CHARACTERISATION OF A LIQUID-LEVEL MEASUREMENT SYSTEM BASED ON A GROUNDED CAPACITIVE SENSOR

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This paper describes the design and characterization of a liquid-level measurement system based on a grounded capacitive sensor. The sensor electrodes are built with affordable materials: a rod of stainless steel and a PTFE-insulated wire. The interface circuit relies on a common relaxation oscillator (which performs a capacitance-to-period conversion) and a microcontroller (which carries out a period-to-digital conversion). Furthermore, a cable with active shielding interconnects the sensor with the interface circuit. Over a level range of 70 cm, the system has a non-linearity error smaller than 0.35 mm and a resolution better than 0.10 mm for a measuring time of 20 ms.

Keywords: Liquid-level sensor, capacitive sensor, active shielding, relaxation oscillator, microcontroller.

1. INTRODUCTION

Liquid level in rivers, reservoirs or containers can be monitored by measuring the electrical capacitance between two electrodes immersed in the liquid [1]. In some applications, for instance, when measuring the level of a conductive liquid in a metallic container connected to ground, it is advisable to use a grounded capacitive sensor, i.e. a sensor in which one of the two electrodes is connected to ground [2]. This paper deals with a liquid-level measurement system based on a grounded capacitive sensor that is remote from the electronics. In these conditions, the active shielding technique [3] must be applied in order to reduce the effects of both external noise/interference and parasitic capacitances of the interconnecting cable.

2. SENSOR

When capacitive sensors are applied to measure the level of conductive liquids, at least one of the two electrodes must be insulated in order to avoid a short circuit. Below the liquid-air interface, the liquid behaves as a conductor and, therefore, the effective distance between electrodes is just the thickness of the electrode insulation, and the dielectric of the capacitance is just the electrode insulation. Above the liquid-air interface, the capacitance between electrodes is much smaller since the distance between them is much greater, and the dielectric of the capacitance is the electrode insulation together with the air between electrodes. As the liquid level increases, so do the area of the electrodes below the liquid-air interface and, hence, the capacitance.

Figure 1 shows a picture of the designed sensor prototype. The length of the sensor is about one meter. The non-insulated electrode is made of stainless steel. This electrode and the metallic container will be connected to the system ground. The insulated electrode is built with a PTFE-insulated wire whose nominal internal and external diameters are 1 mm and 1.5 mm, respectively. Since the sensor capacitance depends a lot on the thickness and the dielectric constant of the insulation, it is essential to use a material such as PTFE (commonly known as "teflon"), which is temperature-stable, non-porous and strain-resistant. The wire is set in a U-shape so that both ends are out of the water. This configuration avoids the problem of sealing one of the wire ends and, in addition, doubles the sensor capacitance [2]. At the top of the sensor, there is a rigid-plastic piece for setting the tension of the wire.

