MICROSYSTEM FOR CAPACITIVE FORCE AND TORQUE MEASUREMENT

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Abstract

In the fields of automation, drives and production engineering the measurement of force and torque is of particular importance for the monitoring and control of industrial processes. Today's sensors applied for this purpose are mostly based on strain gauges with a limited range of applications. Reasons therefore are rooted in the short duty cycle, the poor overload safety and the complex mounting. In order to avoid the disadvantages mentioned an innovative micro-system based capacitive force and torque sensor has been developed. By attachment at two distinguished points the sensor is mountable in an easy and robust manner on static and rotating parts.

Introduction

Besides of the precise acquisition of the measurand sensors for industrial applications have also to provide an easy and robust attachment on different components. In the following a capacitive sensor is described which shows an almost universal field of applications for the acquisition of force, load and torque as a result of the measuring principle, the compact design and the low-cost production technology.

Sensor Principle

The measurement of force and torque is primarily based on the the acquisition of the mechanical strain occuring as deflection or elongation of the stressed unit or as a torsion of a shaft. In the range of nominal load these deformations usually are in the range of a few microns. For a precise transformation of this extremely small mechanical measurand in an electrical signal the application of capacitive techniques is advisable using the variation of the distance between the electrodes of a capacitor. The principle of measurement is based on the mechanical acquisition of the distortion between two points in a specified distance and the transformation into a corresponding modification of the gap between the electrodes and the angle, respectively. The design of the capacitor itself can be performed in different ways. Within a former development the capacitor was consisting of two planar combs providing a high output capacitance due to number of parallel electrode pairs. The torsional displacement resulted in a variation of the air gap and thus in a change of the capacitance [1,2]. Due to technological and functional reasons the sensor principle has been simplified by the application of two electrodes which are arranged under a certain angle (Fig. 1).

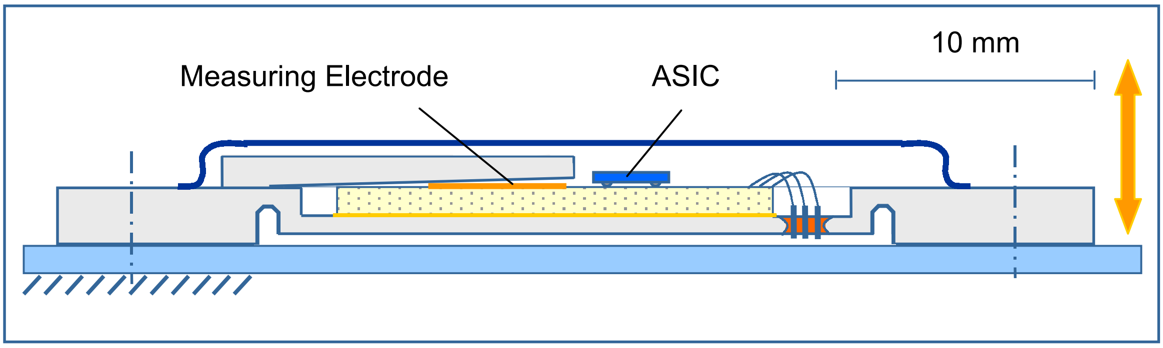

Figure 1: Sensor Principle

Depending on the applied load the angle between the two electrodes is changing and causes an alteration of the sensor's capacitance. The value of the capacitance can be calculated by the integral of the incremental capacitances of the corresponding distances between the electrodes. By theory the calculated capacitance is reciprocally proportional to the applied force and torque, respectively. The correlation between the measured strain and the change of the capacitance is shown in Figure 2 and the equations (1) to (4).

