# An Ink-Jet Printed Capacitive Sensor for Angular Position/Velocity Measurements

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***Abstract*—This paper presents the prototype of a capacitive angular position/velocity sensor which exploits the advantages of flexible/printed electronics. The sensor belongs to the incremental encoder type with two quadrature channels. Instead of the commonly used structure of planar capacitor, in this paper a cylindrical capacitor structure with digitated electrodes, for both the stator and the rotor, was implemented. The flexible printed electrodes are attached to the inner wall of the stator and to the perimeter of the rotor cylinder. The rotor has no external contacts; electrical connection is established with the stator only. The working principles of the sensor and the signal conditioning circuit were demonstrated through experimental results based on in-house developed mechanical and electronics platforms.**

***Index Terms*—angular velocity, capacitive sensors, flexible electronics, rotation measurement, sensor systems and applications.**

## I. Introduction

In many industrial applications, such as automotive industry, robots, industrial automation, metrology, etc. [1], there is a need for the angular position and speed of a shaft to be measured using different types of capacitive sensors. These sensors have to resist harsh environment such as vibration, excessive ambient temperature and dirt [2]. Capacitive displacement sensors usually comprise two parallel conducting plates and they are classified into two categories depending on whether the detecting variable is the spacing between the plates or the area of overlap of the plates [3]. A contact-type linear encoder-like capacitive displacement sensor was proposed for measurement of a long-range displacement with high accuracy, due to the separation of electrodes using a thin dielectric layer. This type of sensor can easily control the gap between the facing electrodes, thus maximizing the sensitivity of the sensor itself [4]. The experimental assessment of a micromachined capacitive incremental position sensor for nanopositioning of microactuator systems with a displacement range of 100 μm or more was reported in [6]. This incremental sensing in combination with quadrature detection reduces the requirements for dynamic range for the sensor. Angular-position sensors are used to determine the rotational displacement of a moving part, the rotor, relative to its stator [7], whereas angular/speed sensors measure angular velocity between the moving parts. 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 exited by a high frequency signal to measure capacitance [8]. One approach uses two (usually circular-shaped) electrodes, one of them is fixed, while the other one rotates with the shaft. The other approach uses two stationary electrodes with a rotating plate placed between them, made either from dielectric or conducting material [9]. In order to form the incremental signal when an absolute encoder is used, the capacitance should be measured very precisely, before the decision about the current state of output can be made. This procedure implies the use of a microcontroller, A/D converters and extensive numerical calculations, with all this leading to slower response, thus limiting the shaft speed upper limit that can be detected by the sensor [10]-[11]. The time needed for the data acquisition and the evaluation of the ratiometric algorithm limits the applicable speed measurement range to about 1000 rpm based on absolute angular position [11]. For the incremental design also presented in [12], reported rotational speed was 3600 rpms. An accurate measurement of very low speeds can be achieved using this technology [13]. On the other hand, when a native capacitive incremental encoder is used, the signal processing circuit can be simplified and the overall processing time can be shortened. There are just a few native incremental encoders presented in open literature up to now and none of them has two quadrature channels. A single channel incremental capacitive sensor for harsh environments was presented in [14]. Moreover, a capacitive linear encoder characterized by its untethered slider (stacked on a stator) was presented in [15]. This encoder has two-phase transmitting and four-phase receiving electrodes, but electrodes are not ink-jet printed and they are not used in curved/flexible form. Additionally, implemented structure with untethered slider in planar construction, based on electrostatic induction, is complicated for fabrication and for handling.

The field of flexible electronics attracted a significant interest from both academia and industry in recent years [16]. According to market analysis, the revenue of flexible electronics is estimated to be 30 billion USD in 2016 and over 300 billions USD in 2028 electronics [17]. This paper fully uses all advantages of flexible electronics based on ink-jet printing technology, which can rapidly fabricate prototype circuits and represents additive method and therefore it does not produce waste and harmful substances, for fabrication of angular position/velocity sensor in cylindrical shape. In this paper, a prototype of a capacitive angular-speed sensor printed on flexible substrate (Kapton film foil) along with experimental results is presented. The sensor is of incremental encoder type having two quadrature

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channels. The sensor has a resolution of six pulses per full turn. The advantages of the presented electrodes topology are a consequence of applied ink-jet additive technology and they are: mechanical flexibility, lightweight design (flexible substrates), ultra low-cost (particularly important for application in automotive industry), lack of any electrical contact to the moving parts, conformal design, etc. Additionally, the proposed design enables simple sensor replacement as well as an uncomplicated mounting procedure.

