42.6: A Contactless Capacitive Angular-Position Sensor

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Abstract
An absolute capacitive angular-position sensor with a contactless rotor is presented. The sensor is mainly composed of three parts: the capacitive sensing element, a signal processor and a microcontroller. The electrically-floating rotor can be either conductive or dielectric. Glass has been chosen for the dielectric material because of its low losses, and high hardness and flatness. For the conductive rotor we have chosen steel. A redundant structure has been used for the sensing element in order to reduce the mechanical errors. The signal processor has a multi-capacitance input and a single output. The output signal is a period-modulated square-wave voltage. The microcontroller acquires output data from the processor and sends them to a PC, which calculates the rotor position. The resolution of the capacitive angular-position sensor over the full range (360°) *is better than* 1″. *The nonlinearities are* 0.06° *and* 0.15° *for the dielectric and conductive rotor respectively.*

Keywords
Angular position measurement, contactless angle encoder, rotary position, absolute position encoder, capacitive sensor.

INTRODUCTION

Capacitive angular-position sensors offer low energy consumption, simple structure and construction, and high accuracy and resolution [1]. Peters [6] presented a simple structure with two fixed transmitting electrodes and two moving receiver plates forming a capacitive bridge. He used a sinusoidal signal to drive the bridge and a differential amplifier for picking up the received signal. The measured range was 180°. Wolffenbuttel and Van Kampen [9] presented a contactless sensor with four driving electrodes (connected to four sinusoidal voltages with relative phase differences of 90°) and one receiver electrode. Both the transmitters and the receiver were mounted in the same plate and the measurement range was 360°. In order to improve the linearity and resolution of the sensor the authors implemented a more complex pattern for the electrodes. Even in this case the nonlinearity amounted to 3°. De Jong et al. [4] presented a sensing element with a symmetrical and redundant structure that reduces the mechanical errors. In order to reduce the electric-field-bending effect and the external interference they applied guarding electrodes and used a grounded metal-house. The electronic interface was designed based on a simple and low-cost capacitance-to-period converter and a measurement technique that reduces the effect of the parasitic capacitances and eliminates additive and multiplicative errors. The measurement range was of 90°. Li et al. [3] extended the measurement range to 360°. They achieved a resolution of 1.5″ and a nonlinearity of ±0.034°. With additional processing they reduced the nonlinearity to ±0.016°. However, both designs used a conductive rotor grounded by, for instance, a sliding contact, which causes long-term reliability problems. In [2] the authors avoid this contact by proposing a nonconductive rotor grounding by means of stray capacitances. The nonlinearity amounts to 0.25° and the measurement range was 180°. The working frequency was 15 MHz that could prevent the use of a simple electronic interface.

This paper presents a contactless capacitive absolute angular-position sensor with full-circle range (360°) combining some of the best qualities from these previous designs and providing new experimental results. The sensing element and the electronic interface are based in the ideas presented in Ref. [3] and [4] in order to reduce the mechanical errors and to use a simple low-cost electronic interface. A contactless rotor has been used in order to improve the reliability of the sensor, although this can increase the errors due to mechanical tolerances. This floating rotor can be either conductive or dielectric. In the above previous work, no attempt has been made to use dielectric rotors, maybe because this could bring additional problems as static charge effects and increased sensitivity to moisture and pollution. Also, the sensitivity (capacitance change) with the dielectric rotor will be lower than that obtained with a floating conductive rotor. Even then, the only commercially available capacitive encoder known to the authors has a dielectric rotor [5]. This could be because it is the only alternative if a contactless sensor with a conductive shaft has to be used.

A prototype of the sensor has been designed and built in order to test the performance of the electrically floating rotor, either conductive or dielectric. Some preliminary results are shown.

SYSTEM OVERVIEW AND PRINCIPLES

The capacitive angular-position sensor is composed of three parts: the capacitive sensing element, a signal processor and a microcontroller (Fig. 1). The sensing element is a multielectrode structure whose capacitances are sensitive to the angular position of the rotor. The signal processor sequentially converts the capacitance values of the sensing element to a period-modulated signal. The microcontroller is used to acquire and process output data from the signal processor and to communicate with the outside world.

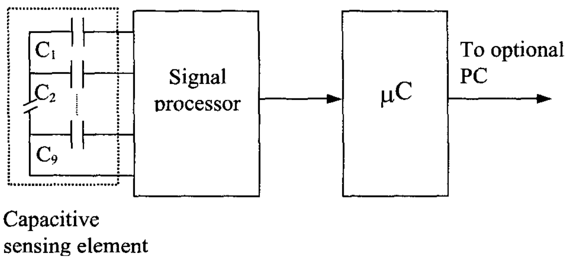


Figure 1. Overview of the capacitive angular-position sensor.

