Design Rules for Robust Capacitive Sensors

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***Abstract*—Capacitive technologies play an increasingly important role in the fields of industrial and automotive sensors. The noncontact working principle, on the one hand, is the main advantage of this technology; on the other hand, the sensor is thus sensitive to electromagnetic disturbances. This paper describes methods to successfully develop capacitive sensors, which can reliably be operated in harsh industrial and automotive environments. A carrier frequency system combined with a ratiometric evaluation algorithm and a frequency hopping strategy can guarantee safe operation of capacitive sensors.**

***Index Terms*—Angular rate sensor, automotive and industrial application, carrier frequency system, electromagnetic compatibility (EMC) measures, ratiometric measurement, reliable capacitive sensors.**

I. INTRODUCTION

FOR MANY years, scientists have worked on the design of highly reliable capacitive sensors [1]. In recent years, capacitive sensing has become more and more popular even for industrial and automotive environments [2]. One reason is the availability of small, reliable, robust, and low-cost electronic components leading to a powerful smart sensor technology. Besides the sensing element, the sensor has to encompass the complete analog and digital signal processing, power supply and output drivers to communicate with a master unit. It is mandatory for capacitive sensing to have electronics directly at the front-end as the sensing signals are very small and can easily be disturbed. Usually, the capacitive values to be measured are in the pF range and sometimes far below. Reliable and precise capacitive measurements in the harsh environment thus require a ratiometric evaluation algorithm combined with a narrow-band carrier frequency system.

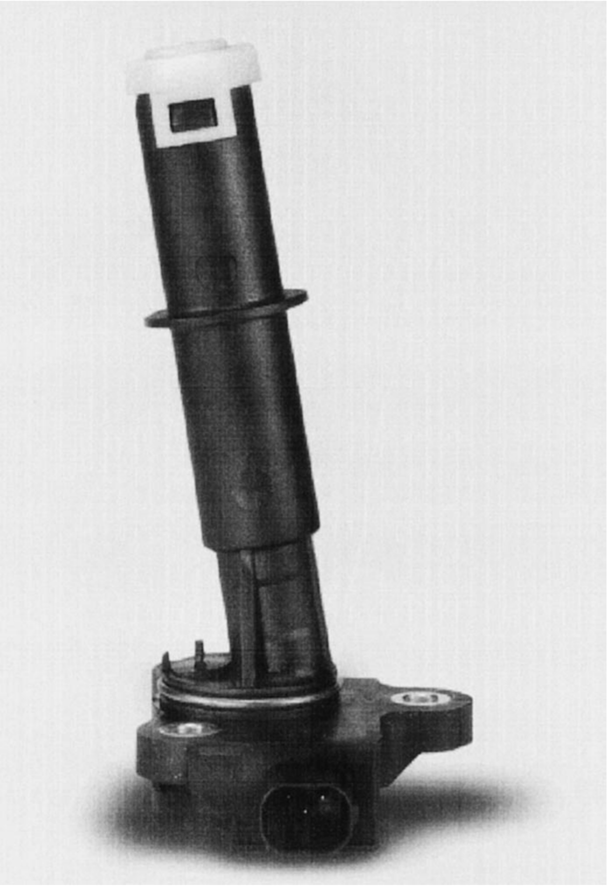

Fig. 1. Capacitive oil quality, leve, and temperature sensor [3].

Figs. 1 and 2 give examples of capacitive sensors already used in mass production. Fig. 1 shows a capacitive oil quality, level and temperature sensor supplied by Temic [3]. Oil quality is related to the dielectric constant ε_r of the oil, measured with a capacitor. A second capacitor measures the oil level. Temperature and aging effects are compensated by taking the variations of the dielectric constant ε_r into account. The oil temperature is measured by a Pt-1000 element. The measured values are transmitted as pulse-width-modulated signals or other interface standards like SPI, CAN, BSD, LIN, etc., to a control unit. Another state of the art capacitive sensor, a low-g acceleration sensor [4], is depicted in Fig. 2. Such accelerometers are widely used—depending on the measurement range—in electronic stability programs (ESP) or in passenger restraint systems to tighten the safety belt and/or to deploy an air bag in the case of an accident.