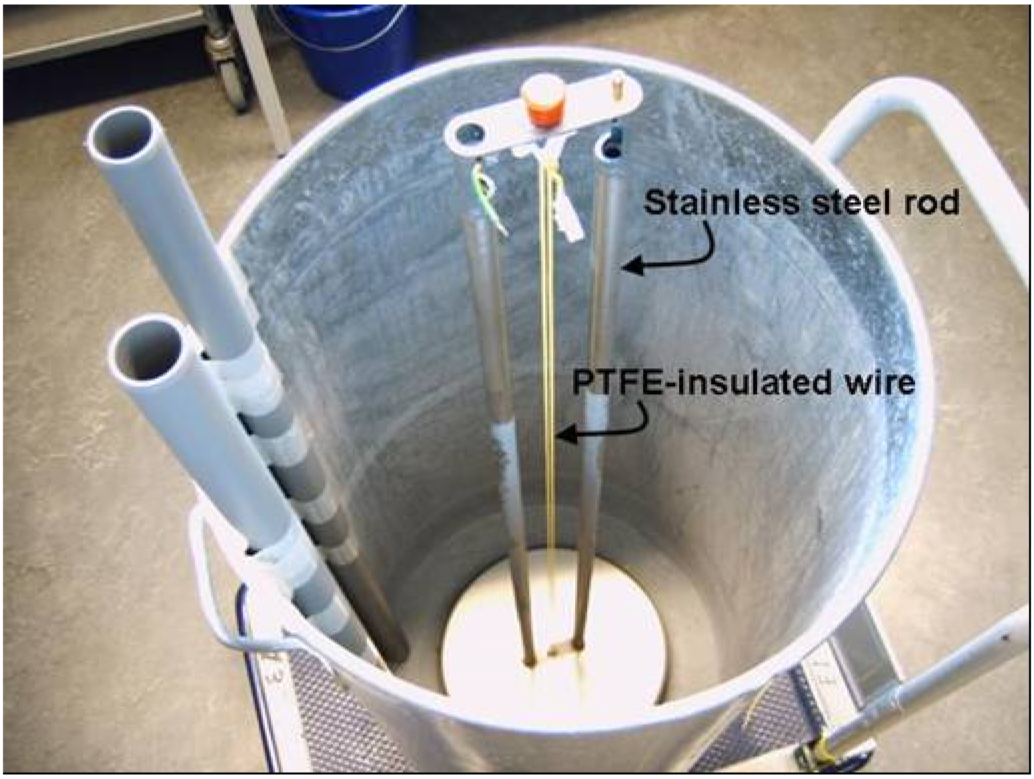

Figure 1. Prototype of the liquid-level sensor inside a metallic container.

Using an impedance analyzer (Agilent 4294A), the sensor was characterized for different levels of tap water (with a conductivity of 0.50 mS/cm). As expected, the capacitance of the sensor C_x increased linearly with the level. The sensitivity was 0.47 pF/mm.

3. INTERFACE CIRCUIT

Figure 2 shows the interface circuit designed for the grounded capacitive liquid-level sensor. The main blocks are: (a) an analog multiplexer, which selects the capacitance to be measured, (b) a relaxation oscillator, which performs a capacitance-to-period conversion, (c) a microcontroller, which carries out a period-to-digital conversion, and (d) an interconnecting cable with active shielding.

The interface circuit is auto-calibrated in terms of additive and/or multiplicative errors by applying the three-signal technique [4], which involves three measurements: (a) a sensor measurement, (b) a reference measurement, and (c) an offset measurement. For this reason, the interface circuit shows three possible inputs: (a) the sensor capacitance (C_x), (b) the reference capacitance (C_{ref}), and (c) the offset capacitance (C_{off}). As a reference we used an NP0 ceramic capacitor of 330 pF, which is approximately the maximal value of the sensor capacitance. The capacitance C_{off} represents the overall stray capacitance (of the interface circuit, not of the sensor) to ground, which affects the three measurements.