The sensing element

Figure 2 shows the structure of the capacitive sensing element. As can be seen, it is composed of three main parts: a fixed segmented plate with multiple electrodes (on the left), a electrically-floating moving rotor (in the center), and a fixed common plate with a single electrode (on the right). The purpose of the whole system is to accurately determine the position of the moving rotor with respect to the fixed plates.

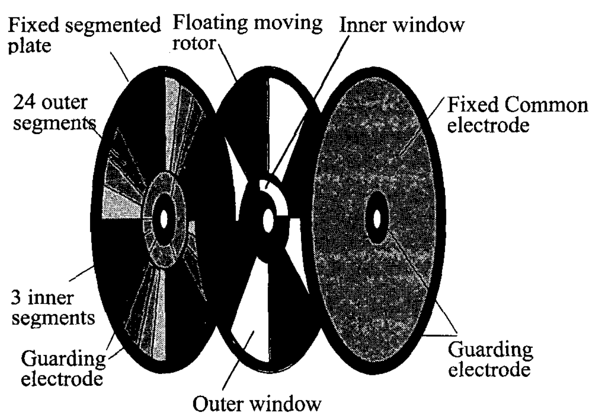


Figure 2. Structure of the capacitive sensing element.

As shown in [3], the outer segments of the fixed segmented plate (Fig. 2, left side) that have the same gray level are interconnected. These 24 outer segments (15° wide) form 6 different electrodes with 4 segments (90° apart) each. These 6 electrodes together with the common electrode (Fig. 2, right side) form the capacitances C_1 to C_6 in Fig. 1. The three inner electrodes of the segmented plate (120° wide) together with the common electrode form the remaining capacitances C_7 to C_9. Guarding electrodes, which surround the segmented and common electrodes, are used to reduce the influence of the electric-field-bending and of electromagnetic interference.

The four outer windows (45° wide) of the rotor (Fig. 2) are aligned with the outer electrodes of the segmented plate and have a pitch of 90°. Then, the rotor together with the outer segments form a redundant structure that is repeated every 90°. The value of the capacitances C_1 to C_6 will depend on the position of the floating rotor and will be the same for each quarter of the circle. The use of this structure significantly reduces the influence of both the random and the systematic mechanical errors, such as the eccentricities, the non-flatness and the obliqueness of the fixed plates and the rotor [3]. The inner window of the rotor (120° wide) is aligned with three inner electrodes of the segmented plate (Fig. 2). The value of the capacitances C_7 to C_9 will depend on the position of the inner window. The algorithm for retrieving the angular position will be described in the next section.

To reduce the electric-field-bending effect and to increase the sensitivity the distance between the fixed electrode plates and between these ones and the rotor, should be decreased. However, this will increase the errors due to the non-flatness of the surface of the electrodes and rotor. No experimental results about this item are presented in this work but it should be considered for future research.

Glass has been chosen as the dielectric material for the rotor because of its high permitivity, hardness and flatness, and its low losses. Steel has been selected as the conductive material because of its high hardness and flatness. Water and laser cutting were used to cut the glass and the steel rotors respectively.

The measurement algorithm

Figure 3 shows a partial section view of the sensing element for the outer capacitances C_1 to C_6.

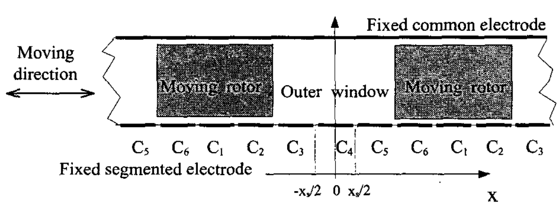


Figure 3. Partial section view of the sensing element for the outer capacitances.

Due to the presence of the electrically floating rotor the capacitances C_1, C_2, and C_6 will have (in this case) a higher capacitance value than the remaining ones (C_3 to C_5). As the rotor is moving, the capacitance values of C_1 to C_6 will change. So, the values of these capacitances will depend on the angular position of the rotor. The capacitance-value change will be higher when using the conductive rotor. The same principle applies with the inner capacitances (C_7 to C_9) and the inner window of the rotor (Fig. 2).