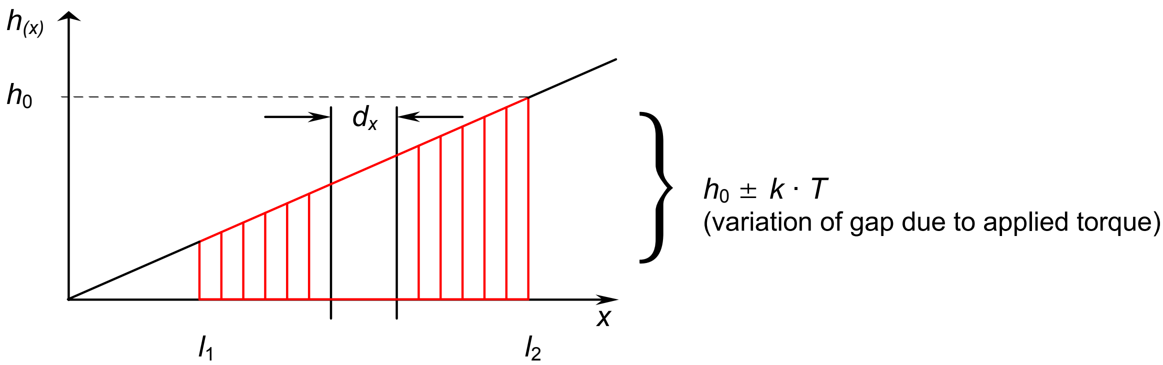

Figure 2: Capacitance of Angular Electrode

$$dC = \frac{\varepsilon_0 \cdot b}{h(x)} \cdot dx \tag{1}$$

$$C = \int_{l_1}^{l_2} \frac{\varepsilon_0 \cdot b \cdot l_2}{(h_0 \pm k \cdot T) \cdot x} \cdot dx \tag{2}$$

$$C = \frac{\varepsilon_0 \cdot b \cdot l_2}{(h_0 \pm k \cdot T)} \cdot \ln \frac{l_2}{l_1} \tag{3}$$

$$T = \frac{\varepsilon_0 \cdot b \cdot l_2}{k} \cdot \ln \frac{l_2}{l_1} \cdot \left(\frac{1}{C_0} - \frac{1}{C_T} \right) \tag{4}$$

T: Torque *k*: Elasticity Constant *b*: Width of Electrode h_0: Initial Gap of Electrodes

In order to achieve a linear function between the impedance $1/\omega C$ and the force and accordingly the torque, the stray field of the angular electrodes has to be reduced as far as possible by the design of the sensor layout. Figure 3 shows the model on which FEM analysis is based and the resulting distribution of the electrical potential of the stray capacity.

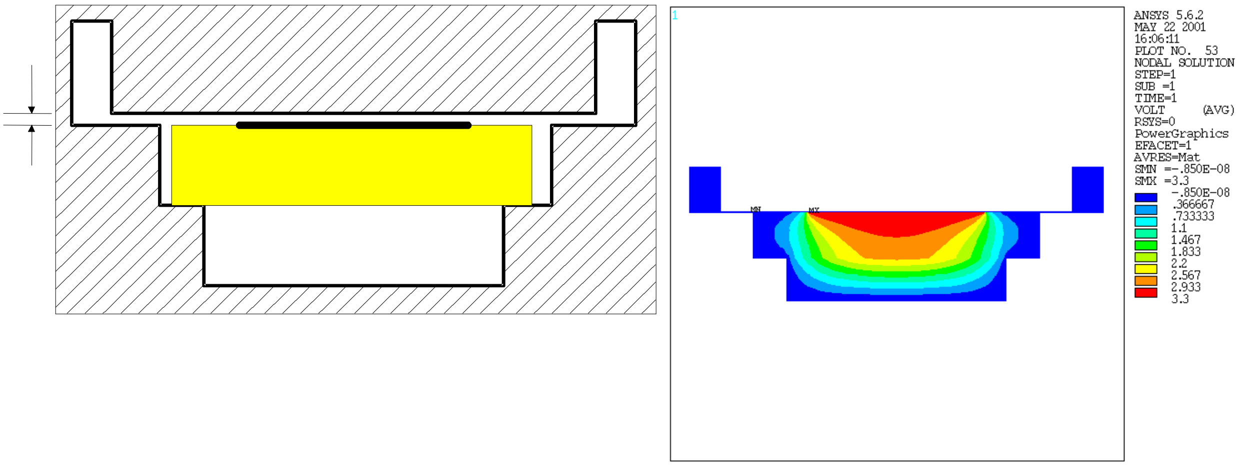

Figure 3: Simulation Model and Distribution of Electrical Potential of the Stray Capacity

System Design

Primarily the sensor consists of the sensor body, the angular electrode and the capacitive microsystem. In order to acquire the mechanical deformation the sensor body is shaped as a bending beam. By means of a defined weakening of the beam two mechanical joints are realized which determine the deformation behavior of the sensor.