## II. Design of Capacitive Sensing Electrodes

The capacitive sensing element exploits the properties of ink-jet printing technology, mechanical flexibility of substrate and its ability of conforming to curve surfaces. Flexible capacitive electrodes were mounted (wrapped) on the sensor's mechanical parts, the rotor and stator, which have been made in cylindrical shape. The layouts of the flexible printed electrodes with their dimensions are shown in Figure 1, while Figure 2 shows the photograph of their physical appearance, after fabrication. The capacitive electrodes were printed on a flexible substrate using ink-jet additive technology. Dimatix ink-jet materials deposition printer DMP-3000 (http://www.fujifilmusa.com) was used to print conductive silver nanoparticle ink (Suntronic Jet Silver U6503, http://www.sunchemical.com) on mechanically flexible substrate (Kapton foil, http://www.gts-flexible.co.uk), 75 µm thick and with a relative dielectric constant equal to 3.2. After printing, the electrodes were dried for 45 minutes at a temperature of 200 °C. Figure 1a) shows the layout of the stator electrodes. There are two pairs of electrodes forming two stators for two channels. The first channel is formed by *stator1-1* and *stator1-2* electrodes, while the second is formed by *stator2-1* and *stator2-2* electrodes. Figure 1b) shows rotor electrodes for two channels. The electrodes are shifted relatively to each other, providing a phase shift of $\pi/2$ between channels, thus creating quadrature signals.

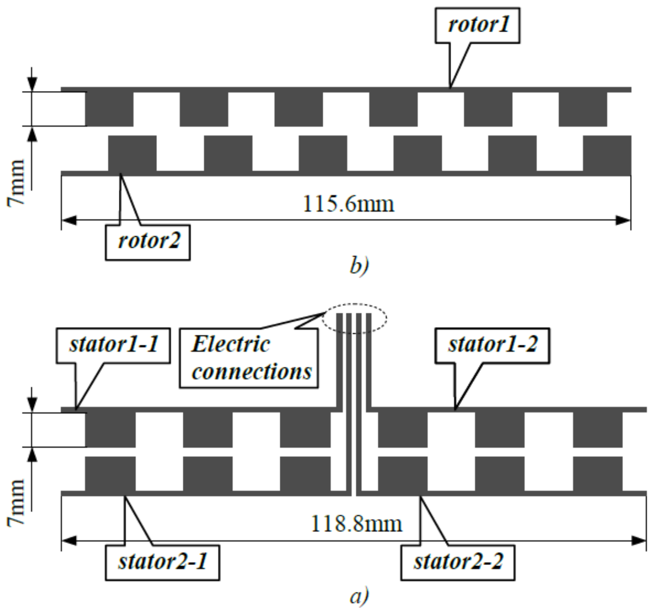


Figure 1. Layout of the conductive electrodes printed on flexible foil. Fig a) shows two pairs (for two channels) of stator electrodes (matching pairs are placed horizontally). Fig b) shows rotor electrodes for two channels

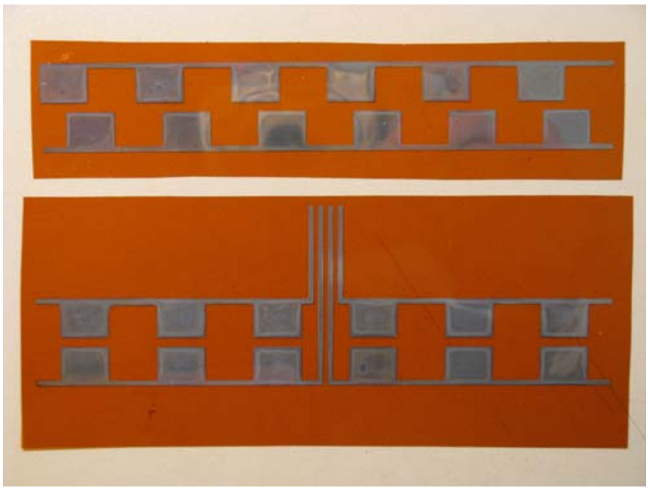

Figure 2. Unrolled topology of the stator and rotor silver printed electrodes on flexible foil (Kapton film)

