Analysis of the Mechanical Inaccuracies in Capacitive Encoder with Flexible Electrodes

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Abstract—**This paper addresses the errors that were seen in capacitance measurement of the capacitive encoder implemented with flexible electronics technology. The sensor has a cylindrical structure with two sensing capacitors featuring digitated electrodes made on flexible foil and a common floating electrode attached to the rotor (common rotor). This common rotor, due to stray capacitances, exhibits mutual influence between these two sensing capacitors. Mechanical inaccuracies introduce errors in measurement. The influence of the mechanical inaccuracies on measurement errors is analyzed in this paper with the introduction of a simple model of mechanical inaccuracies.**

Keywords-flexible electronic, capacitive, sensor, encoder.

I. Introduction

In many industrial applications, such as automotive industry, robots, industrial automation, metrology, etc. [1], there is a need for measuring the angular position of a shaft. In the last decade capacitive sensors emerged as a possible solution for such applications [2]. Capacitive sensors can generally be categorized in micromachined capacitive sensors [3] (built on a silicon wafer) and macroscopic capacitive sensors [4] (usually manufactured on a printed circuit board - PCB). Angular-position sensors are used to determine the rotational displacement of a moving part, the rotor, relative to the stator [5]. The most popular concepts for capacitive encoders, presented in open literature up to now, are two-plate and three-plate topologies. Both concepts use planar electrodes excited by a high frequency signal to measure capacitance [2]. One approach uses two, usually circular-shaped electrodes, where one of the electrodes is fixed, and the other one rotates with the shaft. The other approach uses two mechanically static electrodes with a rotating dielectricum between them. Already reported capacitive sensors, fabricated in PCB technology (using copper as a conductive layer) have had structures with two plates [5] or with three coaxial parallel plates [1], [6], [7]. There were some attempts to decrease the systematic errors of the absolute angular position through an optimized layout [8], [9], but again, the capacitive sensor was planar and fabricated on rigid substrate.

In our previous work [10] a prototype of a capacitive angular-position sensor printed on flexible substrate (Kapton foil) was presented. The sensor can be used as an absolute or an incremental encoder. During experiments a simple mechanical platform was used to set angular displacement. It was noticed that mismatches exist between the measurement and calculated values and there is also some deviation from the predicted sensor characteristic. We assumed that the main contribution to such situation comes from mechanical inaccuracies of the mechanical platform used and inaccuracies in the attachment of the flexible foil to the platform. This paper attempts to prove this by introducing a simple model of the mechanical inaccuracies and making analytical calculations based on measurements.

II. Sensor Design

A prototype of a capacitive angular-position sensor printed on a flexible substrate [10] can be used as an absolute or an incremental encoder. When it is used as an absolute encoder the measurement range is $\pi/2$. As an incremental encoder the sensor provides two channels in quadrature with four pulses per cycle. If the sensor is to be used as incremental encoder, the resolution can easily be increased. Instead of the commonly used structure of a planar capacitor, a cylindrical capacitor structure has been implemented. This sensor structure consists of two flexible electrodes; one of them is wrapped around the stator and the other is wrapped around the rotor part of a simple mechanical platform used to set angular displacement.

A. Flexible Foil Layout

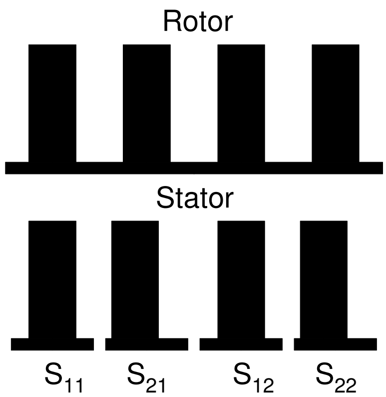

Figure 1. Construction with two channels, contactless and common rotor; physical layout

Fig. 1 shows the physical layout of a silver-printed foil for the sensor. The upper part is attached to the rotor and it is common for both channels, while the bottom part represents the two parts attached to the stator. The sensor is formed when the stator and rotor parts overlap, forming this way a cylindrical capacitor structure. The configuration with the common rotor is used as an attempt to achieve better symmetry between channels. The rotor is contactless and each channel's capacitance is formed as serial connection of two capacitors. These two channel capacitances are serial connections of electrodes S_{11}-R and R-S_{12} for one channel and electrodes S_{21}-R and R-S_{22} for other (see Fig. 1). The rotor movement influences the channel's capacitance. The theoretical (ideal case) dependency of the channel capacitance on rotor angular position is shown in Fig. 2.

