slider (connected to a microactuator) and one on a sense-structure (fixed) with gap-distance of $\sim 1\ \mu\text{m}$. A relative displacement between the two results in a periodic change in capacitance. In normal operation (i.e. the Incremental Capacitance Measurement Mode (ICMM)) the change in capacitance vs. slider displacement is measured directly using a charge amplifier and synchronous detection at 1 MHz. Adjusting the minimal gap-distance by additional sense-actuators increases the capacitance and the S-N Ratio. In a second mode of operation, Constant Capacitance Measurement Mode (CCMM), the gap between sense-structures and slider is actively controlled to keep the sensor-capacitance at a pre-set value for all positions of the slider. Thus, the control signal (i.e. the voltage for the sense-actuator) becomes a measure for the position of the slider. Our results indicate that the position measurement accuracy is increased to $\sim 10\ \text{nm}$ in CCM operation compared to $46\ \text{nm}$ in normal operation [3]. Further results (using normal operation) show that the realized capacitive sensor can be used in ICMM for frequencies above the resonance frequency ($f_{\text{res}} \sim 1.6\ \text{kHz}$) of the device and therefore also characterizes the important dynamic properties of the test-vehicle.

Keywords— micromachined capacitive position sensor, periodic geometries, synchronous detection, nano-positioning

I. INTRODUCTION

Accurate positioning over a large range of displacement is of paramount importance for many applications of micro-systems. Microactuators for example have a high potential in future probe memory applications [1,4], scanning probe microscopy [5], medical analysis [6] and cell manipulation (e.g. DNA scanning [7]), optical mirror manipulation, microtooling and robotics (e.g. microgripper) etc, provided that nm position accuracy can be obtained over 10's of μm displacement range. In many cases position

sensing and closed-loop control is required to obtain such accuracies and improve the systems' dynamic performance. In order to make such systems both economically viable as well as compact, on-chip position sensing appears to be a requirement.

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 [2,8,9]. 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 capacitive sensing principle offers relative easy integration of sensor and electrostatic microactuator through micromachining technology. Furthermore, this sensing principle offers possibilities for monolithic CMOS compatible integration and a wide range of electronic interfacing possibilities [2, 10]

In this work the concept, fabrication and measurements for an incremental capacitive long-range position sensor for microactuators are presented. Integration of the position sensor with a micromachined electrostatic microactuator facilitates 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.

II. MEASUREMENT CONCEPT

The micromachined capacitive incremental position sensor consists of two opposing periodic geometries (period $\approx 8\text{-}16\ \mu\text{m}$) on a slider (connected to a microactuator) and one on 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, Fig. 1. In Incremental Capacitive Measurement Mode (ICMM) the change in capacitance vs. slider displacement is measured directly.

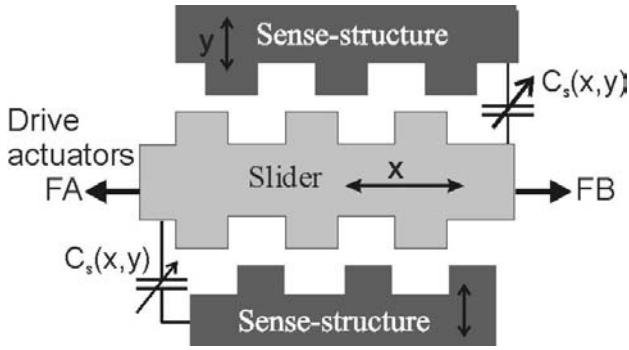


Fig. 1: Concept of the capacitive long-range incremental position sensor.

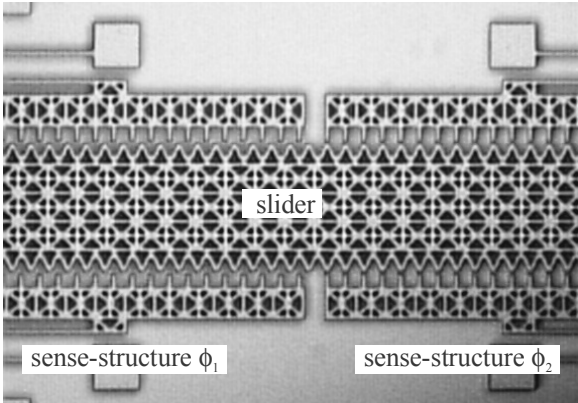


Fig. 2: Micromachined long-range capacitive position sensor with a sine vs rectangular finger geometry and period size of 10 μm . Minimum gap $g \approx 1.5 \mu\text{m}$. Two pairs of sense-structures are shifted a quarter period to make a quadrature detection technique possible.

