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Contactless Interrogation System for Capacitive Sensors with Time-Gated Technique †

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Abstract: This paper presents a measurement technique and system for the contactless interrogation of capacitive sensors via electromagnetic coupling. The interrogation unit employs a primary coil to periodically excite the capacitive sensor connected to a secondary coil forming an LC resonant circuit. When the excitation to the primary coil is switched off the damped response of the LC circuit is detected. As a fundamental advantage compared to techniques based on reflected impedance, this approach ensures that the readout frequency is to first order independent of the interrogation distance between the two coils. The system has been tested with reference capacitors and with a capacitive liquid level sensor. The experimental results are in a good agreement with theoretical expectations and show a sensitivity of about −23 kHz/pF at 5.4 MHz and the possibility to operate with interrogation distances up to few centimeters.

Keywords: distance-independent contactless interrogation; capacitive sensors; LC resonant circuit; time-gated technique

1. Introduction

Capacitive sensing is increasingly investigated due to its versatility. Besides sensing applications for pressure, position, proximity, liquid level measurement and material analysis, capacitive techniques are promising for contactless operation. Passive wireless humidity sensors [1] and non-contact passive electromagnetic interfaces especially dedicated to capacitive sensors [2–4] have been demonstrated, but these adopted measurement techniques generally suffer from a dependency on the interrogation distance, which makes them difficult to apply in real operating conditions. Differently, this paper presents a contactless interrogation system for capacitive sensors that exploits a specific time-gated technique firstly developed for piezoelectric resonant sensors [5,6]. As a fundamental advantage compared to techniques based on reflected impedance, this novel technique ensures that the readout frequency is to first order independent of the interrogation distance between the two coils. The effectiveness of the proposed interrogation system has been tested by emulating a capacitive sensor with different capacitance values connected to the resonant circuit. Thereafter, a test application using capacitive liquid level sensor has been proposed.

2. Time-Gated Contactless Interrogation System for Capacitive Sensors

Figure 1 shows the block diagram of the interrogation system which implements the time-gated technique. The technique works in two interleaved phases, namely excitation and detection phases. The rectangular signal $v_g(t)$ is used to switch between the excitation and detection phases. During the excitation phase, the primary coil L_1 is connected to the sinusoidal signal $v_e(t)$ at frequency f_e to excite the sensor unit which is composed of a capacitive sensor C_S connected to the secondary coil L_2

forming a LC resonant circuit. With the additional tuning capacitance C_0 the resonant frequency f_R is set to:

$$f_R = \frac{1}{2\pi\sqrt{L_2 C_T}} \tag{1}$$

where $C_T = C_S + C_0$. With the values of C_S and C_0 adopted in this study f_R is in the order of 5 MHz. During the detection phase, the excitation signal is turned off and L_1 is connected to the high-impedance input of the readout amplifier with gain $G = 8$ that virtually sinks no current. Therefore, the output signal $v_O(t)$ starting at the beginning of the detection phase results in a damped sinusoid as follows:

$$v_O(t) = M\, A_m\, G\, e^{-t/\tau} \cos(2\pi f_D t + \theta_m) - L_1 i_{L1} \delta(t) \tag{2}$$

where the damped resonant frequency f_D can be expressed as a function of f_R and the quality factor Q of the LC circuit as follows:

$$f_D = f_R \sqrt{1 - \frac{1}{4Q^2}} \tag{3}$$

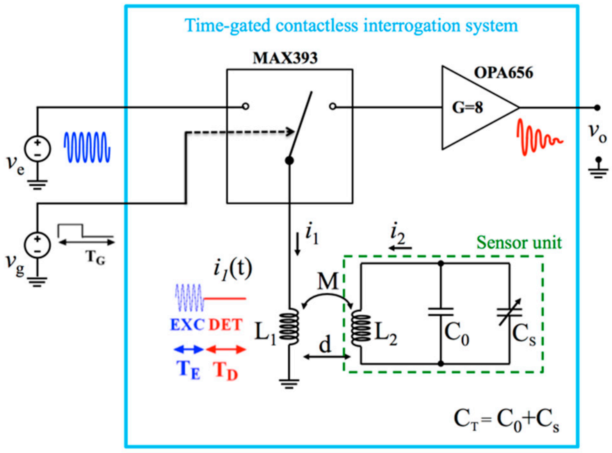

Figure 1. Block diagram of the time-gated contactless interrogation system. The sensor unit is represented by the secondary coil L_2 and the capacitance $C_T = C_0 + C_S$, where C_S represents the sensor capacitance.