A drop ink-jet process is used. The best uniformity of printed layers was obtained for drop diameter of 36 µm and drop spacing equal to 18 µm. The structural characterization of printed layers after drying and sintering was performed using scanning electron microscopy (SEM). SEM micrographs can be seen in Figure 3. Fig. 3 illustrates that the width of a conductive silver layer is around 260 nm.

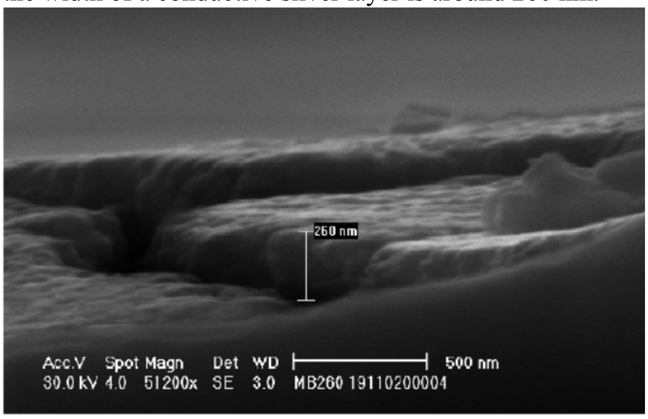


Figure 3. SEM micrograph of ink-jet printed silver layer for sensing electrodes

Instead of a commonly used structure of planar capacitor, in this paper a cylindrical capacitor structure with digitated electrodes for both the stator and rotor has been implemented. A comparative analysis of cylindrical and planar capacitive structures with respect to sensitivity on mechanical displacement was performed. Results are presented in Table I.

TABLE I. COMPARATIVE ANALYSIS OF PLANAR AND CYLINDRICAL STRUCTURES ON AXIAL AND RADIAL OFFSET

| Structure | Error | |
|---|---|---|
| | Axial | Radial |
| **Planar electrodes** | 32.083 % | 0.080% |
| **Cylindrical electrodes** | 0.066 % | 4.625 % |

The cylindrical structure in comparison to planar shows less sensitivity in axial direction, while the planar shows less sensitivity in radial direction. For both structures one axis shows at least two orders of magnitude more sensitivity compared to the other. For the cylindrical structure the more sensitive axis is radial and less sensitive is axial. For planar structure it is vice versa. If comparison is made between more sensitive axis of both structures as well as less sensitive axis it can be concluded that cylindrical structure has better overall performances. Thus, we have proposed the cylindrical sensor structure which consists of two flexible electrodes for each channel. The stator electrodes for both channels are printed on the same piece of foil. The same case is with the rotor electrodes. The stator electrodes are attached to the inner wall of the stator, while the rotor electrodes are attached to the outer perimeter of the rotor. The rotor electrodes exhibit a phase shift made by introducing a displacement in the appropriate direction between the electrodes. The stator is a hollow cylinder, while the rotor is a bulk cylinder that resides inside the stator. Both were made of a solid material (polypropylene). There are two identical stator electrodes placed symmetrically across the stator circumference for both channels, which, in combination with the one of the rotor electrodes, make the structure of two capacitors connected in series. This way the rotor is without any external electrical contacts and the measurements can be made on the stator side only. The electric connections are placed only on one side. This layout enables simpler mechanical construction and assembly procedure.

## III. Design of Complete Sensor

The sensor's mechanical construction consists of stator, rotor, shaft, ball bearings and lids. The physical appearance of the dismantled sensor is depicted in Figure 4, while the assembled sensor is shown in Figure 5.