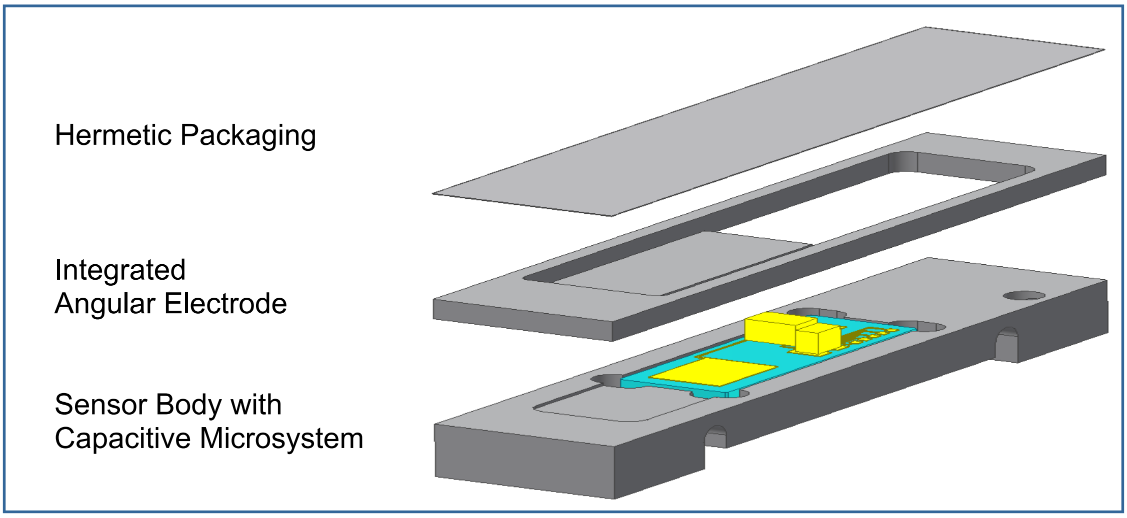

Figure 4: Sensor Design

To achieve a compact sensor design the angular electrode is integrated in the frame of the enclosure. By special design features the attachment of the angular electrode on the quasi static side of the sensor is ensured, thus preventing any deformation due to stress. Between the bending joints of the sensor body the capacitive microsystem is embedded. The modul is aligned and fixed in such a manner that there is a maximum opening of twenty microns at one end of the angular electrode. On the glass substrate measuring electrode, reference capacitance and wiring are implemented via a single thin-film-circuit (Figure 5). In order to define the active area of the capacitor, the measuring electrode is situated on the substrate which additionally is isolating the electrode from the enclosure. Corresponding to the area of the measuring electrode and the initial gap a capacitance of 10 pF is achieved in the unstressed state.