The acceleration sensor combines a micromachined, capacitive sensing element with an integrated signal conditioning circuit and power conditioning ASIC [see Fig. 2(a) and (c)]. Sensitivity, offset and filter characteristics are factory customized via a programming interface. To cope with interfering influences, like stray capacitance and offsets, the acceleration *a* is derived by means of a ratiometric measurement principle:

$$a = \frac{C1 - C2}{C1 + C2}. \tag{1}$$

II. PROBLEMS ASSOCIATED WITH CAPACITIVE SENSING

Small signal levels with poor signal to noise ratio usually come up as one of the first problems during the design process of a new capacitive sensor. A solution to this problem paves the way to some more sensor tests in a real life industrial environment. During these tests electrically conductive contamination,

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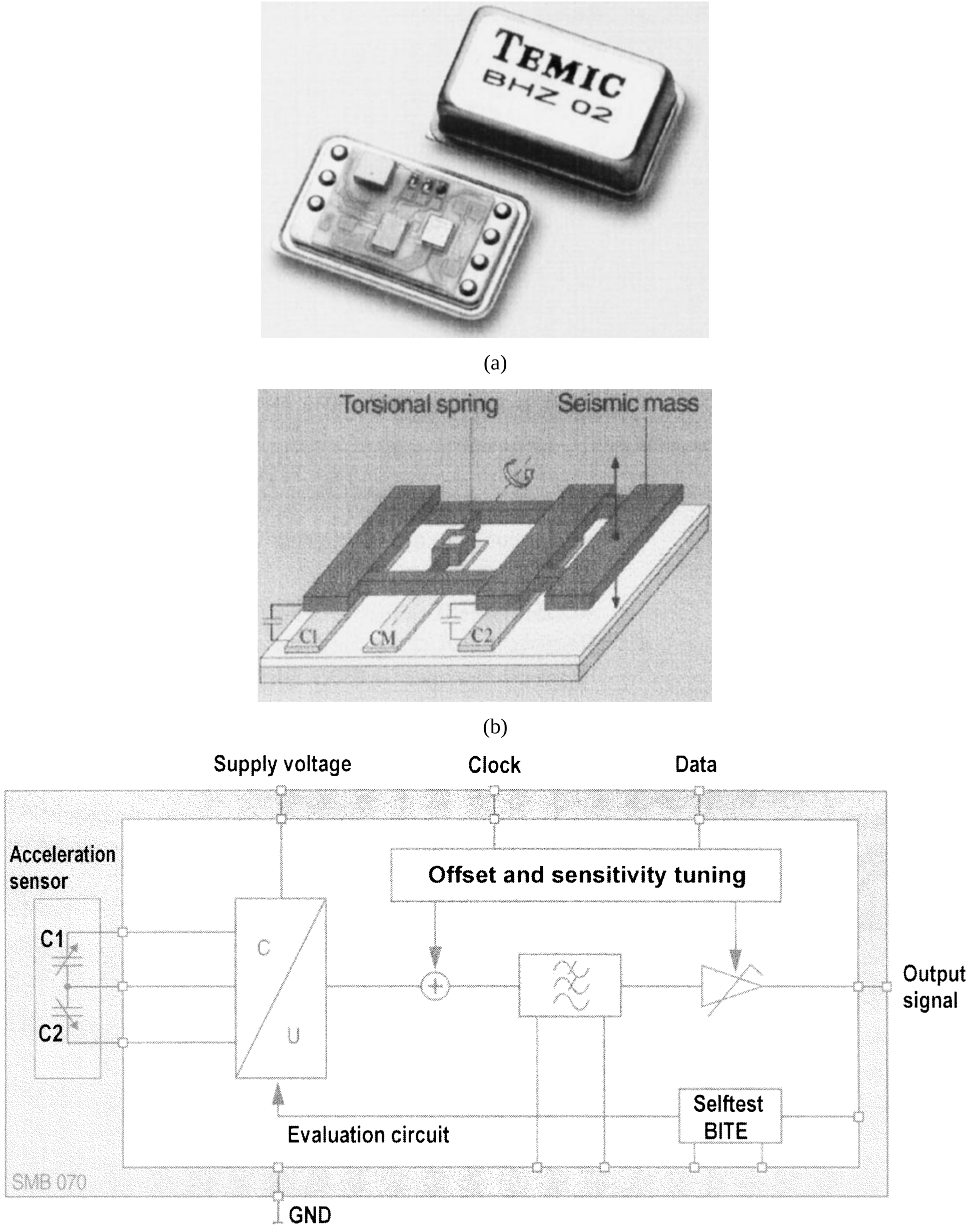

(a)

(b)

(c)

Fig. 2. Micromachined, capacitive, low-g acceleration sensor [4]. (a) Package, (b) principle of operation, and (c) block scheme of an evaluation ASIC [5].

moisture and dew will come in contact with the sensor. An hermetically sealed housing solves this "contamination problem" as with the sensors described above, but not with sensors where the environment needs direct access to the sensing elements, like with angular sensors [6]–[8] and torque sensors [9]. Consequently, the transducer can not be hermetically sealed and some other provisions have to be made to cope with the "contamination problem." If the sensor housing can not serve as an entire electromagnetic shield, electromagnetic compatibility (EMC) tests at a field strength of up to 200 V/m in a frequency range from 100 kHz up to 2 GHz are most severe during the qualification procedure of an industrial or automotive sensor.