Similar as that presented in [3], the calculation of the absolute angular position from the measured nine capacitances (C_1 to C_9) is performed in three steps: a first and a second coarse measurement over ranges of 90° and 360° respectively, and an accurate fine measurement over a range of 15°. Firstly, by comparing the capacitance values C_1 to C_6 we determine in which electrode i (i = 0, ..., 5) of the segmented plate the rotor is situated. Secondly, the values of C_7 to C_9 together with the electrode i determine in which quadrant q (q = 0, ...,3) the rotor is. Finally, supposing that the rotor is as shown in Fig. 3, its position is determined accurately over a range of 15° by

$$\frac{x_m}{x_s}=\frac{(C_2+C_3 \quad (C_5+C_6)}{2(C_1-C_4)} \quad \frac{x_p}{x_s}, \quad \left(-\frac{1}{2}\leq\frac{x_m}{x_s}\leq\frac{1}{2}\right) \quad (1)$$

where x_m is the measured position, x_s is the width of one segment (15°), and x_p is the actual position over a range of 15° (±7.5°). If the nonidealities of the sensing element are neglected, $x_m = x_p$. Also, the use of (1) considerably reduces the electric-field-bending effect [3].

The measured absolute angular position, both for the dielectric and the conductive rotor, is found using the equation

$$\varphi_m=\left(\frac{x_{mi}}{x_s}+i+\frac{1}{2}\right)\times 15^\circ+q\times 90^\circ \quad (2)$$

where x_m/x_s is calculated using (1).

Electronic circuit and signal processing

Figure 4 shows the electronic interface used for the capacitive angular-position sensor. The signal processor is composed of a capacitive-controlled oscillator and a multiplexer. It linearly converts the nine-capacitor values into a period-modulated signal. The multiplexer sequentially selects the nine capacitors to be measured. The microcontroller controls the multiplexer and digitizes the period-modulated signal from the signal processor.

The period T_i of the signal processor output is related to the capacitor values by the linear equation

$$T_i = aC_i \quad b, \quad (i=1,...,9) \quad (3)$$

where a and b are constants. By substituting (3) into (1) for the fine measurement, it is found that

$$\frac{x_m}{x_s}=\frac{(T_2+T_3)-(T_5+T_6)}{2(T_1-T_4)}, \quad \left(-\frac{1}{2}\leq\frac{x_m}{x_s}\leq\frac{1}{2}\right) \quad (4)$$

As can be seen, the parameters a and b are eliminated. Therefore, the influences of the unknown offset and gain of the electronic interface and other linear systematic errors are eliminated.

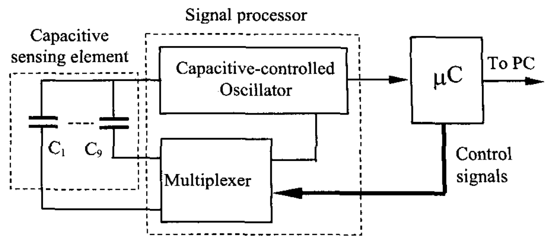


Figure 4. Electronic interface for the capacitive angular-position sensor.

EXPERIMENTAL RESULTS

A contactless capacitive angular-position sensor based on the structure shown in Fig. 2 and on the signal processor shown in Fig. 4 has been built and tested. The electrodes and the rotor have been mounted in a metal housing (outside diameter of 60 mm), which is connected to ground and shields against external interference. The fixed electrodes have been made using standard printed-circuit-board technology. They are 2 mm thick and have a diameter of 50 mm. The distance between the fixed electrodes amounts to 3.5 mm as fixed by a circular ring. The capacitance value (without the rotor) for the outer electrodes (C_1 to C_6) is 0.3 pF and for the inner electrodes (C_7 to C_9) is 0.2 pF. The outside diameter of the rotor is 47 mm. The thickness of both materials, glass and steel, is 3 mm. A shaft with dielectric material (Delrin) has been used to avoid external interferences and to achieve electrical isolation of the rotor from the metal house.

The nine capacitances have been measured using the electronic interface of Fig. 4. This interface has been implemented with a Universal Transducer Interface, UTI, [7] as the capacitive-controlled oscillator, a MUX03 [8] as the multiplexer, and a PIC16F873 (Microchip) as the microcontroller. Measurement time for the nine capacitances amounts to 250 ms. To further reduce the jitter noise we have averaged the capacitance values with 10 measurements. The final jitter on the measured angle is less than 1″. The data are sent to a PC via a RS232 interface.