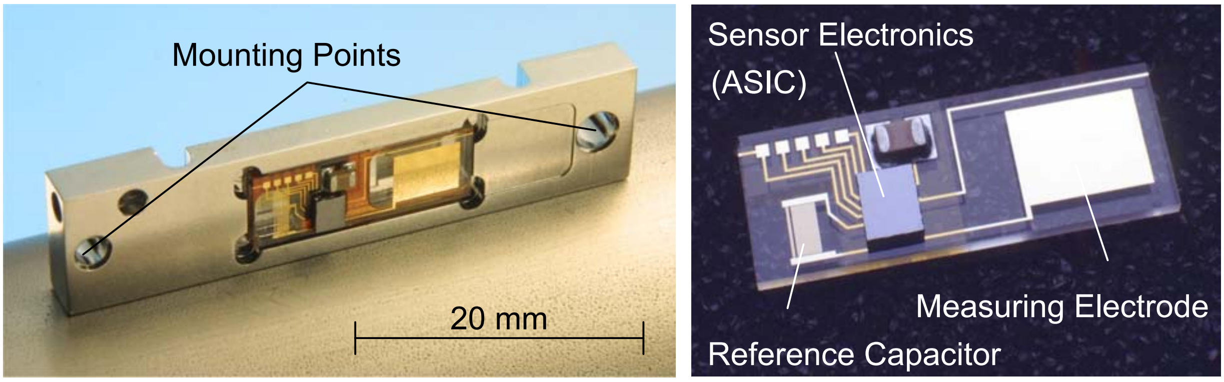

Figure 5: Sensor Body with integrated Microsystem

For the measurement of the capacitance change resulting from the applied force and torque a customized CMOS ASIC is implemented. A reference capacitor which is built up as a planar inter-digital capacitor acts as a comparator for the analog-to-digital conversion based on a switched-capacitor circuit. The measured value is digitised with twelve bits and is output as 1/*C* value via a manchester-coded bit stream. The ASIC is connected on the thin-film-circuit by means of flip-chip-bonding. Thus, the hermetically encapsulated parts of the sensor are representing an integrated micro-system.
For torque sensor applications the thin-film-circuit is completed with a planar inductive micro-coil to provide a wireless power and signal transmission. Compared to strain gauge based sensors the particular advantage of this capacitive sensor principle with respect to wireless transmission is its low power consumption.

Results

The design of the sensor has been developed and optimized on the base of extensive FEM analysis regarding the mechanical and electrical properties. Within numerous tests the required production technologies have been reviewed and refined. Essential production technologies for the manufacturing of the sensor are thin-film-technology, flip-chip-bonding and laser welding [3]. The function of the sensor was tested in the lab after different steps of assembly. Figure (6) shows the analog sensor signal versus the opening of the angular electrode due to the applied load. The measured values for hysteresis and repeatability are better than 0.1%.

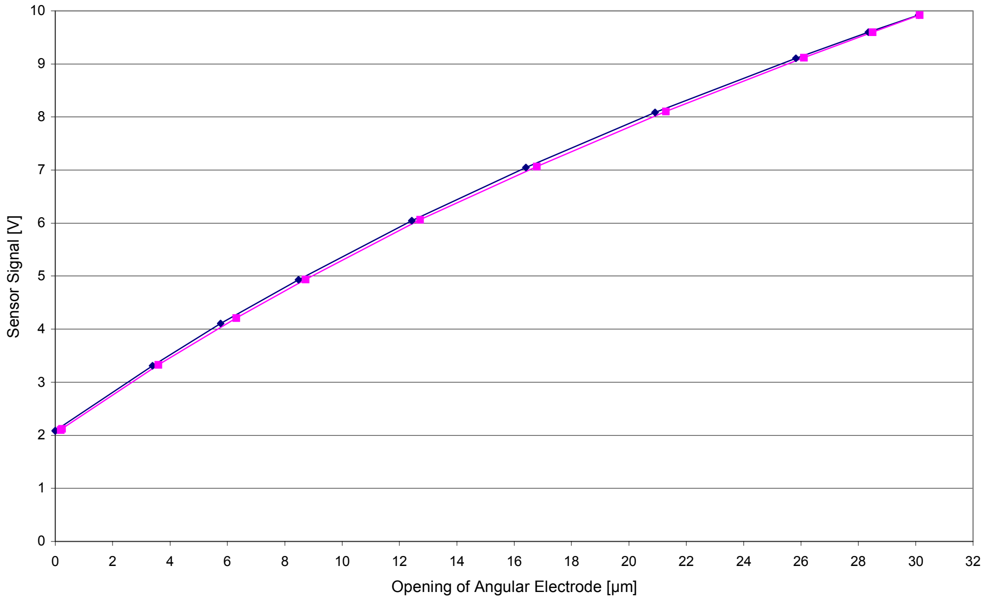

Figure 6: Sensor Signal vs. Opening of the Angular Electrode

Conclusion

The capacitive sensor principle described here significantly expands the field of applications of today's industrial force and torque measurement due to the following system-based features:

- Almost unlimited load cycles and high overload safety.
- Easy mounting on various materials, also in field applications.
- Low power consumption provides easy wireless power and signal transmission.
- Low-cost high-volume production by extensive use of standard technologies and equipment as applied in micro-electronics.

The applications of the sensor are covering the total scope of industrial metrology. Due to the low power input this capacitive sensor is particularly suitable for applications with industrial field buses and for telemetric systems with wireless power and signal transmission.

References

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[2] Siemens, „Capacitive Torque Sensor - Description of Product", Erlangen1996
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