The aim of this paper is to present three generally valid measurement methods to cope with the "small signal," with the "contamination," and with the "EMC" problems. By using these methods reliable capacitive sensors for an industrial environment will result.

III. THREE GENERALLY VALID MEASUREMENT METHODS

The first step to obtain a robust capacitive sensor is the use of a ratiometric measurement principle. This method copes with small measurement signals and improves signal to noise ratio as each new sensor output value calculates from differences and ratios of a few measurement values [see (1)]. This method is well established in science and industry [2], [4]–[8] and thus needs no further explanation.

To obtain insensitivity to the "contamination problem," as explained above, a carrier frequency system should be used for the analog part of the sensor electronics. The receiving electronics

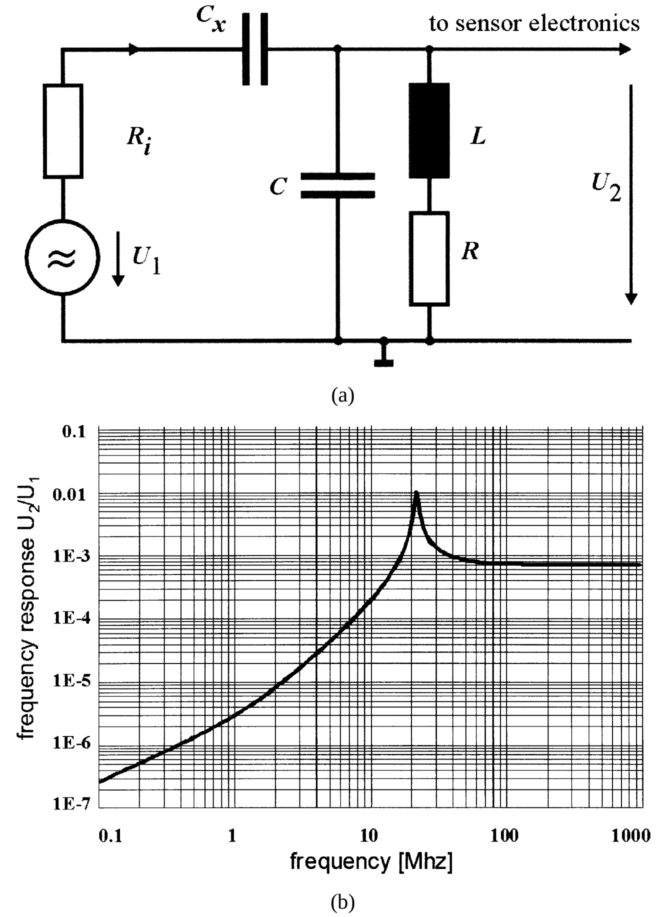

Fig. 3. (a) Equivalent circuit of the front-end of a carrier frequency system. (b) Frequency response of the transfer characteristics U_2/U_1 of the front-end resonant circuit [10].

includes a tuned resonant circuit located at the front end (see Fig. 3). It provides a low impedance of the receiver resulting in the demanded insensitivity to leakage currents [10].

To cope with the above mentioned "EMC" problem a new approach is presented here: The sensor electronics (see Fig. 4) has the ability to use more than one carrier frequency. The most simple design utilizes two frequencies f_1 and f_2 matching the passband of the "high Q bandpass" filter and the bandwidth of the front-end resonant circuit. The carrier frequency difference $\Delta f = |f_1 - f_2|$ has to be smaller than the bandwidth B of the receiver electronics to guarantee proper operation of the sensor. Normally, the electronics uses the carrier frequency f_1 for measurement. As long as the evaluation algorithm does not detect disturbances in the received signals, the carrier frequency f_1 remains unchanged. If an interfering signal produces an EMC problem, the electronics switches to the carrier frequency f_2. Usually, switching to carrier frequency f_2 will solve the EMC problem, as due to power concerns, an interfering signal will either have a rather narrow bandwidth or a low power level. Consequently, the mixing product of carrier and disturbance will be filtered by the electronics and the measurement algorithm. However, a compromise must be found between a rather large carrier frequency difference Δf and a rather small bandwidth B of the receiver electronics. A large carrier frequency difference Δf will cope with interfering signals with a large bandwidth for good EMC performance. A small bandwidth B of the receiver electronics will have a high signal to noise ratio resulting in an excellent measurement accuracy and resolution.