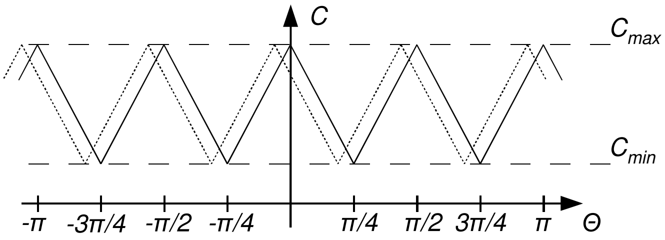

Figure 2. Dependency of the channel capacitance on rotor angular position

The solid line represents the first channel capacitance and the fine dashed line represents the second channel capacitance. These two capacitances are shifted for an electrical angle of π/4 which corresponds to a mechanical angle of π/16. This sensor can be used as an absolute encoder in the range ±π/4 or as a two channel incremental encoder with four pulses per revolution.

B. Prototype Construction

A simple mechanical platform is used to set angular displacement and to hold the rotor and stator flexible foils. The platform with the mounted foils is shown in Fig. 3.

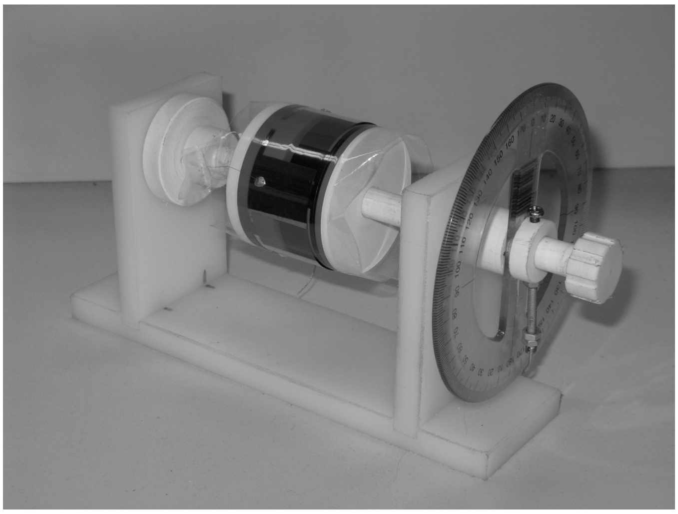

Figure 3. Mechanical platform used as a sensor prototype

III. Analysis of the Capacitance

The analysis of the capacitance value and its dependence on the angular position was done in our previous work [10]. Theoretical dependence on the angular position is presented in Fig. 2, where C_{min} and C_{max} depend on physical properties of the sensor. C_{min} represents stray capacitance while the contribution of the sensor to the capacitance is ΔC which has a maximum of C_{max}-C_{min}. Since the channel capacitances are mutually dependent due to the common rotor, which is the middle electrode for both capacitors, the attention of this work is focused on the capacitance measurement and errors in it.

A. Measurement Configuration

The equivalent circuit of the sensor is shown in Fig. 4. Circuit a) represents the sensor itself and circuit b) represents the equivalent circuit when one sensor's capacitance is measured in a real system. The sensor equivalent circuit consists of four capacitances: C_{S11R} - first stator-first electrode to rotor capacitance, C_{RS12} - rotor to first stator-second electrode capacitance, C_{S21R} - second stator-first electrode to rotor capacitance, C_{RS22} - rotor to second stator-second electrode capacitance. The channel capacitance C_{ch1} is series connection of the capacitance C_{S11R} and C_{RS12}, while the channel capacitance C_{ch2} is series connection of the capacitance C_{S21R} and C_{RS22}. A symbol *CR* marks the common rotor electrode. In a real situation the measurement can only be done on the channel capacitance. Fig. 4b shows the situation in which C_{ch1} is measured. One stator electrode is connected to the measurement equipment (represented in the figure with a voltage source) and the other stator electrode is grounded. The stator electrodes of the second channel are left floating which is modeled with the stray capacitances $C_{stray21}$ and $C_{stray22}$ coming from the measurement equipment and parasitic capacitances.