Figure 5 shows the experimental setup used to test the performance of the capacitive sensor (left side). An optical encoder (on the right side of Fig. 5) RON 285 (Heidenhain), with an accuracy of 5″, is used as the reference measurement. The angular position is manually changed.

Fig. 6 shows the measured nonlinearity over the full range (360°) of the contactless capacitive angular-position sensor for the dielectric, Fig. 6(a), and the conductive rotor, Fig 6(b).

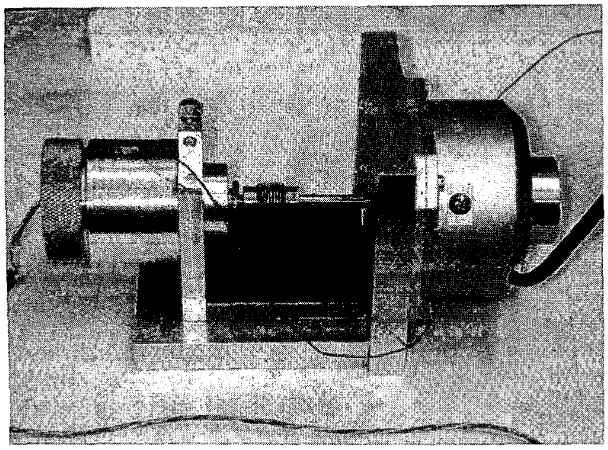
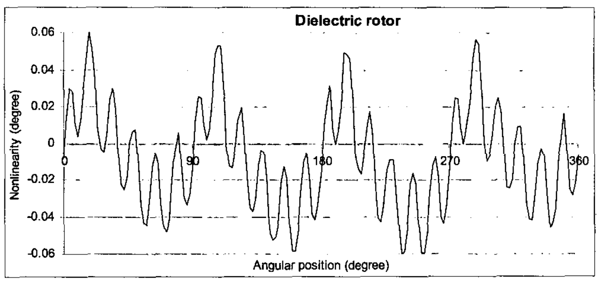
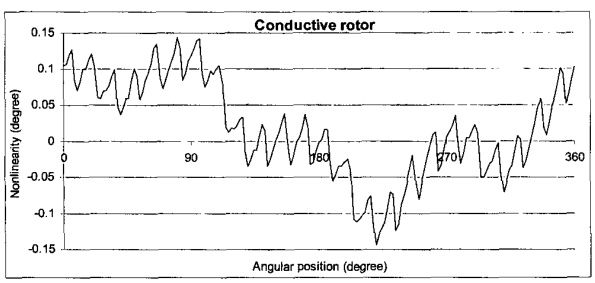


Figure 5. Experimental setup composed of the capacitive encoder (left) and the reference optical encoder (right).



(a)



(b)

Figure 6. The measured nonlinearity (a) with the dielectric rotor, (b) with the conductive rotor.

The measured nonlinearities amount to ±0.06° for the dielectric rotor and to ±0.15° for the conductive rotor. In both cases the nonlinearity error in Fig. 6 mainly consists of three periodic parts: the first one with a period of one segment width (15°), the second one with a period of six segment widths (90°), and the third one with a period over the full range (360°). The effect of the electric-field bending mainly causes a nonlinear component with a period of one segment width (15°), because of the repeatability of one segment width for the accurate fine measurement. This error is about 0.05° (peak to peak) in both cases. The mechanical errors, such as the non-flatness, the obliqueness, and the eccentricity, and the pattern errors of the electrodes can cause a nonlinear component with a period of six segment widths (90°), because the measurement with the outer electrodes repeats itself after six segment widths. For the dielectric rotor this term amounts to 0.06°. The third type of error (with a period of 360°) is more visible on the conductive rotor. One of the reasons for this phenomena could be the larger tilt and eccentricity observed in the conductive rotor when mounted on the dielectric shaft.

CONCLUSIONS

A contactless capacitive angular-position sensor has been designed, built and tested. The use of an electrically floating rotor avoids the long-term reliability problems encountered in angular-position sensors that use a physically grounded rotor. These preliminary results show nonlinearity of ±0.06° for the dielectric rotor and of ±0.15° for the conductive rotor. This difference could be due to the larger tilt and eccentricity observed in the conductive rotor when mounted on the dielectric shaft. The electronic interface has been realized using the low-cost commercial chips.

More research is required to fully understand the sources of nonlinearity errors. Also, more experiments are required under conditions that can easily create static charge. An improved electronic interface specifically suited for the capacitive angular-position sensor could reduce the measurement time.

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