The detection of interfering signals can be done by calculating the standard deviation of consecutively measured capacitance values or by calculating the correlation of the transmitted to the received signals. Without an interference, the standard deviation σ of consecutively measured capacitance values stays within certain limits. If an EMC problem occurs the standard deviation σ exceeds the limit and the microcontroller switches the carrier frequency f_1 to f_2 and vice versa.

A sensor using the posted three principles of operation

- a ratiometric measurement principle;
- a carrier frequency system;
- an algorithm for interference detection combined with a variable carrier frequency system

was built and evaluated. To make the presentation as simple as possible but still show the benefits of the approach, a prototype is used with only two possible carrier frequencies. It uses a standard microcontroller and a discrete carrier frequency electronics (see Fig. 4) working on the carrier frequencies $f_1 = 14.9$ MHz and $f_2 = 15.1$ MHz, respectively. An advanced design derived from this prototype was recently introduced to the market as an angular rate sensor in an electrically supported power steering system (see Fig. 5).

The following section presents measurements of the prototype sensor to show and prove the quoted benefits of a two channel carrier frequency system in terms of EMC performance.

IV. MEASUREMENT RESULTS

The measurement setup used for the susceptibility tests of the prototype sensor comprises a test rig with a rotatable shaft to fix the rotor and a support for the sensor housing. An interference voltage is coupled to the electrically conductive shaft and thus to the metallic rotor. The frequency f_D and the level of the disturbing voltage is varied and the impact on the measurement values taken at the sensor output are plotted and discussed below. In one case frequency hopping is prohibited, and in the other case allowed. The algorithm used to detect EMC problems compares the standard deviation σ of 50 consecutively taken measurement values with the average value μ of the same data. If a specific ratio $r = \sigma/\mu$ is reached or overtaken the carrier frequency is altered.

During the *first test* the frequency, f_D of the disturbing voltage is varied between 14.7 MHz and 15.3 MHz. The level of the interference voltage is set to a value used for EMC qualifications in the automotive field (4 V^{PP} over 50 Ohm at the shaft).

In case one [see Fig. 6(a)] a "frequency hopping" sensor is used and the standard deviation σ is plotted versus the disturbing frequency f_D. During the complete test the standard deviation σ remains below 0.8%.

In case two [see Fig. 6(b)], "frequency hopping" is prohibited at the same prototype sensor resulting in an unacceptable deviation of the measurement value at a disturbing frequency f_D of around 15 MHz (pay attention to the different axis scale compared to case a).

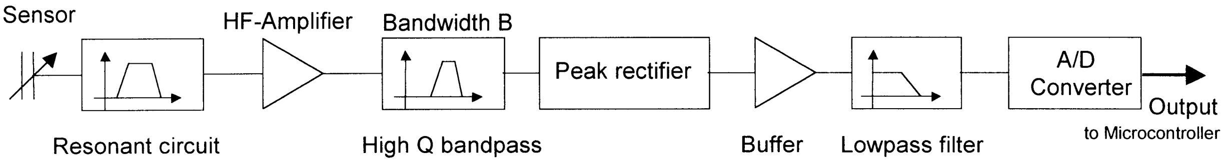

Fig. 4. Block diagram of a well-approved signal processing unit of a capacitive angular sensor using a discrete carrier frequency circuitry with an external microcontroller.

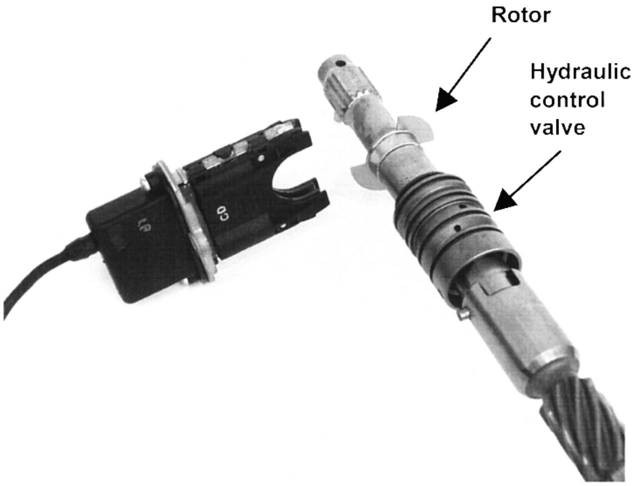

Fig. 5. Location of the angular rate sensor versus the shaft of an electrically supported, hydraulic power steering supplied by TRW.