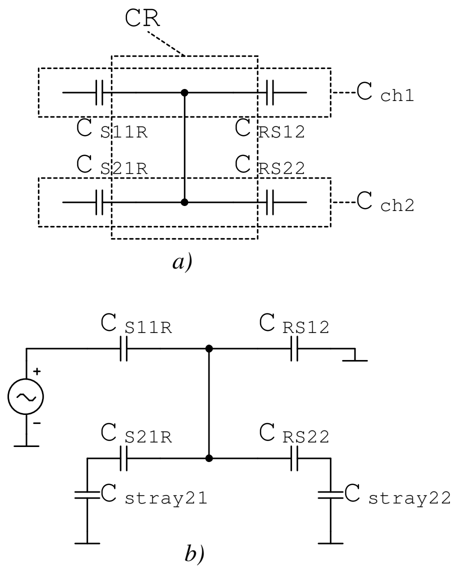

Figure 4. Equivalent circuit of the sensor (a) and measurement setup (b)

Let's consider a case of ideal symmetry of the capacitor structure. This means that all capacitors can be modeled as segments of a cylindrical capacitor with a constant ratio of inner and outer diameter. This setting is software simulated and the results are shown in Fig. 5 in the range from -π/4 to π/4 of a mechanical angle. Thick lines represent the channel capacitances without mutual influences as they are represented in Fig. 4. Thin lines represent the channel capacitances with mutual influence in some real measurement system. Existence of the stray capacitances enables the mutual influences.

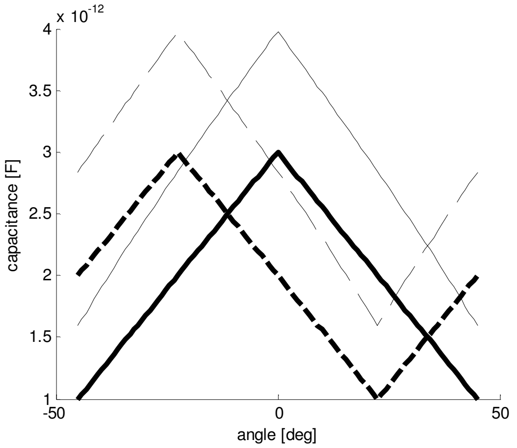

Figure 5. Simulated channel capacitances (thick lines) without mutual influences and the channel capacitances with mutual influence (thin lines) contributed by stray capacitances in case of an ideal mechanical symmetry.

The values of all capacitors in the circuits are chosen according to the expectation from the sensor (ΔC_{max}=2 pF) and measured values of the stray capacitors (C_{stray}=10 pF) when a microcontroller is used to measure the capacitances. It can be seen that the measured capacitances with mutual influences are shifted upwards, that the phase remained unchanged (compared with the capacitances without mutual influence) and that the characteristic's linearity deteriorates.

IV. Experiments and Discussion

The conducted experiments are aimed to prove the simulated results. The measurements were not conducted in some devoted hardware; instead a HP4277A LCZ Meter is used. The stray capacitors are replaced with real ones since they do not exist in this setup.

The channel capacitances of both channels without mutual influences and for the full turn of the sensor's rotor are measured first. Afterwards, measurement of the channel capacitances with mutual influences is conducted. Using the equivalent circuit from Fig. 4b with the assumption of the ideal mechanical symmetry and using the measured values of the capacitances without mutual influences, the values of the capacitances with mutual influences are calculated and compared to the measured values. Since only the channel capacitances can be measured, inner capacitors (e. g. C_{S21R} and C_{RS22}) are assumed to be half of the channel capacitance due to the assumed ideal mechanical symmetry. The results are shown in Fig. 6. The thin line is the measured capacitance with mutual influences for one channel and the thick line is its calculated (assumed) value based on the measured capacitance without mutual influences. It can be seen that certain disagreement exists between the results that deserve to be addressed.