Additional sense-actuators (comb-drives) are used to reduce the design-gap between slider and sense-structure, only once before the actual measurement operation starts, thus, increasing the capacitance $C_s(x)$ and capacitance variation $\Delta C_s(x)$ (i.e. $C_s(x) = C_{\text{mean}} + \Delta C_s(x)$) and the signal-to-noise ratio SNR.

In a second mode of operation, Constant Capacitance Measurement Mode (CCMM), the gap between sense-structure and slider is actively controlled to keep the sensor-capacitance at a pre-set value for all positions of the slider. Thus, the y-position of the sense-structure or the control signal (i.e. the voltage for the sense-actuator U_c) becomes a measure for the position of the slider.

By counting the number of periods and measuring the change in capacitance $\Delta C_s(x)$ or voltage $\Delta U_c(x)$ within one period, in principle a (infinitely) long-range position measurement is obtained with high resolution and high accuracy i.e. an incremental position sensor.

The preferred shape for $\Delta C_s(x)$ or $\Delta U_c(x)$ would be either pure sine or triangular to apply a quadrature detection technique [2]. Previously, various geometry combinations were examined through 2D-FE simulations for both CIMM and CCMM with respect to performance i.e. large capacitance changes. Further optimization is necessary to find the ideal geometry

combination producing sine- or triangular output functions. Also the accuracy of the micromachining process to make these geometries needs to be scrutinized as well. In this paper we describe the improved measurement results for both modes of operation.

III. EXPERIMENTAL ASSESSMENT

This section describes quasi-static measurement results for CIMM and CCMM and dynamic measurement results for CIMM using a similar device as depicted in Fig. 2. The aim with these experiments is to demonstrate the performance of these modes of operation at low- and high frequency actuation.

The device is made through surface-micromachining as described by Legtenberg [11]. It contains a poly-silicon structural layer with a height limited to 5 μm , which is deposited on top of a sacrificial Silicon-oxide (SiO_2) layer with a thickness limited to 3 μm .

A. Quasi-static Measurements CIMM

The change in capacitance vs. slider displacement is measured directly using a charge amplifier and synchronous detection at 1 MHz [3]. In earlier work we reported results using an impedance analyzer [12].

The output voltage of the synchronous detector U_{out} is linearly changing with the capacitance $C_s(x,y)$ in Fig. 1 and measured with an HP34401A Multimeter [3].

The slider is driven in x-direction by two electrostatic comb-drive actuators over a range spanning from $x = x^{\text{min}}$ to x^{max} [12, 3].

Fig. 3 gives a measured mean output voltage and standard deviation for 5 cycles of displacement and 3 different gap-sizes. Each cycle starts and ends in $x=0$ position and ranges from x^{min} to x^{max} .

The sense-actuators can either reduce or increase the gap-size relative to the initial design gap-distance $g \sim 1.5 \mu\text{m}$. Applying 14Vdc in forward mode reduces the gap resulting in changes of the synchronous detection signal ΔU_{out} of 11.8 mV per half period of 5 μm i.e. a average sensitivity of $S_x = \Delta U_{\text{out}} / (P_x/2) = 2.4 \text{ mV nm}^{-1}$. The same voltage in reverse mode (14VdcRev) pulls the sense-structures away from the slider thus increasing the gap and reducing $\Delta C_s(x)$.

Fig. 3 (bottom) shows a decrease in standard deviation (std) for 5 cycles for a larger $\Delta C_s(x)$. The maximum standard deviation $\text{std}(U_{\text{out}})$ for curve a) in Fig. 3 means a position uncertainty of $|\Delta x|_{\text{max}} = \{\text{std}(U_{\text{out}})\}_{\text{max}} / S_x = 24 \text{ nm}$. For the initial gap-size (curve b) 0Vdc) $|\Delta x|_{\text{max}} = 79 \text{ nm}$, and for curve c) 14VdcRev, $|\Delta x|_{\text{max}} = 533 \text{ nm}$.