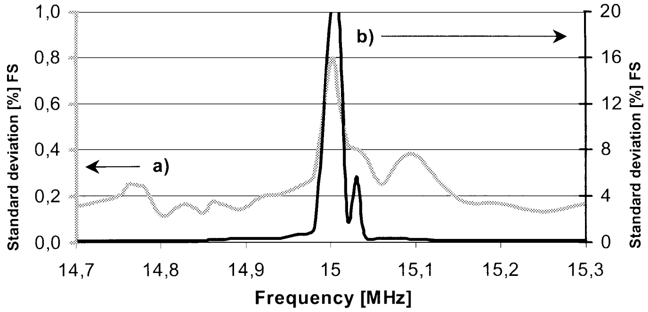

Fig. 6. Standard deviation σ with respect to the disturbing frequency f_{D} for a prototype sensor using "frequency hopping" (light gray line, axis a) and a sensor without "frequency hopping" (black line, axis b).

At the *second test* the disturbing frequency f_{D} is tuned to the worst case value in terms of impact to the standard deviation σ of the sensor's output value. This means ±1 kHz beside the carrier frequency. The value of the interference voltage coupled to the rotor is increased and the standard deviation σ is plotted in Fig. 7.

Case a) shows an increase of the output error due to the disturbing voltage as "frequency hopping" is prohibited.

In case b), the sensor primarily uses a carrier frequency of $f_1 = 15.1$ MHz. The software detects an EMC problem at a disturbing voltage level of around 40 mV and switches to the frequency $f_2 = 14.9$ MHz resulting in a reduction of the standard deviation σ to around 0.2% (d).

In case c), the sensor primarily uses a carrier frequency of $f_2 = 14.9$ MHz. The software detects an EMC problem at a disturbing voltage level of around 30 mV and switches to the frequency $f_1 = 15.1$ MHz which reduces the standard deviation σ to around 0.1% (e).

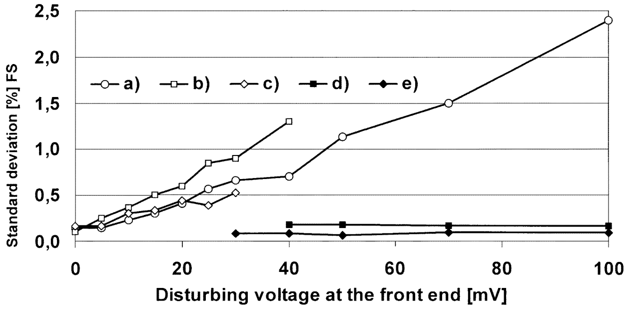

Fig. 7. Standard deviation σ with respect to the disturbing voltage level for a prototype sensor using "frequency hopping" (b to e) and a sensor without "frequency hopping" (a).

For the presented prototype sensor, the offset of the disturbing frequency f_{D} with respect to the carrier is in compliance with a measurement cycle. Therefore, the sensor is most sensitive to this interference signal. At real-life conditions the disturbing frequency f_{D} will always be different to the measurement frequency as the software usually measures consecutively at a few carrier frequencies before a decision is made which frequency currently has the smallest standard deviation σ and thus should be used for the measurement of the angular position or rate. Consequently, interfering signals will hardly reduce the measurement accuracy and resolution of the sensor.

V. CONCLUSION

The capacitive measurement principle was applied to a robust sensor system performing very well in industrial and automotive environments. The small sensor signal is evaluated with good signal-to-noise ratio by a narrow-band carrier frequency system, reducing any EMC problems to this small bandwidth. The influences of slowly varying environmental conditions due to electrically conductive contamination, dew or moisture are eliminated by the ratiometric measurement principle. The introduction of a frequency hopping strategy eliminates the remaining problem of EMC disturbances in the narrow operating-frequency band of the system.

To further improve the system robustness to interfering signals, a more complicated approach is possible. The center frequency f_0 of all filters within the signal-processing unit can be altered jointly. The bandwidth B of all filters is kept rather small, yielding an excellent signal-to-noise ratio. Furthermore, the carrier frequency f_0 can be varied in a wide range. If an EMC problem is detected, the algorithm changes the carrier frequency f_0 plus the center frequency of all relevant filters, until the system operates flawlessly. This approach combines a narrow-band system with the ability to “move away” from disturbing signals over a large frequency range. The outstanding performance of such a design will be presented later.

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