Capacitive sensor technology based on area variation for precise position detection

M. Pufke [1], F. Hilbrunner [2], C. Diethold [1], T. Fröhlich [1]

[1] Technische Universität Ilmenau, Institute for Process Measurement and Sensor Technology,
[2] Sartorius Weighing Technology GmbH, Göttingen, Germany

ABSTRACT

For position sensors lots of different measurement systems are well known. In a balance, which bases on the electromagnetic force compensation principle, optical sensors for further control are state of the art. First steps with application of an alternative capacitive measuring arrangement had been made, which had shown that nanometer resolution could be achieved. In this paper, two different types of structures, based on capacitive changes of gap and area between electrodes, are compared and discussed. It can be pointed out, that nanometer resolution is achievable, even with simple electrode structures and materials. A basic suitability as position detector for use in a balance system can be found, but further steps have to be made for successful adaption.

Index Terms: differential capacitor, capacitive position sensor, area variation, space variation, capacitance-to-digital converter, balance, electromagnetic force compensation

1. INTRODUCTION

For position sensors lots of different measurement systems are well known. In a balance, which bases on the electromagnetic force compensation principle (EMFC-balance, cf. [1]), optical sensors for further control are state of the art. Figure 1 shows an EMFC-balance schematically. Mostly, the required position detection of an EMFC-balance lever arm is handled with a system, which comprises of a light source, a differential photodiode and a slit aperture. Both the photodiode and the LED are fixed, while the aperture is part of the lever arm, thus it is movable.

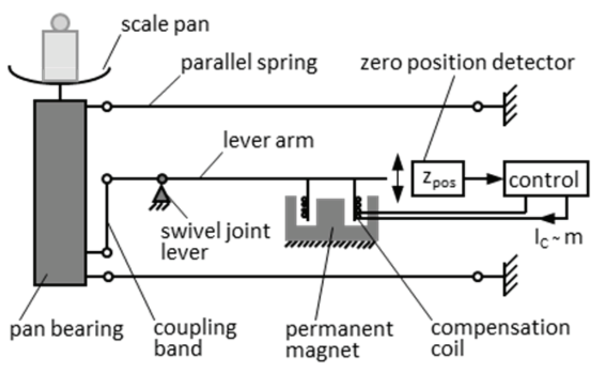


Figure 1: Schematic of an EMFC-balance

This system is characterized by a sufficiently measurement range with good resolution. Though, drift phenomena of photodiodes, high costs and only an analog output signal are disadvantages. A measurement system, which depends on capacitive changes could be an alternative. Long time ago first solutions were described by use of ring electrodes in EMFC-balances (cf. [2]), but without arrangement on a lever arm.
In this work, different kind of electrode structures, which based on area and space variation, are investigated and compared to each other. Care has been taken on resolution, stability and high measurement rates.

2. CAPACITIVE SENSORS

A change of capacitive value is the basis of all capacitive measurement systems. From the well-known formula of a simple two plates capacitor

$$C = \varepsilon_0 \, \varepsilon_\mathrm{r} \, \frac{A}{d} \tag{1}$$

changes in capacitance C could be made by variation of distance d between the electrodes or by both electrodes overlapping area A. A combination of both is also imaginable. Changes on relative permittivity ε_r of dielectric are possible, but in fact of unavoidable air gaps between electrodes and dielectric material, not practical for displacement measurements.
From constructive perspective, differential capacitor arrangements with two fixed and one moveable electrode are advisable to use (cf. [3, 4]).
Advantages of differential arrangements are:

- Doubling the sensitivity in comparison to a two plates capacitor
- The differential capacitance ΔC is theoretically zero in the neutral center position
- A possible tilting of the movable electrode plate around its own axis in a parallel arrangement of the fixed electrodes does not take an effect
- In the center position the electrostatic force is theoretical zero
- The differential assembly results in a lower temperature and humidity dependence, because of their congenerous influence in both capacitances

Three possibilities of differential capacitors based on space and area changes are shown in figure 2.

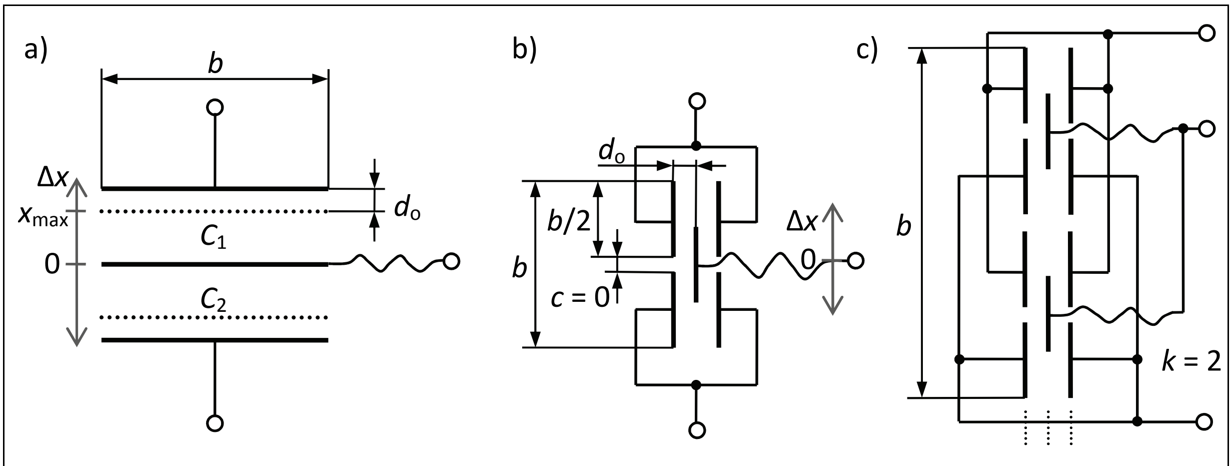


Figure 2: Schematic side view of a differential capacitor with a) space, b) area and c) cascaded area variation