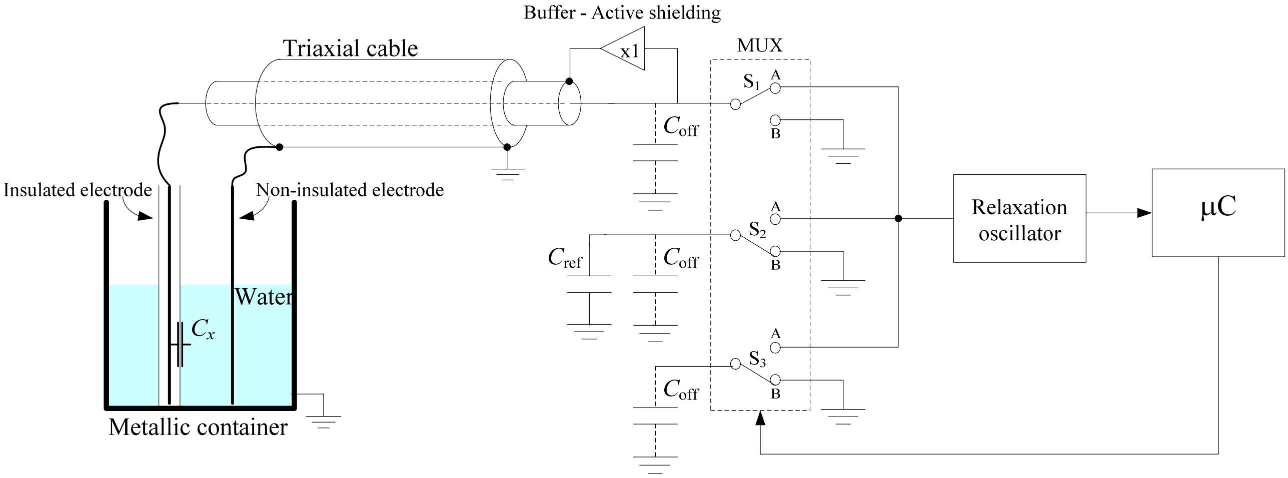

Figure 2. Interface circuit designed for the grounded capacitive liquid-level sensor.

Table 1 summarizes the value of the equivalent capacitance connected to the oscillator, the period of the oscillator output signal and the number resulting from the period-to-digital conversion for each of the three measurements. In this table, α is a proportionality constant that depends on the components of the oscillator, T_s is the timing resolution of the timer embedded in the microcontroller, and k is the number of consecutive periods measured.

Table 1. Capacitance, period and digital number for each of the three measurements.

Measurement	**Input capacitance**	**Period of the oscillator output signal**	**Digital number**
Sensor	$C_x + C_{off}$	$T_x = \alpha(C_x + C_{off})$	$N_x = k\, T_x/T_s$
Reference	$C_{ref} + C_{off}$	$T_{ref} = \alpha(C_{ref} + C_{off})$	$N_{ref} = k\, T_{ref}/T_s$
Offset	C_{off}	$T_{off} = \alpha C_{off}$	$N_{off} = k\, T_{off}/T_s$

Once we have the digital numbers N_x, N_{ref}, and N_{off}, the following ratio is calculated [4]

$$M = \frac{N_x - N_{off}}{N_{ref} - N_{off}}, \quad (1)$$

thus offset and gain errors (for instance, due to changes of temperature or supply voltage) are auto-compensated.

The sensing element is connected to the interface circuit by using a triaxial cable. A buffer amplifier drives the first shield at the same potential as that of the inner conductor (i.e. active shielding), so that the effects of parasitic capacitances of the cable are reduced. The second shield is connected to ground and behaves as a current return path. The parasitic components of both the cable and the sensor determine the maximal allowable bandwidth of the buffer amplifier in order to have a stable circuit [5].

4. EXPERIMENTAL RESULTS AND DISCUSSION

The performance of the designed measurement system was experimentally tested using the setup shown in Fig. 1. The sensor was put inside a metallic container (84 cm of height and 42 cm of diameter) connected to the system ground. The water was added/withdrawn to/from the bottom of the container by two pipes. The actual level value was calculated from the volume of water added/withdrawn (which was carefully controlled by means of chemical test tubes) and the area of the container. The sensor was connected to the interface circuit using a 1 m interconnecting cable.

Figure 3 shows the ratio *M* measured for different levels of water and the straight line fitted by the least-square method. To avoid hysteresis effects, all of the levels shown in Fig. 3 were reached in increasing mode. The sensitivity of *M* was about 0.015 cm^{-1}. The maximal non-linearity error was about 0.05 % FSS (Full Scale Span), which corresponds to 0.35 mm. These linearity results are very good considering the simplicity of the measurement system.