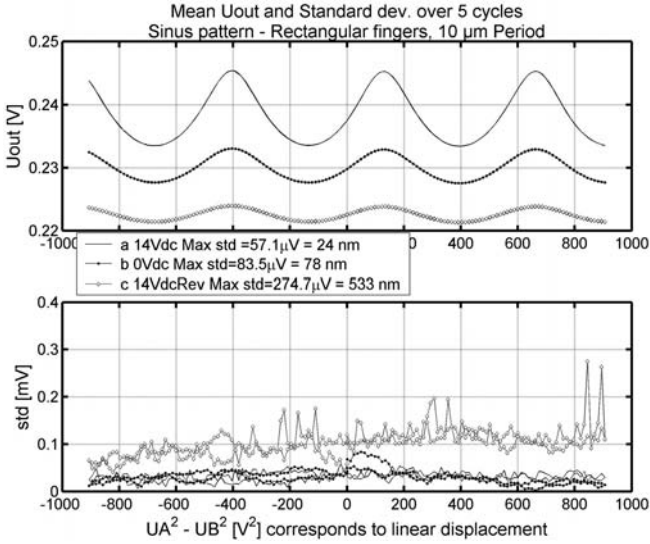


Fig. 3: (top) Measured mean output voltage $\Delta U_{out}(x)$ (i.e. $\Delta C(x)$) for 5 displacement cycles and 3 different sense-actuator voltages i.e. gap-sizes. (bottom) standard deviation $std(U_{out})$.

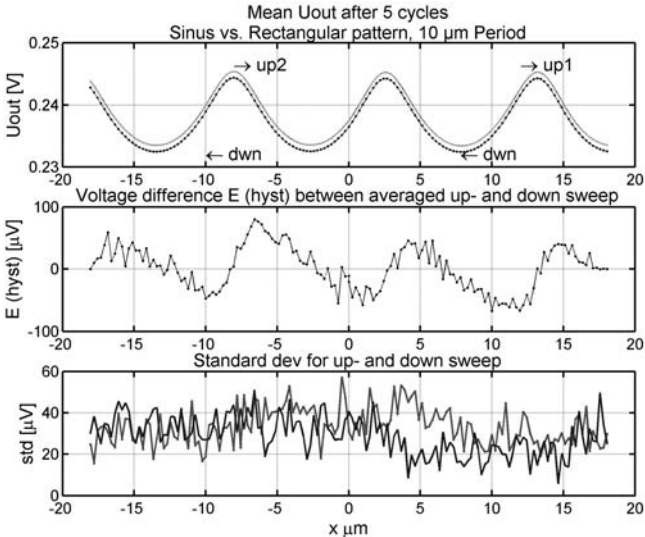


Fig. 4: The difference (E_{hyst}) in $mean(U_{out})$ between up-sweep and down-sweep, and the standard deviation for up-sweep and down sweep

It is assumed that the standard deviation is related to noise or disturbance. Therefore, these results clearly demonstrate that the SNR decreases for smaller gap-sizes.

The previous calculation does not take into account the possibility for a difference (hysteresis) between the up-sweep and the down-sweep i.e. simply put, going from $x = x_{min}$ to $x = x_{max}$ instead of the opposite direction. To visualize this, the up- and down sweep of $(U_{out}(x))_{mean}$ for curve a) in Fig. 3 have been shifted vertically in Fig. 4 (Top). This difference can be defined as an estimation of the reproducibility which includes hysteresis, drift and noise [8]. Fig. 4 (middle) shows the difference between up- and down sweep is dominated by a periodic hysteresis E_{hyst} . This effect is probably caused by an attractive electrostatic force between slider and sense-structures.

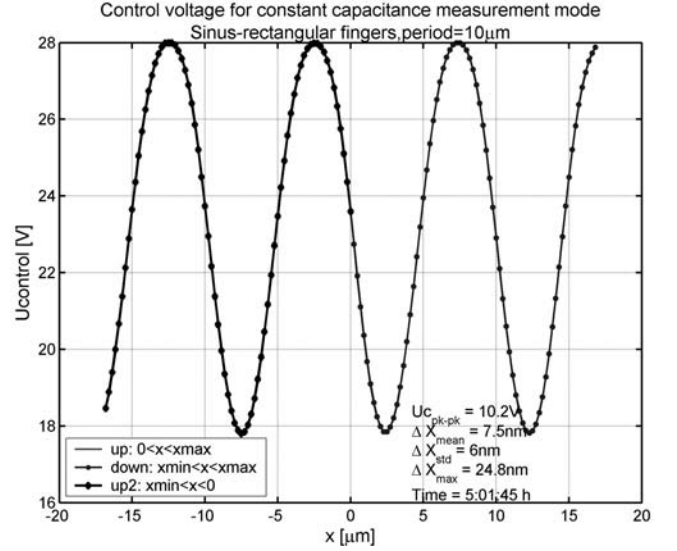


Fig. 5: Control voltage U_c for CCMM

The absolute value $|(E_{hyst}(x))|$ relative to the average sensitivity $S_x = 2.4 \text{ mV nm}^{-1}$ is used to estimate the maximum and average position reproducibility and the standard deviation:

$$|\Delta x|_{max,h} = 34 \text{ nm}, |\Delta x|_{mean,h} = 12 \text{ nm}, |\Delta x|_{std,h} = 8 \text{ nm}.$$

Further analysis and experiments using video analysis are necessary to explain this effect.