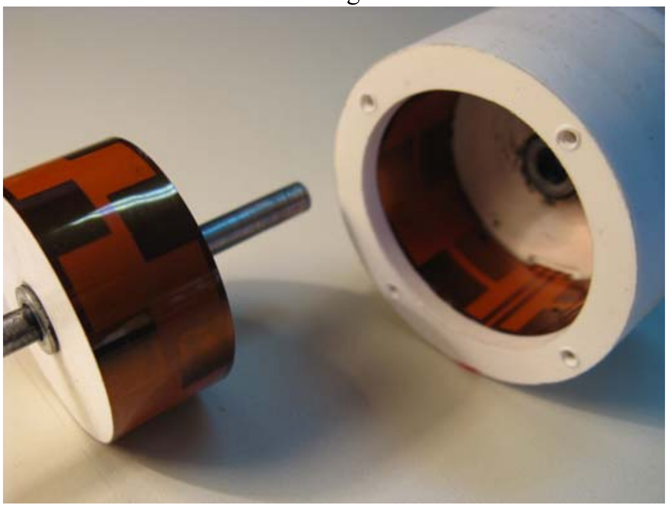

Figure 4. Picture of the dismantled sensor. The rotor with shaft and attached rotor electrode is shown on the left hand side. The right hand side shows the stator with back lid and attached stator electrode

The printed electrodes are carefully attached to the outer perimeter of the rotor and inner wall of the stator. A double-sided adhesive tape is used for this purpose. The thickness of the used tape is 100 µm. This thickness has been incorporated in the calculation of appropriate dimensions (length) of the printed electrodes. The diameter of the rotor is 36.7 mm and the inner diameter of the stator is 38 mm while the outer is 50 mm. With these dimensions and thickness of the adhesive tape and Kapton foil, an air gap 300 µm wide between the rotor and stator is formed. This rather large air gap was chosen in order to avoid friction between the stator and rotor or accidental jamming due to mechanical and assembly tolerances of the in-house made sensor mechanics.

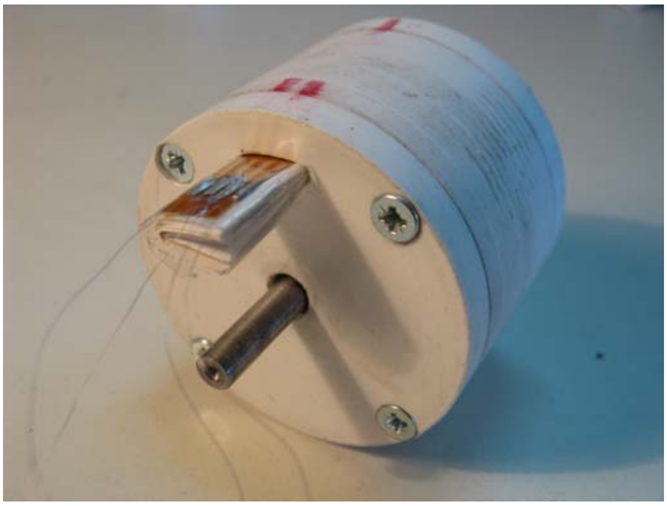

Figure 5. Picture of the assembled sensor. The stators electric contacts are taken out and the thin conductive wires are glued to the contacts using conductive epoxy paste

As can be seen in Figure 5 the stator's electric contacts are taken out, and the thin conductive wires are glued to the contacts using a conductive epoxy paste. The wires are connected to the signal conditioning electronic circuit.

## IV. Capacitance Calculation

For presented structure three capacitors can be recognized. The first one is the rotor electrode capacitor ($C_R$) with Kapton foil as dielectric material. The second is the air gap capacitor ($C_A$) and the third is the stator electrode capacitor ($C_S$), again with Kapton foil as dielectric material. The rotor and stator capacitors exist since the printed side of the foil is oriented toward the adhesive tape in order to avoid accidental mechanical damage of the printed layer. The overall capacitor is the series connection of all these capacitors. Let us assume the full cylindrical structure. Then, these capacitances can be calculated as follows:

$$C_{R\_whole} = 2\pi\varepsilon_0\varepsilon_{r\_kapton}\frac{L}{\ln\frac{d_{r2}}{d_{r1}}} = 307\,\text{pF}, \quad (1)$$

$$C_{S\_whole} = 2\pi\varepsilon_0\varepsilon_{r\_kapton}\frac{L}{\ln\frac{d_{s2}}{d_{s1}}} = 313\,\text{pF}, \quad (2)$$