In case of area variation as shown in figure 2 a) the differential capacitance ΔC between the capacitances C_1 and C_2, in the ideal homogeneous case and depending on a change in distance Δx of the movable plate from its neutral center position, is:

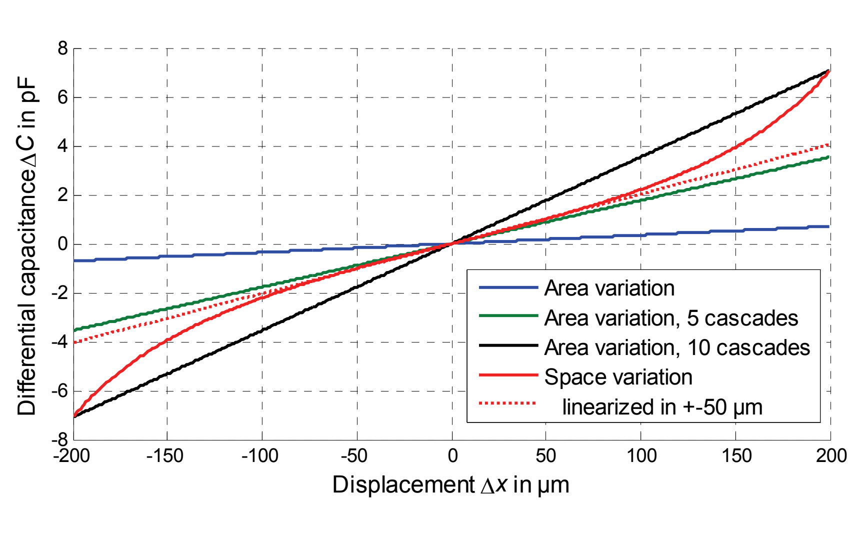
$$\Delta C = C_1 - C_2 = -2\,\varepsilon_0\,\varepsilon_r\,\frac{A \cdot \Delta x}{(d_0 + x_{max})^2 - (\Delta x)^2} = -2\,\varepsilon_0\,\varepsilon_r\,\frac{a \cdot b\,\cdot \Delta x}{(d_0 + x_{max})^2 - (\Delta x)^2} \qquad (2)$$

The problem of this aperture is the small deflection range in fact of needed mechanical stops of both fixed electrodes. Mechanical and electronic defects could be taken into account if no mechanical limitation is arranged to this system.
To compensate these disadvantages a differential capacitor, which makes use of an area variation could be taken, as can be seen in figure 2 b). Its simplified equation is described by:

$$\Delta C = C_1 - C_2 = 4\,\varepsilon_0\,\varepsilon_r\,\frac{A \cdot \Delta x}{d_0} = 4\,\varepsilon_0\,\varepsilon_r\,\frac{a \cdot \Delta x}{d_0} \qquad \text{with } c = 0 \qquad (3)$$

The last formula shows that the differential capacitance is geometrical independent of width b and only depends on length a of the electrodes.

In fact of the limited volume of an EMFC-balance the available sensor area (a * b) should not exceed 1 cm² at all. The typically movement Δx of the balance lever arm end is ± 200 µm. Furthermore the minimal distance d_0 between the electrodes is given by 100 µm.
Comparing both last mentioned formulas with parameters close to reality and without consideration of slits c (see figure 2b) between the fixed electrodes, theoretical sensitivities for area and space capacitive changes can be calculated, like illustrated in figure 3.



Parameter

Width/length of electrodes: b, a = 10 mm

Range of displacement: Δx = ±200 µm

Min. electrodes distance: d_0 = 100 µm

Sensitivity

Area variation:

Single: 3.54 aF/nm

5 cascades: 17.71 aF/nm

10 cascades: 35.42 aF/nm

Space variation, linearized: 20.24 aF/nm

Figure 3: Comparison of differential capacitors with parameters close to reality (without consideration of slits)

By taking a linearization in the range of ±50 µm a sensitivity about 20.2 aF/nm can be found for space variation. Compared to, area variation has a 6 times lesser sensitivity of about 3.5 aF/nm. However, area variation have a theoretical linear relation between distance and capacitance.
To compensate this deficit of sensitivity a cascading of area structures into x-direction (see figure 2 c) helps to increase the differential capacitance by building up electrode combs. Thus, expression 3 is extended to

$$\Delta C = 4\,k\,\varepsilon_0\,\varepsilon_r\,\frac{a \cdot \Delta x}{d_0} \qquad \text{with } c = 0 \qquad (4)$$

with k as number of cascades. As can be seen in figure 3 sensitivity is approximately 17.7 aF/nm with 5 cascades and even 35.4 aF/nm with 10 cascades. It should be noted, that cascading is associated with a much larger effort for the electrical connections of the electrode combs. Furthermore, small slits *c* and electrode widths lead to greater capacitive fringe effects, especially on conductor edges.