Fig. 4 (bottom) gives the standard deviation for the up-sweep and down sweep i.e. $U_{std,up}$ and $U_{std,dwn}$. This relates to a position uncertainty and can be defined as an estimate for the repeatability:

$$|\Delta x|_{std,up} = 14 \text{ nm}, |\Delta x|_{std,dwn} = 12 \text{ nm}$$

B. Quasi-static Measurements CCMM

In this constant capacitance measurement mode the measured output voltage U_{out} of the synchronous detector is held at a chosen setpoint value U_{set} by applying a proportional control to the sense-actuators. $U_c(x(n)) = K_p \cdot (E(x(n))) = K_p \cdot (U_{out}(x(n)) - U_{set})$. The resulting control voltage for all x -positions in one cycle is given in Fig. 5. The absolute difference in U_c between up- and down sweep is related to a mean position accuracy $|\Delta x|_{mean} = 7.5 \text{ nm}$ and a standard deviation $|\Delta x|_{std} = 6 \text{ nm}$ [3]. One complete cycle took 5 hours, therefore this implementation for CCMM is far from real-time operation. However, the position uncertainty is lower than for CIMM, even after 5 hours and without compensation for changes in the environmental conditions by means of an additional reference capacitance [2, 3]. Clearly, this demonstrates the potential of this concept due to a larger capacitance and thus a larger SNR.

C. Dynamic Measurements CIMM

This section presents the result of a dynamic measurement for the same device, actuated in pull-pull at higher actuation frequencies up to 10 KHz.

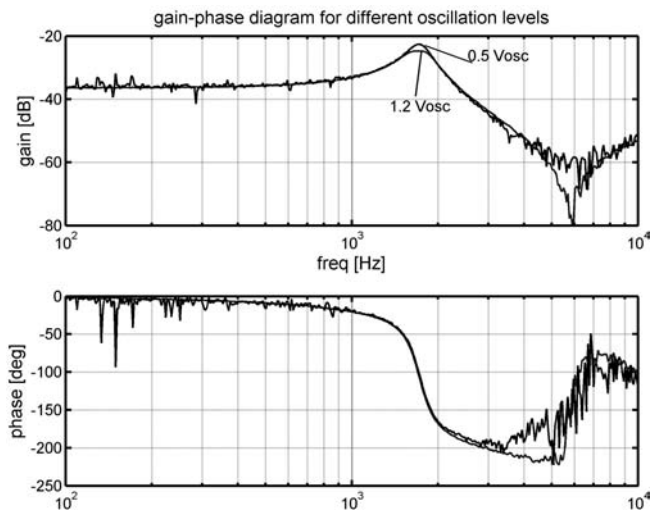


Fig. 6: Mechanical frequency response measured in CIM mode for an amplitude $\Delta x \sim 1 \mu\text{m}$ around $x=0$.

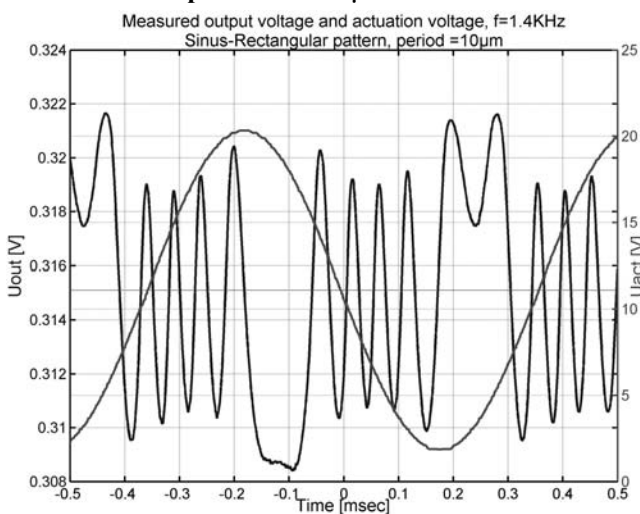


Fig. 7: Response measured in CIMM at $f_{\text{act}} = 1.4 \text{ KHz}$. The total range of displacement is $\sim 45 \mu\text{m}$.