$$C_{A\_whole} = 2\pi\varepsilon_0\frac{L}{\ln\frac{d_{a2}}{d_{a1}}} = 24.27\,\text{pF}, \quad (3)$$

where $L$ is the height of the digit (or finger), which is 7 mm and $d_{x1}$ and $d_{x2}$ are starting and ending diameters of each capacitor. The difference between the starting and ending diameter is the thickness of the corresponding dielectric material. The overall capacitance is the series capacitances of all, and its value is 21 pF. Since the active area of the stator and rotor is half of the whole cylinder, because of the digitated shape of the electrodes, the obtained capacitance has to be halved. Furthermore, there are two stator segments per each channel and the capacitance value once again has to be halved. Therefore the final value is 5.25 pF. This value corresponds to the maximum capacitances change.

## V. Sensing System Overview

The sensor is composed of two parts: a capacitive sensing element and a signal conditioning circuit (Figure 6). The capacitive sensing element is shown on the left hand side in Figure 6 and consists of four capacitors divided into two subgroups, this way forming two sensing channels. The capacitors $C_{SR1CH1}$ and $C_{SR2CH1}$ form the first channel, while other two capacitors form the second channel. The capacitance of all capacitors depends on the relative angular displacement between the rotor and stator. The common electrodes for the two capacitors of each channel are placed on the rotor.

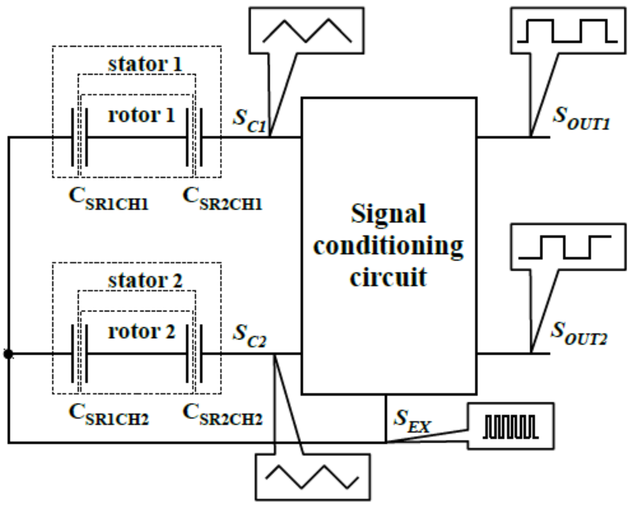


Figure 6. Sensing system composed of: the capacitive sensing element ($C_{SR1CH1}$, $C_{SR2CH1}$, $C_{SR1CH2}$ and $C_{SR2CH2}$) and a signal conditioning circuit

The stator of each channel consists of two electrodes, the first which forms the first channel capacitor with the rotor electrode ($C_{SR1CH1}$ for the first channel and $C_{SR1CH2}$ for the second channel) and the second similarly forming the second channel capacitor ($C_{SR2CH1}$ for the first channel and $C_{SR2CH2}$ for the second channel). The stator structures are also indicated by the surrounding dashed lines and marked with labels stator 1 and stator 2. The channel capacitors are in this way connected in series. This structure provides that the external electrical contacts are placed only on the stator. The signal conditioning circuit is represented with the block and will be discussed later in the next chapter. It provides the excitation signal ($S_{EX}$) for the capacitive sensing element, the pickup inputs ($S_{C1}$ and $S_{C2}$) for both capacitive sensing element channels and the two output digital signals in quadrature ($S_{OUT1}$ and $S_{OUT2}$). The signal shape is shown in callouts for easier understanding. The charge to the charge amplifier is supplied through the sensing capacitors (signals $S_{C1}$ and $S_{C2}$) that are excited by the high frequency square wave signal $S_{EX}$. The signals $S_{C1}$ and $S_{C2}$ represented in the callouts are not electrical signals, but they represent the capacitance change of the capacitive sensing element when constant angular velocity is applied to the sensor. The signals $S_{OUT1}$ and $S_{OUT2}$ presented in the callouts represent the output electrical signals (with a phase shift of $\pi/2$ between them) when constant angular velocity is applied to the sensor.