3. ELECTRONICS

3.1 Overview

According to the constructive dimensioning the downstream electronics is of significant importance.
There are a number of different possibilities, which can be reduced mainly to the following circuit principles:

- Voltage divider circuits
- AC bridges
- Resonance methods
- RC- and LC-oscillators
- Charge and discharge methods

Voltage divider circuits are simple designed amplitude-analog circuits, in which the capacitance is used as measured impedance. They show a great dependence on parasitic impedances. This can be compensated by the use of higher source frequencies, although this leads to problems in amplitude measurement and lower resolution. [5]
Alternating current bridges are the most common used amplitude-analog method [6]. With a differential capacitor a linear behavior between bridge voltage and distance-dependent deflection could be described. However, AC bridges also show the same problems as the voltage divider circuits.
The resonance method is based on voltage divider circuits with a voltage source in resonance mode (cf. [7]). It is used for measurement of the capacitance and its loss resistance. A compensation of stray capacitances is possible, cf. [8]. Because of the necessary adjustment and detection of the resonance condition [8] this method is not suitable for fast measurements.
There are lots of different oscillator circuits known from literature (cf. [6, 9, 10]). Generally the capacitance to be measured is the frequency-determining element in such an oscillator circuit.
RC oscillators can be characterized by its easy design and independence from analog voltage levels [5]. Because of their non-usage of inductivities it is possible to adapt them into integrated circuits [11]. Disadvantages are poor frequency stability [6], low sensitivity in the field of small capacitive changes and bad stray capacitance immunity [8].
With the help of LC oscillators the dynamic range could be extended up to several hundred MHz [12]. A problem is the construction of a temperature- and timestable inductivity, which leads to higher component costs [5]. The hysteresis dissipation of the ferrite coil core is another disadvantage. A solution for this could be the use of an air coil, but this substantially reduces the value of inductivity and the descriptiveness above 10 MHz is difficult [13]. A drawback is also that stray capacitances increase the measurement uncertainty.
The charge and discharge principle is based on the charge and discharge of a measurement capacitance (cf. [15, 16]). Mostly this is made in comparison to another reference capacitance. Advantages of this method are low temperature drifts, a possible dependence only on the DC component of the discharge current pulses and an almost independence from ohmic losses in the capacitor [8]. A negative fact is the non-immunity towards stray capacitances [8], which can only compensated by an extended electronics design.

3.2 Integrated circuits

Today, integrated circuits consisting of high functionality with a low fault liability are more and more used, reducing development and component costs. On the market a wide range of different capacitive analog-digital transducers are available, mostly based on the aforementioned charge and discharge method. Examples for a lot of capacitive circuits can be found in touch sensors for displays or simple incline and acceleration sensors in mobile phones.
In fact of these great advantages two high precision integrated capacitive A/D-converters were chosen, which comply the need of a necessary resolution in the single digit aF-range for experimental purposes of figure 2 arrangements.
With comparison of their characteristics two IC's with integrated A/D-converter could be found. These are the AD7747 from Analog Devices, Inc. (cf. [16]) and the PCap01 from acam Messelektronik GmbH (cf. [17]). Both based on the charge- and discharge method, which is recommended for precision measurements at high frequencies [8].
The converter AD7747 is especially designed for measurement of a differential capacitor in a range of ±8 pF. The possible maximum effective resolution is approximately 20 aF (at 8 Hz). However, this could be achieved only at a low update rate. The measurement frequency is limited to 45.5 Hz. [16]
In differential mode the PCap01 has a maximum data rate of 6.25 kHz and is more flexible on measurement settings. A resolution about 6 aF (at 5 Hz) can be achieved. [17]

For easier adapting of different capacitive sensor arrangements modified evaluation boards were used in the following (cf. [18, 19]).

4. MEASUREMENT ARRANGEMENTS

4.1 Measuring arrangement for space variation

The aim of this work was to build up a capacitive differential capacitor for use at the end of an EMFC-balance lever arm. It is sufficient for first experiments to construct a system, which imitates the movement of a lever arm with realistic geometric sizes.

For this purpose, a simple differential capacitor arrangement was chosen with space variation according to Figure 2 a), in which two fixed electrodes are braced against each other. Between these fixed electrodes is a movable electrode assembly, which symbolizes the lever arm. The latter can be moved by means of coupling to a micro positioning table setting in up to 0.1 µm increments between the two stationary electrodes. The main body of the electrodes forms a LTCC multilayer ceramic (see [20]), which was produced by the "Zentrum for Mikro- und Nanotechnologien (ZMN)" in Ilmenau. As conductive layer gold electrodes were chosen. All electrodes have, as already assumed in chapter 2, a 1 cm x 1 cm large sensor area with a mutual distance ($x_{max} + d_0$) of 300 µm in neutral position. A deflection of ± 200 µm is also applicable. Because of identical geometrics, sensitivity of 20.24 aF/nm could be taken from theoretical calculation in figure 3. Besides the schematic side view, figure 4 shows the finished measurement setup with appropriate coaxial cables to connect the electrodes to electronic boards.