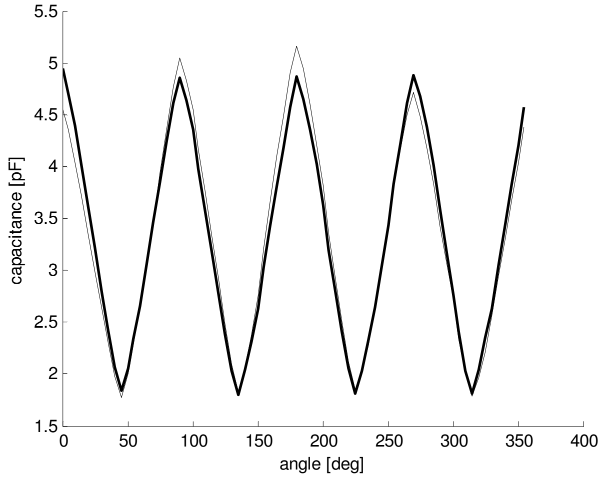

Figure 6. Values of the channel capacitances with mutual influence when directly measured (thin line) and its supposed value based on the channel capacitances without mutual influence measurement

A. Modeling Mechanical Inacuracies

We assume that the main contribution to the results disagreement comes from the mechanical inaccuracies of the mechanical platform used and inaccuracies in the flexible foil montage on the platform. The main contribution of this paper is to prove this assumption but not to precisely determine mechanical inaccuracy. Therefore a simple model of the inaccuracy is adopted. It assumes an eccentricity of the rotor (or stator) or situation in which the stator's and rotor's axes don't coincide sufficiently. The mechanical inaccuracies are modeled with the sinusoidal function of an unknown amplitude and phase. All calculations are conducted with the approximation that all capacitors can be modeled as plane capacitors. The approximation is justified with the fact that the difference between rotor and stator radius (cylindrical capacitor plates) is much lower than their lengths. The stator plates for each channel are opposite to each other. The introduced model changes the distance between stator and rotor plates in a simple periodic manner, in that way reducing the distance for one capacitor and enlarging it for its counterpart capacitor in the same amount. If we take capacitors C_{S11R} and C_{RS12} for example, in ideal case their values are equal for any rotor angular position:

$$C_{S11R} = C_{RS12} = \varepsilon \frac{S(\alpha)}{d} \ . \tag{1}$$

An overlapping area S depends on the angle of rotor position (α), while in this ideal case distance between plates is constant and marked with d. This distance is equal to the half of difference of the stator and rotor diameters. In the case of mechanical inaccuracies these two capacitances are unequal:

$$C_{S11R} = \varepsilon \frac{S(\alpha)}{d_{11}}; \quad C_{RS12} = \varepsilon \frac{S(\alpha)}{d_{12}} \tag{2}$$

and:

$$d_{11} + d_{12} = 2d \ . \tag{3}$$

Concerning the adopted model d_{11} and d_{12} vary in the simple periodic manner and can be represented by modulation of the basic distance (d):

$$d_{11} = d \cdot m_{11} = d \cdot (1 + A(\cos\alpha + \beta_{ph})), \quad (4)$$

where m_1 is the modulation (function) of the C_{S11R}. Amplitude A and phase β_{ph} are unknown and have to be determined. The phase represents the difference between the angle that defines the maximum of capacitance value and an angle where rotor and stator are closest (farthest). From (3) we obtain the modulation for the capacitor C_{RS12}:

$$m_{12} = 2 - m_{11}. \quad (5)$$

In this case the second stator is shifted $\pi/2$ from the first stator, therefore its modulations are:

$$m_{21} = 1 + A(\sin\alpha + \beta_{ph}), \quad (6)$$

$$m_{22} = 2 - m_{21}. \quad (7)$$

The measurement provides only the channel capacitance and not the inner capacitances. Since each channel capacitance is a series connection of two inner capacitors in our model, they are expressed as:

$$\begin{aligned} C_{S11R} &= 2C_{ch1}\frac{1}{m_{11}}, \quad C_{RS12} = 2C_{ch1}\frac{1}{m_{12}}, \\ C_{S21R} &= 2C_{ch2}\frac{1}{m_{21}}, \quad C_{RS22} = 2C_{ch2}\frac{1}{m_{22}}. \end{aligned} \quad (8)$$

In these equations channel capacitances are measured channel capacitances without mutual influences. Using this values and the model presented in Fig. 4b channel capacitances with mutual influences are calculated.