## VI. Signal Conditioning Circuit

A signal conditioning circuit implements only analog processing and uses a charge amplifier circuit to convert a capacitance to a voltage. The advantage of using the charge amplifier is the elimination of influence of parasitic stray capacitors. A simplified circuit of the signal conditioning circuit for one channel is shown in Figure 7. At all significant points in the figure, the shape of the signals are shown in corresponding callouts. The square wave signal generator (G) injects a high frequency signal into the sensor. The capacitor $C_{SRX}$ represents the series connection of both channel capacitors. The charge amplifier consists of the operational amplifier ($OP_1$) and the feedback capacitor $C_{REF}$. The output signal ($S_{CA}$) from the charge amplifier is an amplitude modulated square wave signal. The modulation index is proportional to the value of $C_{SRX}$. This signal is then sampled at a sampling frequency ($F_S$) that corresponds to the sampling interval ($T_S$). The sampling signal is placed in the middle of half of the signal's period and it is shorter than it.

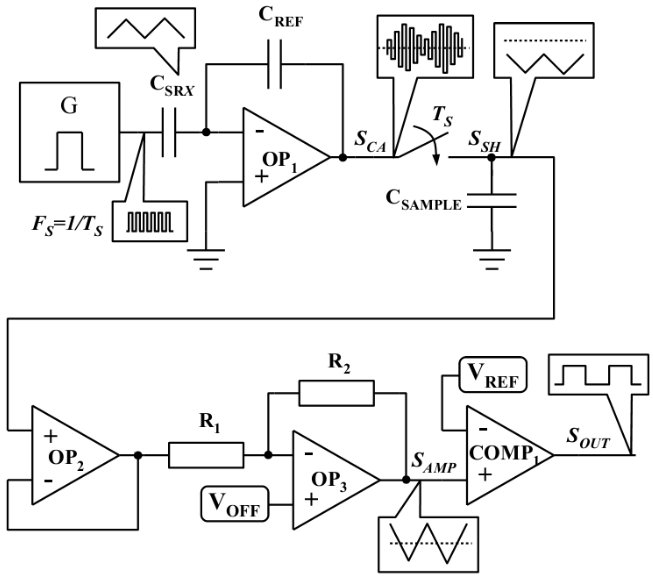


Figure 7. Signal conditioning circuit. The signal passes through charge amplifier, sample and hold circuit, buffer, differential amplifier and comparator, providing the square wave output

Depending on the chosen half period either the top or the bottom envelope is obtained at the sample-and-hold output ($S_{SH}$). The final stage of the signal conditioning circuit is the voltage comparator ($COMP_1$) with adjustable threshold voltage ($V_{REF}$) that provides the square wave output signal ($S_{OUT}$).

## VII. Experimental Results and Discussion

In order to test developed sensor prototype, an experimental platform was developed as it is shown in Figure 8. The experimental platform consists of three parts: sensor, motor and read-out electronics. The motor transfers its rotational movement through a belt to the sensor. The motor is supplied with a constant DC voltage and runs at approximately constant speed. The sensor electronics implements signal conditioning as described previously.

All measurements were done using an Agilent Technologies DSO3062A digital storage oscilloscope. The excitation signal (channel 2) and sampling signal for the sample-and-hold circuit (channel 1) are shown in Figure 9. The sampling signal occurs during the positive half period of the excitation signal and it is shorter than the half period.