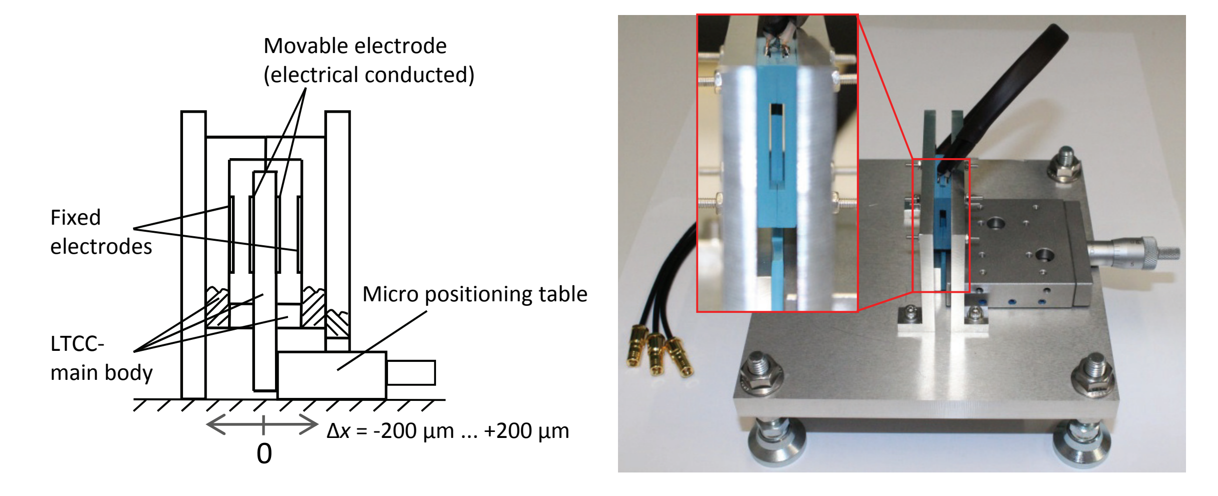


Figure 4: Schematic and photographic illustration of space variation experimental setup

4.1 Measuring arrangement for space variation

From the experiences of the first experiments with space variation experimental setup, a second arrangement for area changes was build up as shown in figure 5.

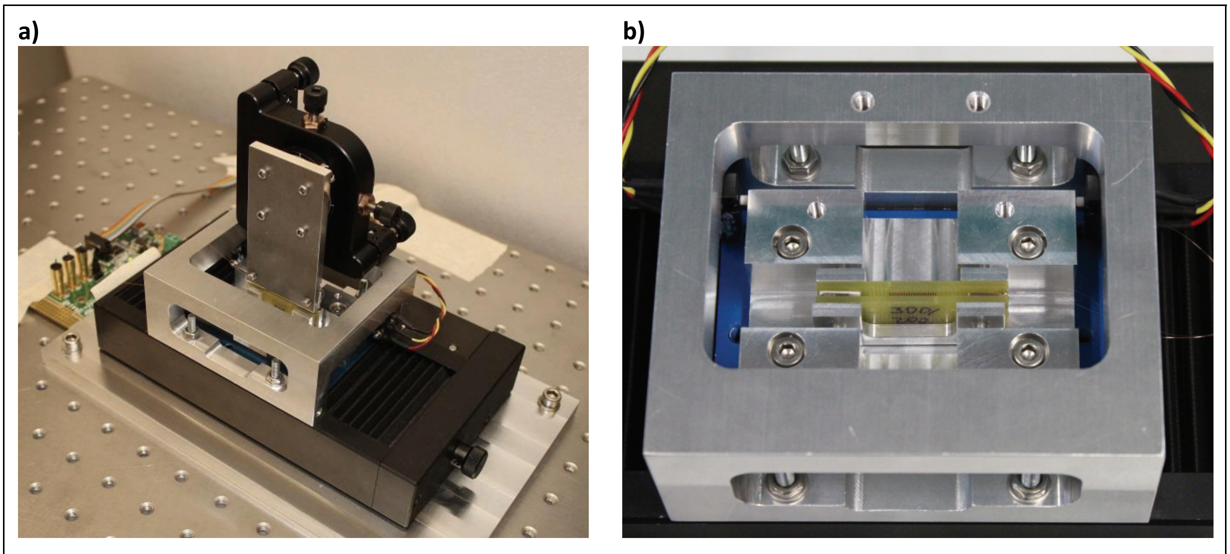


Figure 5: a) Area variation experimental setup, b) detail of portal and slide with "fixed" electrodes mounted on

This system has the possibility to investigate different area changing structures by clamping both fixed electrodes against each other by variable braces. In this setup the fixed and movable electrodes have a reversed movement. The "movable" electrode is stationary arranged on the system between two "fixed" electrodes. Last mentioned are mounted on a slider of a precision linear actuator, which can realize steps of 0.3 µm while having an encoder resolution of 0.1 µm (cf. [21]). The middle electrode is handled by a position unit with a high degree of freedom in all three Cartesian and one angular directions.

For first experiments only machined milled copper coated laminates were available for circuit board electrodes. The board thickness is 1.6 mm with only a possible minimum of 200 µm distance between two conductors and also a conductor width of 200 µm. The board material is relatively cheap and simple FR2 (phenolic and paper).

In Figure 6 the characteristic and parameters of the chosen area variation capacitor is presented, which is used below. The fixed electrodes have conductors of 300 µm width whereas the movable has 600 µm. The Distances between conductors are 200 µm for fixed and 400 µm for movable electrodes. Gaps of 200 µm are realized between mutual electrodes. Thus a sensitivity of approximately 17.8 aF/nm can be calculated in the range of ±100 µm.