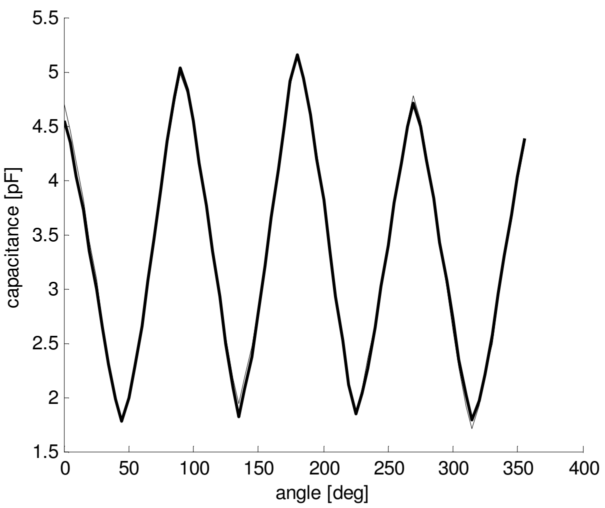

Figure 7. Best fit of the channel capacitances

The main task now is to fit this calculated values to the measured ones as close as possible in order to prove the assumption that the mismatch of these capacitances presented in Fig. 6 is the consequence of mechanical inaccuracies. For that purpose, parameters of the modulation (A and β_{ph}) are varied. The amplitude (A) of the modulation was varied from 0 to 0.2 and the phase (β_{ph}) from - $\pi/2$ to $\pi/2$. As a criterion for selection of these parameters a minimum square error is adopted. The best fit is presented in Fig. 7. As can be seen, the curves are almost identical. This proves the assumption that was made.

V. CONCLUSION

In this paper the mutual influence of the channel capacitances of the capacitive encoder with a common and contactless rotor is analyzed. The mutual influence occurs when stray capacitances are present. The disagreement of the theoretical and measured values for the channel capacitance is successfully justified with mechanical inaccuracies of the platform used as the sensor prototype.

ACKNOWLEDGMENT

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REFERENCES

[1] G. Brasseur, “A capacitive 4-turn angular-position sensor”, Proc. In IEEE Instrumentation and Measurement Technology Conference Ottawa, Canada, May 19-21, vol. 2, pp. 1262 - 1266, 1997.

[2] R. M. Kannel, St. Basler, “New developments in capacitive encoders for servo drives”, Int. Symp. on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2008, pp. 190-195, 2008.

[3] Y. Watanabe, T. Mitsui, T. Mineta, S. Kobayashi, N. Taniguchi, K. Okada, “Five-axis motion sensor with electrostatic drive and capacitive detection fabricated by silicon bulk micromachining”, Sensors and Actuators A, vol. 97-98, pp. 109-115, 2002.

[4] P. L. Fulmek, F. Wandling, W. Zdiarsky, G. Brasseur, S.P. Cermak, “Capacitive sensor for relative angle measurement”, IEEE Transactions on Instrumentation and Measurement, vol. 51, no. 6, pp. 1145-1149, 2002.

[5] H. Zangl, T. Bretterklieber, “Rotor Design for Capacitive Sensors”, Proc. of IEEE Sensors conference, vol. 1, pp. 520 - 523, 2004.

[6] T. Fabian, G. Brasseur, “A Robust Capacitive Angular Speed Sensor”, IEEE Trans. on Instrumentation and Measurement, vol. 47, no. 1, pp. 280-284, 1998.

[7] B. George, V. J. Kumar, “Digital Differential Capacitive Angle Transducer”, Proceedings on IEEE Instrumentation and Measurement Technology Conference, IMTC'2007, pp. 1-6, 2007.

[8] S. P. Cermak, G. Brasseur, “A planar capacitive sensor for angular measurement”, IEEE Instrumentation and Measurement Technology Conference, Budapest, Hungary, May 21-23, pp. 1393-1395, 2001.

[9] V. Ferrari, A. Ghisla, D. Marioli, A. Taroni, “Capacitive angular-position sensor with electrically floating conductive rotor and measurement redundancy”, IEEE Transactions on Instrumentation and Measurement, vol. 55, no. 2, pp. 514 – 520, 2006.

[10] D. Krklješ, D. Vasiljević, G. Stojanović, “A Capacitive Angular Sensor with Flexible Digitated Electrodes”, Sensors Review journal, unpublished, submitted on august 2012.