In Equation (2) the amplitude and phase coefficients A_m and θ_m are functions of both the initial conditions taken at the end of the excitation period and the electrical parameters of the system composed of L_1, L_2 and the capacitive sensor. The exponential decay time τ is related to the quality factor by $Q = \pi f_R \tau$; while Q is determined mainly by the parasitic series resistance of L_2 [5,6]. The additional term in Equation (2) is a voltage pulse which accounts for the initial current in L_1. From Equation (2) it can be observed that for the voltage sensed across the primary coil the mutual inductance M, which in turn depends on the distance d, only acts as an amplitude scaling factor, affecting neither the frequency nor the decay time of the readout signal. Because the measurement technique exploits the free response of the resonator which is independent from the type of excitation, the exact knowledge of the LC resonant frequency f_R is not in principle required. However, if f_e is close to f_R an improvement in the signal-to-noise ratio during the detection phase, and hence in the maximum interrogation distance d, can be attained. In addition it can be seen from Equation (3) that for sufficiently high values of Q, $f_D \approx f_R$. Under these circumstances, for incremental variations dC_S, Equation (1) can be linearized, obtaining the sensitivity of f_D to the sensor capacitance C_S as:

$$\frac{df_D}{dC_S} = -\frac{1}{2}\frac{f_R}{C_T} \tag{4}$$

3. Experimental Results

Figure 2 shows the measured gate signal $v_g(t)$ and the output voltage $v_O(t)$ obtained with a capacitance C_T = 102 pF and interrogation distance d = 20 mm. The frequency f_D is measured during the detection phase by a high-resolution counter triggered by the gate signal using a measurement time t_M = 3.2 μs starting after a delay time t_D to avoid the initial electrical ringing given by L_1 and the input capacitance of the amplifier. A quality factor Q = 60 has been estimated from the exponential decaying envelope giving a relative deviation $(f_R–f_D)/f_D$ of less than 35 ppm.

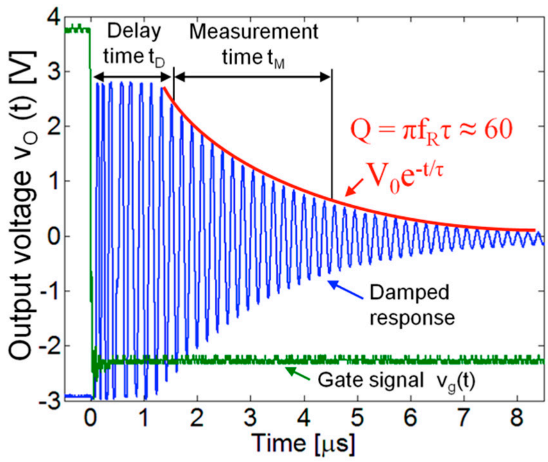

Figure 2. Measured output voltage $v_O(t)$ versus time during the detection phase obtained with interrogation distance d = 20 mm. The quality factor Q can be estimated from the exponential decaying envelope.

The system was then tested by varying the interrogation distance d and with different time delays t_D. Figure 3 shows only slight variations of f_D in the distance range between 20 and 30 mm, confirming the expected independence from d. Figure 4 reports the measured and theoretical values of f_D versus the total capacitance C_T, ranging from 102 to 110 pF. Reference measurements of C_T and L_1 = 8.48 μH have been done with an impedance analyzer (HP4194A). Across such range, a linear trend with sensitivity of about −23 kHz/pF has been obtained in good agreement with the theoretical value of about −25 kHz/pF.

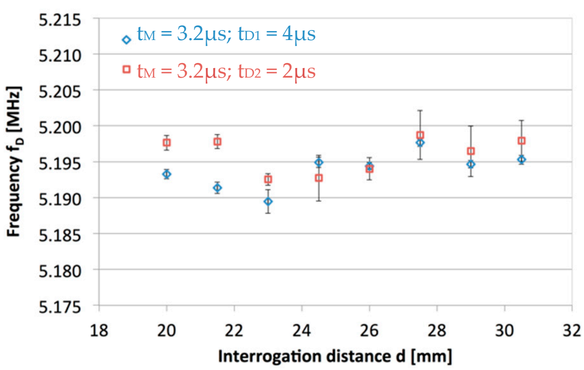

Figure 3. Measured damped frequency f_D as a function of the interrogation distance d with t_M = 3.2 μs and different delay times t_{D1} = 4 μs and t_{D2} = 2 μs.