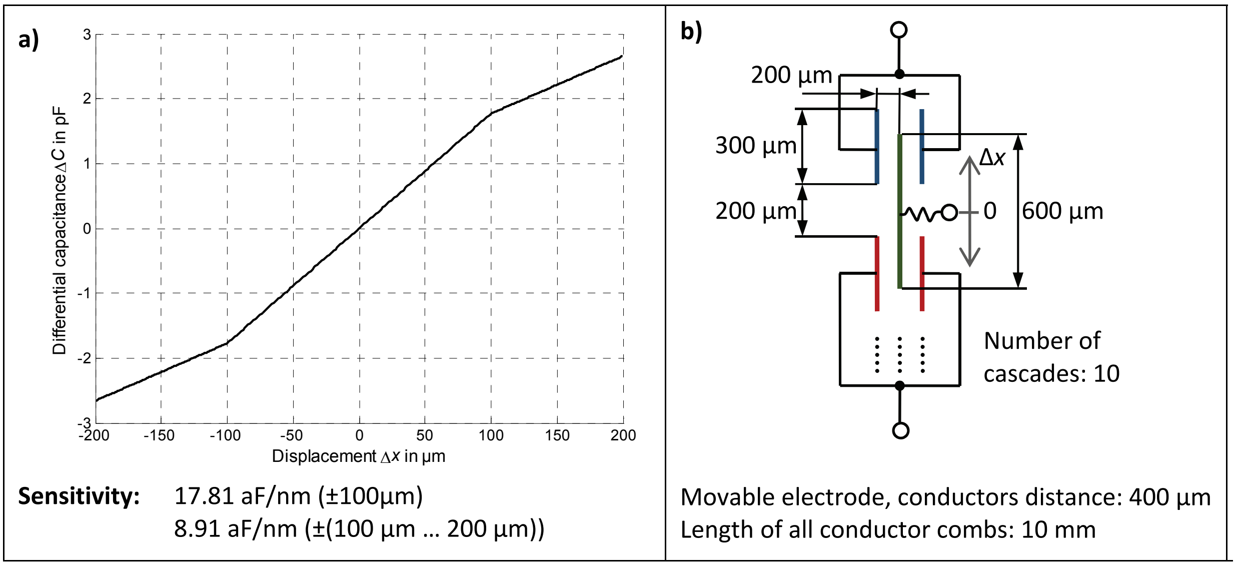


Figure 6: a) Characteristic and b) geometric parameters of experimental used electrodes with area variation

5. EXPERIMENTAL MEASUREMENTS

5.1 Space variation

First steps were made, which had shown, that nanometer resolution (see also [22]) could be achieved with space variation.

Initially, the characteristic of differential capacitance ΔC to the displacement Δx was measured by use of both electronics at a comparable frequency of approximately 45 Hz. In steps of 5 µm (with PCap01: 10 µm) the movable electrode was positioned between both fixed from negative to positive direction. For every movement step the mean of single values over approximately 120 s was calculated and plotted. Afterwards a curve was fitted over all data points. Figure 7 shows the measurement results of electronics.

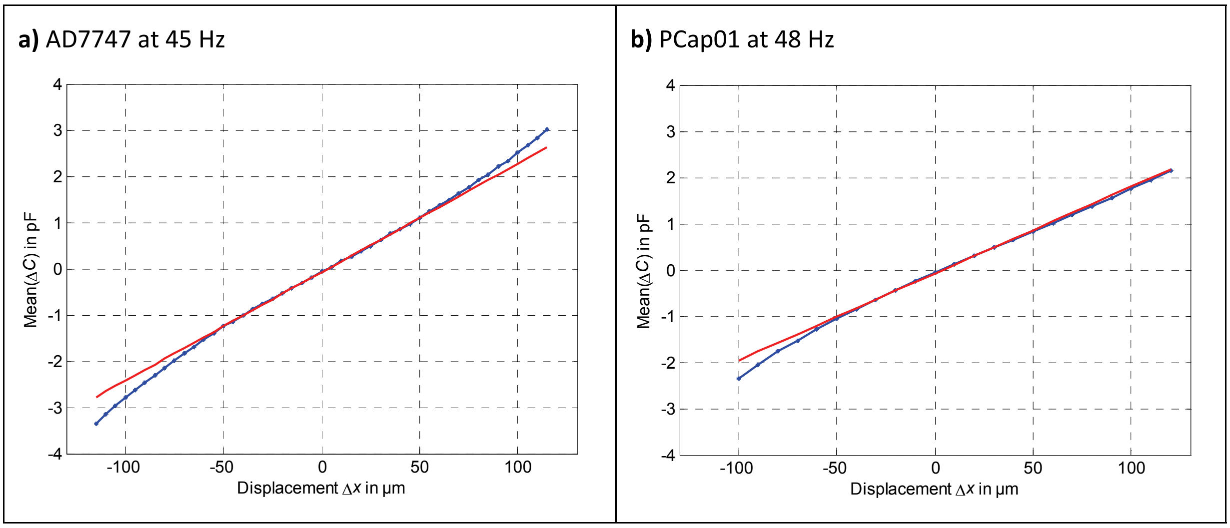


Figure 7: $\Delta C(\Delta x)$-Characteristics of a) AD7747 and b) PCap01 with space variation setup, blue: raw data, red: linearized in the range of ±50 µm

It can be pointed out, that both characteristics showing a high degree of linearity over a wide range near electrical zero position. Deviations are mainly found in the area of small electrode gaps, where especially influences of stray capacitances are much greater than in middle electrode position. Furthermore an asymmetry can be recognized, which may result from unidentified geometric zero position. It could not be calibrated with this simple measurement arrangement. Parasitic differences in wire capacitances can also be taken into consideration.
By linearization in the significant region of ±50 µm around zero position a sensitivity of about 23 aF/nm for AD7747 and 19 aF/nm for PCap01 can be found. Comparing with theoretically calculation (20 aF/nm) these experimental results are in good agreement.