The frequency response in Fig. 6 is measured with a gain-phase analyser (HP4194A) for a small displacement amplitude $\Delta x \sim 1 \mu\text{m}$ around $x=0$. The resonant frequency is about $f_r \sim 1.7 \text{ KHz}$ with a Q-factor of 5. Above $f \sim 6 \text{ KHz}$ the response is affected by cross-talk. Increasing the actuation amplitude from 0.5 V to 1.2 V flattens the resonant peak due to damping but does not reduce the cross-talk.

Fig. 7 gives a large signal response at an actuation frequency $f_{\text{act}} = 1.4 \text{ KHz}$ showing again the periodic output voltage U_{out} and thus the periodic change in capacitance. Counting the periods gives an estimate of the total displacement range of $\sim 45 \mu\text{m}$. This means the maximum velocity amounts to $\sim 20 \text{ cm/sec}$.

These results are obtained after averaging the voltage U_{out} more than 8 times and thus the results are far from real-time accurate position sensing and positioning. Further analysis and characterization is necessary and anticipated in the near future to determine the actual precision or position accuracy [13].

IV. CONCLUSIONS

Measurement results are presented for two related concepts for a capacitive incremental position sensor. The quasi-static results for both concepts demonstrate a position uncertainty of about 10 nm. Therefore, it appears that nm-accuracy over a range of 100 μm or more is feasible. An expected larger SNR for the CCMM concept is demonstrated by a lower position uncertainty than for the CIMM concept. The dynamic results for CIMM demonstrate the potential of this concept at frequencies up to 10 KHz. Further characterization i.e through video analysis is necessary to determine position accuracy and implement quadrature detection and nano-positioning.

REFERENCES

- [1] P.Vettiger, M.Despont, U.Drechler 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] A.A.Kuijpers, R.J.Wiegerink, G.J.M.Krijnen, T.S.J.Lammerink and M. Elwenspoek, Capacitive long-range position sensor for microactuators, MEMS2004, pg 544, Maastricht, Netherlands, Jan 2004.
- [4] L. Abelmann, T. Bolhuis, A. M. Hoexum, G. J. M. Krijnen, J. C. Lodder "Large capacity probe recording using storage robots" IEE Proceedings-Science Measurement and Technology, 150 (2003), no 5, Page 218-221
- [5] S. Deladi, J.W. Berenschot, M.J. de Boer, G.J.M. Krijnen and M.C. Elwenspoek, An AFM-based device for in-situ characterization of nano-wear, Proc. Of MEMS2004, Maastricht, Netherlands, pg 181, January 2004.
- [6] G. Lim, K. Minami, M. Sugihara, M. Uchiyama, and M. Esashi, "Active catheter with multi-link structure based on silicon micromachining," Proc. 8th IEEE Workshop Micro Electro Mechanical Systems, Amsterdam, The Netherlands, Jan. 1995.
- [7] C. H. Mastrangelo, M.A. Burns, and D. T. Burke, "Micro-fabricated devices for genetic diagnostics," Proc. IEEE, 86, 8, Aug.1998, pp. 1769-1787
- [8] P.D.Atherton, T.R.Hicks, The Nano-positioning book, Queensgate Instruments, Berkshire, 2000.
- [9] K.B.Klaassen, C.L.van Peppen, Linear capacitive micro-displacement transduction using phase read-out, Sensors & Actuators, 3, (1982), 209-220.
- [10] M.Elwenspoek, R.J.Wiegerink, Mechanical Microsensors, Microtechnology and MEMS, Berlin Heidelberg New York, Springer-Verlag, 2000
- [11] R.Legtenberg, Electrostatic Actuators Fabricated by Surface Micro-machining Techniques, PhD Thesis, University of Twente, Enschede, 1996.
- [12] T.A.A.Kuijpers, G.J.M.Krijnen, R.J.Wiegerink, T.S.J.Lammerink, M.C.Elwenspoek, Capacitance measurements for micromachined capacitive long-range position sensor, Proc.SAFE, Netherlands, 25 Nov, 2003.
- [13] A.A.Kuijpers, Micromachined capacitive incremental position sensor for nanopositioning of microactuator systems, Ph.D. thesis, expected pub., Dec 2004.

Acknowledgements:

This research is financed by the Dutch technology foundation STW within the project "Microactuator systems for nano-position control". The authors like to thank M. de Boer and E. Berenschot for the micromachining advice and assistance, H. van Wolferen and R. Sanders for technical assistance. The MESA+ laboratory staff is acknowledged for the assistance during processing.