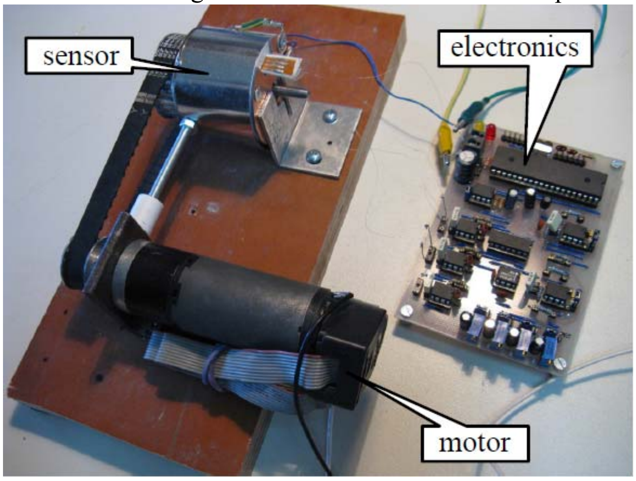


Figure 8. Experimental setup. It consists of motor, sensor and electronics

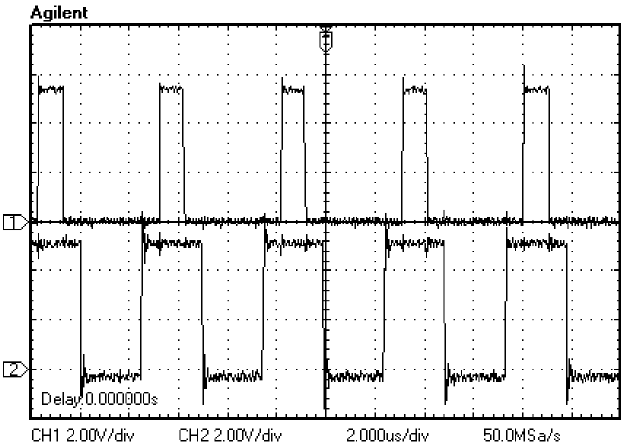


Figure 9. Excitation signal (ch2) and sampling signal for sample and-hold circuit (ch1)

Figure 10 shows the signal from the charge amplifier output (channel 2), where the slew-rate of the operational amplifier can be seen, and the sampling signal (channel 1). It can be seen that the sampling signal starts at the moment when the output stabilizes and ends before a new transition of the excitation signal begins.

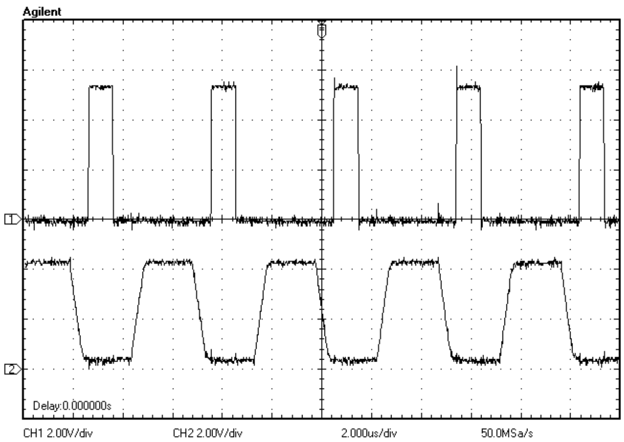


Figure 10. Sampling signal for sample and-hold circuit (ch1) and output signal of the charge amplifier (ch2)

The amplitude-modulated signal from the charge amplifier (channel 2) and the signal on the sample-and-hold capacitor (channel 1) that represents the bottom envelope of the amplitude-modulated signal from the output of the charge amplifier are shown in Figure 11.

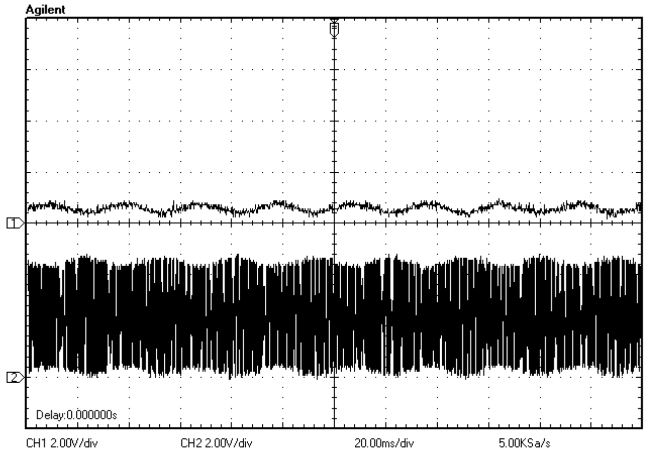


Figure 11. Amplitude modulated signal from the charge amplifier (ch2) and signal on the sample-and-hold capacitor (the bottom envelope of amplitude-modulated signal) (ch1)

The signal from the charge amplifier output is symmetrical with respect to the referent level (in this case the half of the 5 V supply) while the sampled signal is not. After amplification and offsetting of the signal from the sampling capacitors, symmetrical analog signals that represent capacitance variation are obtained. These signals are presented in Figure 12, where both channels are shown.