To get an overview concerning noise performance, the experimental setup (see figure 4) was arranged near the electrical zero position (ΔC = 0 pF). This is of great interest, because the balance system has to be controlled to this position. With the help of the theoretically calculated sensitivities capacitive measurement results could be transformed to equivalent displacement values. Figure 8 shows the results for both integrated circuits as geometric deviation from the mean value over 5 min.

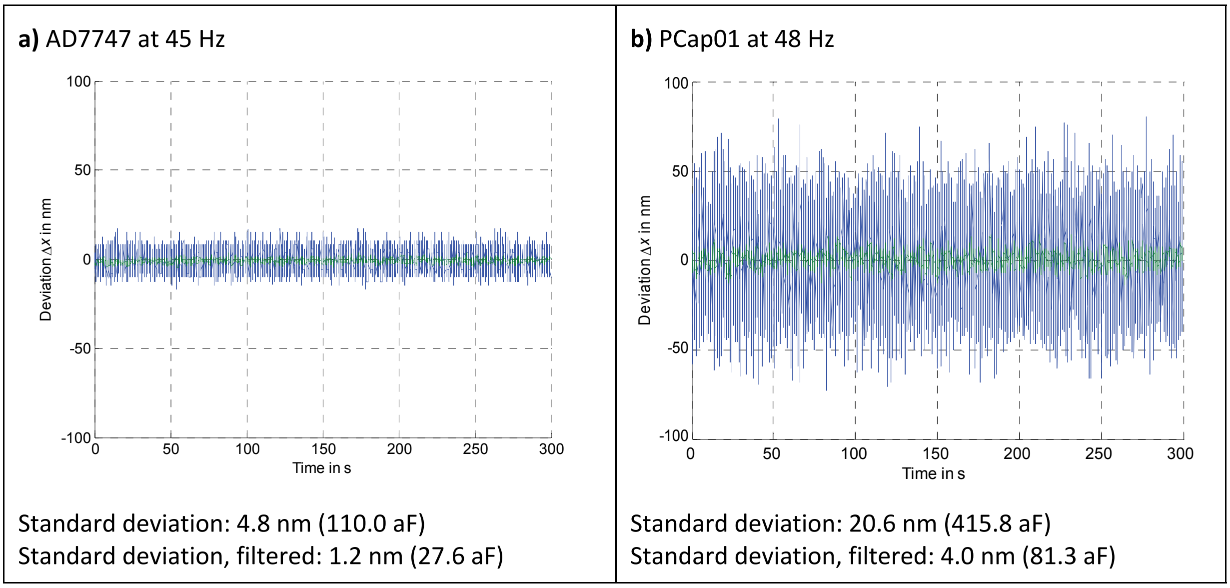


Figure 8: Noise performance of a) AD7747 and b) PCap01 with space variation setup closed to zero electrical position, blue: unfiltered, green: filtered with moving average over 25 single values

AD7747 has a very low noise level with a standard deviation of 4.8 nm. By use of a simple moving average filter over 25 single values, only 1.2 nm could be achieved. In contrast to, PCap01 delivers at same frequency a approximately 3-times greater deviation (4.0 nm, filtered), but has the advantage of a higher measurement rate. Taking the maximum possible speed (1.3 kHz) of PCap01 evaluation board a respectable standard deviation of 34.4 nm (moving average filter over 25 single values) can be found.

It is thus conceivable that for control of an EMFC-balance a measurement setting of the capacitive AD converter could be chosen which initially has a high data rate in the kHz-range at a comparatively low resolution. In the following initial controlling near to zero position, data rate can then be decreased, which results in the required high displacement resolution.

5.2 Area variation

By analogy to previous section, the characteristics of AD7747 and PCap01 were measured. Figure 9 illustrates a good linearity in nearly the same region for both electronics.

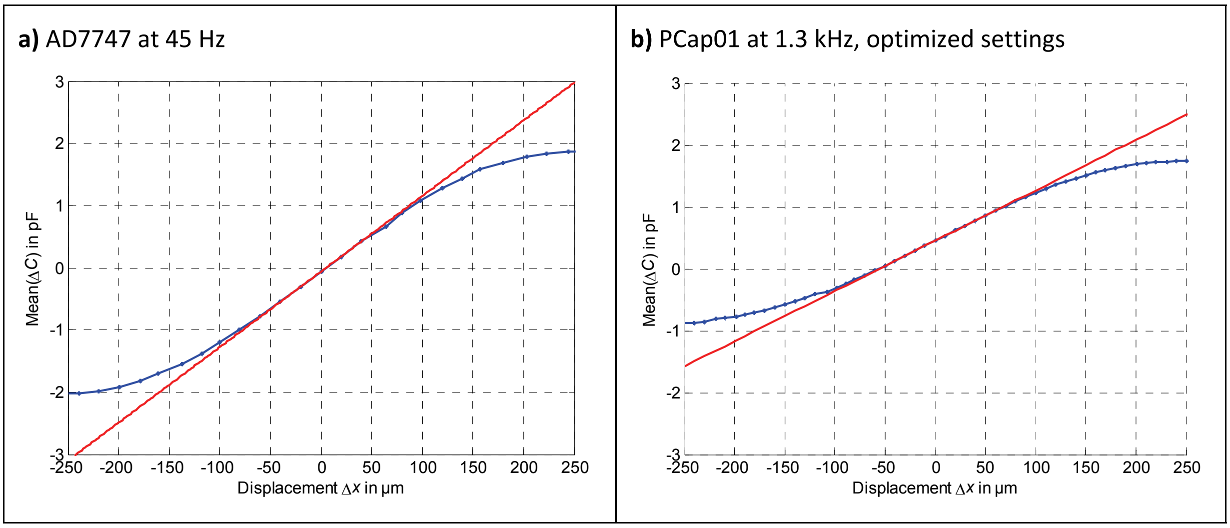


Figure 9: $\Delta C(\Delta x)$-Characteristics of a) AD7747 and b) PCap01 with area variation setup, blue: raw data, red: linearized in the range of ±50 µm