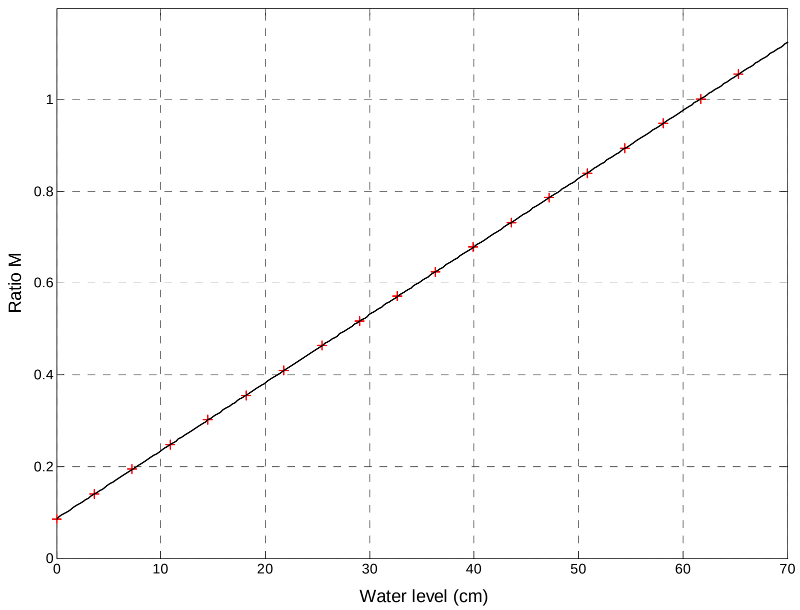

Figure 3. Experimental results of the linearity test.

The standard deviation of the ratio *M* for a fixed and stable water level was less than 25×10^{-6}, which corresponds to 0.02 mm. The histograms of two populations of *M* corresponding to a level *h* and a level *h*+0.10 mm were perfectly distinguishable, which means that the resolution was better than 0.10 mm. The overall measuring time (i.e. for the three measurements involved in the three-signal technique) to achieve this resolution was less than 20 ms.

Figure 4 shows the experimental results of a hysteresis test. The value of the ratio *M* for a certain level depended on what "direction" this level was reached; to be precise, *M* was higher in decreasing mode than in increasing mode. The maximal hysteresis error was 0.13 % FSS, which corresponds to 0.90 mm. The reason of this hysteresis is the "flowback phenomenon" [6]: when the liquid level decreases, it leaves a film on the sensor electrode which causes the system to indicate a value higher than that expected. This flowback film depends on the viscosity, density and surface tension of the liquid. When the liquid level was the same and was reached in the same way (i.e. either increasing or decreasing), the resulting value of *M* was the same. As an example, we have the starting and stopping points of the hysteresis test shown in Fig. 4.

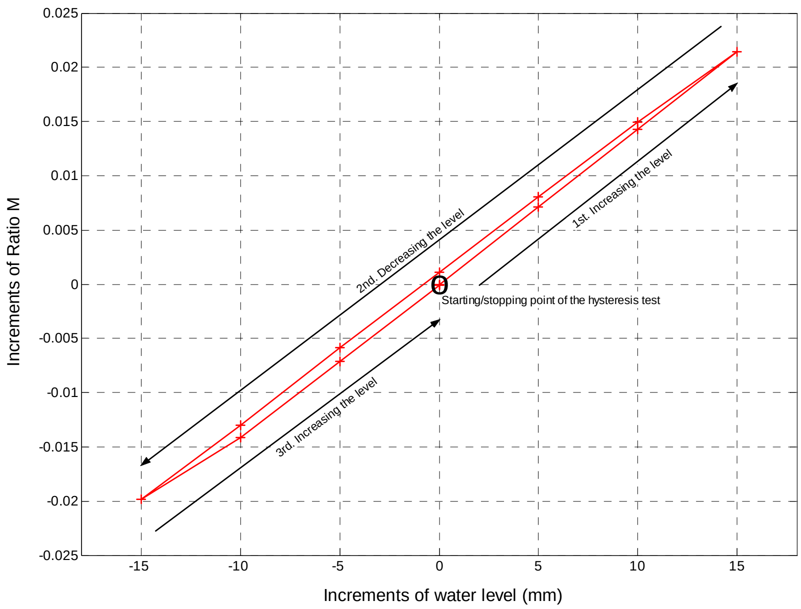

Figure 4. Experimental results of the hysteresis test.

5. Conclusions

A liquid-level measurement system based on a remote grounded capacitive sensor has been presented. In spite of the simplicity of both the sensor and the interface circuit, the performance of the measurement system is quite good. Over a level range of 70 cm, the error is smaller than 1 mm and the resolution is better than 0.1 mm for a measuring time of 20 ms. Accordingly, the system can also be used for leakage detection.

6. References

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