In addition, contactless liquid level measurement is performed as the test application of a capacitive sensor with contactless interrogation. A capacitive level sensor C_S has been built with a graduated cylinder with two copper faced electrodes placed outside. The secondary coil L_2 and a tuning capacitor C_0 = 94 pF are connected to C_S thus forming the sensor unit. Figure 5 reports a picture of the contactless interrogation system and the sensor unit with the graduate cylinder. The secondary coil L_2 has been placed at a fixed distance of approximately 30 mm from the primary coil

L_1 for liquid level measurement. Pouring liquid (water) gradually on the cylinder increases the sensor capacitance and a corresponding decrease occurs in the frequency f_D. The water level inside the cylinder was increased in steps of 3 mm from 40 mm up to about 80 mm. Figure 6 shows the measured frequency f_D and total capacitance C_T as a function of water level h_L. In the explored liquid level range, linearity has been obtained with sensitivities $\Delta f_D/\Delta h_L$ and $\Delta C_T/\Delta h_L$ of about −4.34 kHz/mm and 0.63 pF/mm, respectively.

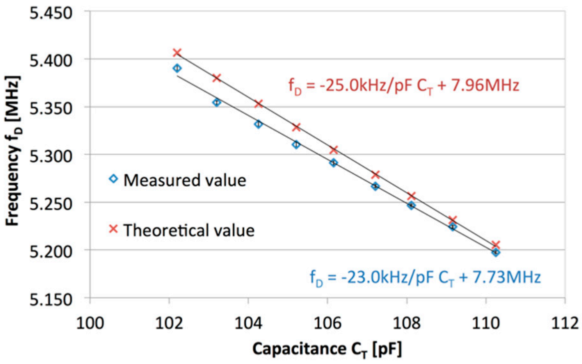

Figure 4. Measured and theoretical values of the damped frequency f_D as a function of the total capacitance C_T.

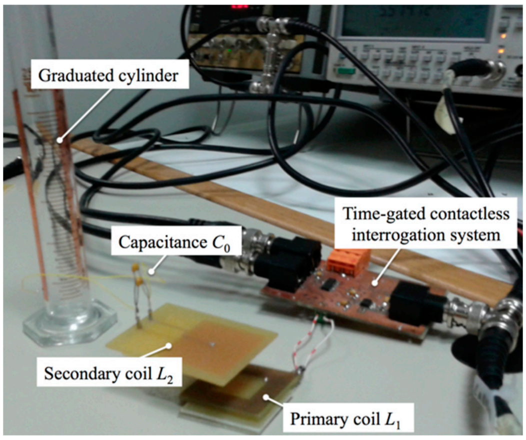

Figure 5. Experimental setup with the time-gated contactless interrogation system, and the graduated cylinder used for liquid-level measurements.

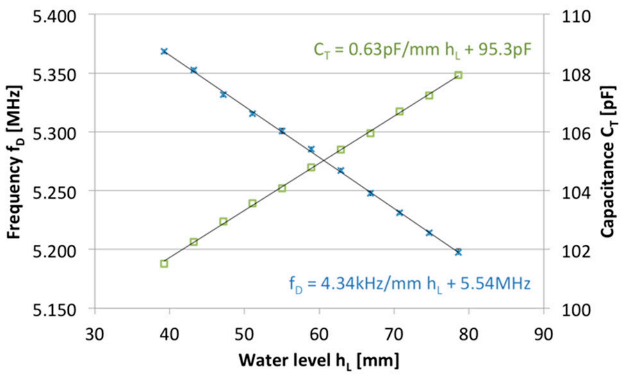

Figure 6. Measured damped frequency f_D and measured total capacitance C_T as a function of the water level h_L.

4. Conclusions

A contactless interrogation technique and system for capacitive sensors have been presented. The sensor unit is composed of the capacitive sensor connected to a tuning capacitor and a coil forming a LC resonant circuit. The interrogation system measures the resonant frequency of the LC network by exploiting a distance-independent time-gated technique. Experimental results show that measurements are independent of the interrogation distance between the primary coil and the coil on the sensor unit in the range between 20 and 30 mm. By varying the sensor capacitance, a sensitivity of about −23 kHz/pF has been measured at a resonant frequency around 5.4 MHz. A test application using a capacitive liquid level sensor has been presented, obtaining a linear trend with sensitivity $\Delta f_D/\Delta h_L$ of about −4.34 kHz/mm. The experimental results foresee the possibility to apply the proposed technique to different types of capacitive sensors fostering, among others, applications based on low-cost printed labels as sensor units.

Conflicts of Interest: The authors declare no conflict of interest.

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