For AD7747 a sensitivity of approximately 12 aF/nm could be found in the range of ±50 µm. This is much lower than theoretically calculated value (17.8 aF/nm) and may result from fringe effects, crosstalking and greater gaps between the different electrode structures.
Compared to AD7747, the PCap01 has only a sensitivity of 8 aF/nm, but at a significant higher update rate of about 1.3 kHz. A greater offset of electrical zero position maybe a result from a larger asymmetry of parasitic capacitances.

PCap01 using an output signal with factor of C_1 divided by C_2. Therefore, in electrical zero position it is one. By a given value for C_2, both capacitances and differential capacitance ΔC can be back calculated. Thus, a look at sensitivity of PCap01 can only be done by knowledge of noise performance, which is compared to AD7747 in figure 10.

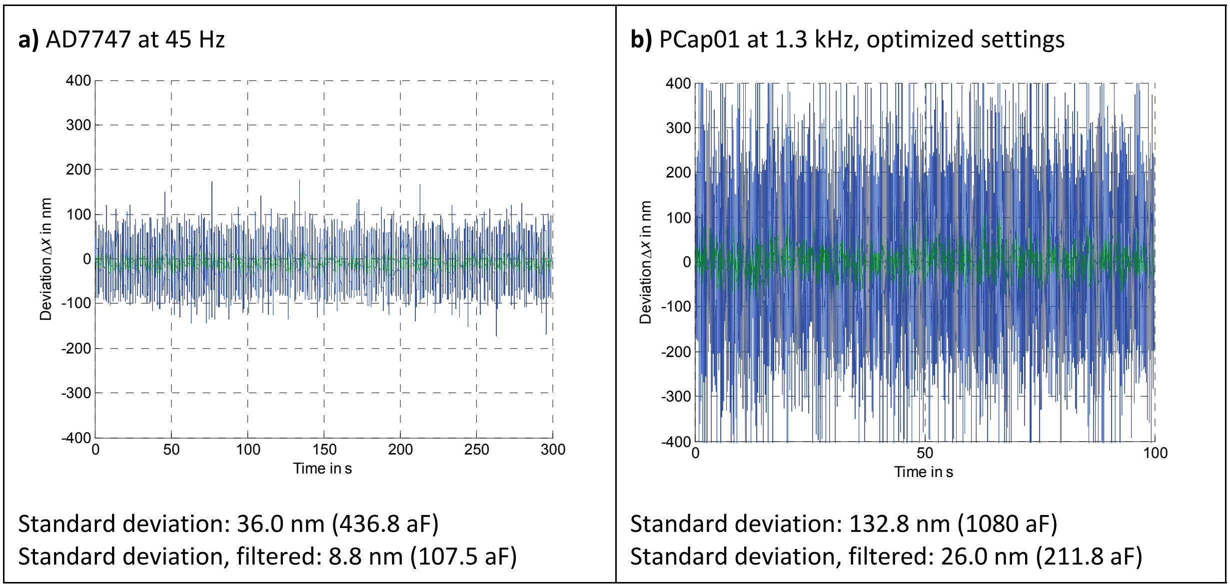


Figure 10: Noise performance of a) AD7747 and b) PCap01 with area variation setup closed to zero electrical position, blue: unfiltered, green: filtered with moving average over 25 single values

The AD7747 shows a greater standard deviation (8.8 nm, filtered) of area variation compared to space variation. This is possibly a result of nonexistence of any shielding or guarding between capacitive sensor and electronics, like it was handled with area variation.
In similarity to previous chapter PCap01 standard deviation is approximately 3-times higher with a value of 26.0 nm (filtered).

Both electronic noises seem to be high, but it has to be pointed out, that the measurement arrangement has some weaknesses.
The previous mentioned missing of shielding could be compensated by a closer arrangement of integrated circuits near the sensor. In the best way directly on the electrodes circuit board.
To keep parasitic capacitances small, wires of 0.05 mm² cross-section were used, thus may change their position a bit during measurement. Possibly, grounding and/or active guarding around electrode structures and conductors will help to solve this, especially if short distances between electrode structures and electronics cannot realized.
Furthermore only electrode circuit boards were used, which have a higher humidity absorption and a greater relative permittivity (cf. [23]) than boards based on ceramics and/or PTFE. Last mentioned have the further advantages of a low surface and conductor roughness as well as a higher board planarity at manageable costs.
A loss in sensitivity could also be a result of not congruent arrangement of both fixed electrode combs to each other or to the movable electrode structures.
Despite aforementioned difficulties, the measurement results showing impressive achievable values down to nanometer resolution.

Other electrode designs are in process, which could lead to a better performance of sensitivity and noise behavior.