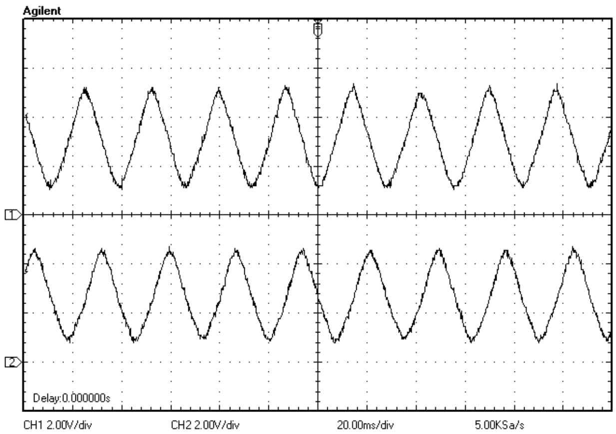


Figure 12. Signals at the outputs of the differential amplifiers. Both signals have large amplitude and are symmetrical with respect to the referent level

Finally, after passing through the comparators, two square wave output signals in quadrature are obtained as can be seen in Figure 13.

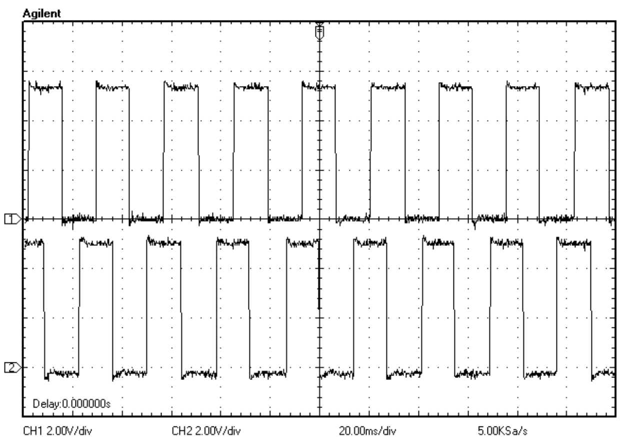


Figure 13. Square wave output signals in quadrature

The change of dielectric constant will influence the output signal in a sense that the impulse width will be modulated, thus producing unacceptable errors. To deal with this, a sensor has to continuously compensate for the variation of the dielectric constant. There are some methods that might be implemented. For example, the sensor can monitor the frequency and duty cycle of output signals. When the sensor recognizes that the frequency is almost constant during some predefined period of time (or number of elapsed periods), based on the duty cycle measured in that interval the system can adjust some variables, for example offset voltage $V_{OFF}$ (Figure 7), to achieve desired duty factor of 50 %. Another way to compensate would include a reference capacitor, which would detect the variation of the dielectric constant through the variation of its capacitance. This capacitor would also have to be placed inside the sensor, but must not depend on the relative angular position between the stator and rotor.

## VIII. CONCLUSION

In this paper the basic concepts of the capacitive angular sensor construction, working principles and signal conditioning have been demonstrated. The main part of the sensor represents two ink-jet electrodes, printed on a flexible substrate to form a cylindrical capacitor. The printed electrodes are carefully attached to the outer perimeter of the rotor as well as inner wall of the stator. The mechanical parts of the complete sensor structure are mostly made of polypropylene material (stator, rotor and lids). This material was chosen due to its good machining properties. The material has also a small value of relative dielectric constant (2.2-2.36). The smaller values are desirable since the values of capacitances of the parasitic capacitors depend directly on it. Only the shaft was made of steel to provide mechanical rigidity that polypropylene of a 5 mm diameter cannot provide. The ball bearings placed inside both lids have been also made of steel. Readout electronic circuit composed of charge amplifier, sample and hold circuit, buffer, differential amplifier and comparator has been realized providing the square wave output. The implemented sensor conditioning circuit showed very good results. We can summarize that advantages of the proposed sensor comparing to standard ones are as follows:

- Small/compact size;
- Light weight;
- Cost effectiveness;
- Less sensitivity to assembly tolerances compared to planar structures;
- Fast signal processing;
- Conformability, which enable applications on many different shapes/volumes.

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