6. CONCLUSION

It can be pointed out, that both investigated differential capacitor systems showing a great potential as an alternative method to the optical detection in an EMFC-balance.
Finally, differential capacitance position sensors, based on a change of area, could also be used for further application as position sensor in an EMFC-balance. It was shown, that the weakness of a lower sensitivity compared to space changing capacitors could be compensated by use of cascaded electrode combs. The biggest advantage to a space changing system is the possibly mounting without any necessary mechanical stop.

Further steps have to be focused on calculation of fringe electrical fields, optimized electrode structures and an arrangement of electronics as closed as possible to the electrodes. It may also conceivable to build up a grounded metallic electrode comb, as fully integrated part of the lever arm end, instead of a movable circuit board. This leads to lower manufacturing and assembly costs.
The use of digital filters for a better noise performance should be also a part for more detailed studies.

REFERENCES

[1] Kochsiek, M.; Gläser, M.: Massebestimmung. Weinheim: VCH, 1997

[2] Akers, C. B.; Applequist, R. A.; Applequist. J. E.; Guzy, D. J.: ELECTROMAGNETIC COMPENSATING BALANCE. United States Patent and Trademark Office. US4034819. Application date: Dec. 15, 1975.

[3] Baxter, L. K.: Capacitive Sensors: design and applications. Hoes Lane: IEEE Press, 1997

[4] Jones, R. V.; Richards, J. C. S.: The design and some applications of sensitive capacitance micrometers. In: J. Phys. E: Sci. Instrum. 6, pp. 589-600, 1973

[5] Huang, S. M.; Scott, A. L.; Green, R. G.; Beck, M. S.: Electronic transducers for industrial measurement of low value capacitances. In: J. Phys. E: Sci. Instrum. 21, pp. 242-250, 1988

[6] Bluth, J.: Modellierung und Realisierung eines digitalen Trägerfrequenzmesssystems zur Messung von kapazitiven Sensoren im Umfeld einer Ultrapräzisionsdrehmaschine. Dissertation, Universität Kaiserslautern, 2006

[7] Parzhuber, O.: Untersuchung und Optimierung von Meßoszillatoren für kapazitive Sensoren. Dissertation, Universität der Bundeswehr München, 1991

[8] Benadda, M. D.; Carru, J. C.; Druon, C.: A measuring device for the determination of the electric permittivity in the frequency range 0.1-300 MHz. In: J. Phys. E: Sci. Instrum. 15, pp. 132-136, 1982

[9] Lauer, G.: Optimierung einer Auswertelektronik für das kapazitive Differenzmessverfahren, Dissertation, Universität Kaiserslautern, 1993

[10] Frank, L.: Elektrische Messaufnehmer für nichtelektrische Größen. Internet (http://www.emg.tu-bs.de/lehre/vl/vl_mng.htm), 2010

[11] Mohles, R.: Hochauflösende Analog-/Digital-Umsetzer für kapazitive Differentialkondensatoren. Düsseldorf: VDI-Verlag, 1996

[12] Harrop, P. J.: Dielectrics. London: John Wiley & Sons, 1972

[13] Pufke, M.: Erprobung ausgewählter Messmethoden zur Lichtbogenerfassung in geschlossenen Geräten. Bachelor Thesis, Technische Universität Ilmenau, 2009

[14] Endress and Hauser Ltd., UK patent 84087, 1984

[15] Huang, S. M.: Capacitance transducers for concentration measurement in multi-component flow process. Dissertation, Manchester University, 1986

[16] Analog Devices Inc.: 24-Bit Capacitance-to-Digital Converter with Temperature Sensor AD7747, Rev. 0. Datasheet, Norwood, 2005

[17] Acam-Messelektronik GmbH: PCap01Ax-0301 Single-chip Solution for Capacitance Measurement with Standard Firmware 03.01.02, V0.4. Datasheet, Stutensee, 2011

[18] Analog Devices Inc.: Evaluation Board for 24-Bit Capacitance-to-Digital Converter with Temperature Sensor EVAL-AD7747, Rev. 0. Datasheet, Norwood, 2008

[19] Acam-Messelektronik GmbH: PCap01-EVA-KIT Evaluation System for PCap01A, V0.0. Datasheet, Stutensee, 2011

[20] Kulke, R.; Günner, C.; Rittweger, M.; Uhlig, P.: LTCC-Mehrlagenkeramik für Funk- und Sensor-Anwendungen. In: Produktion von Leiterplatten und Systemen (PLUS) 12/2001, pp. 2131-2136, Eugen G. Leuze Verlag

[21] Physik Instrumente GmbH & Co. KG: M-605 High-Accuracy Translation Stage. Internet (http://www.physikinstrumente.com/en/pdf/M605_Datasheet.pdf), 2008

[22] Pufke, M.; Hilbrunner, F.; Diethold, C.; Fröhlich, T.: Precision and low cost position detection using capacitive sensor technology. 56th IWK, International Scientific Colloquium, Ilmenau University of Technology, 12 - 16 September 2011

[23] Coonrod, J. (Rogers Corp.): Understanding When To Use FR-4 Or High Frequency Laminates. In: Onboard Technology, pp. 26-30, September 2011

CONTACTS

Dipl.-Ing. M. Pufke	michael.pufke@tu-ilmenau.de
Dr.-Ing. F. Hilbrunner	falko.hilbrunner@tu-ilmenau.de
Dipl.-Ing. C. Diethold	christian.diethold@tu-ilmenau.de
Prof. Dr.-Ing. habil. T. Fröhlich	thomas.froehlich@tu-ilmenau.de