CONDUCTIVITY CELL FOR WATER QUALITY MONITORING

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Abstract – *The measurement of electrolytic conductivity is widely applied as a control parameter and its relevance is continuously increasing, not only in industrial applications but also in the environmental monitoring domain. In this work the attention is focused on the electrical behaviour of a low cost in-situ four electrode conductivity sensor for water quality monitoring in estuaries and oceans.*

The design of the sensor, the method used to determine the conductivity value, the circuit developed for signal conditioning and the data acquisition board that links the sensor to the computer for further signal processing are described in detail. The output values of the conditioning circuit are stored in the computer and compared with more accurate conductivity values obtained from commercial equipment. In order to obtain more accurate results algorithms for digital signal processing are presented and implemented.

Keywords: *conductivity cell, electrolytic conductance, salinity.*

1. INTRODUCTION

The measurement of electrolytic conductivity is widely applied in several application domains and the increase of its relevance has boosted research in the area. In order to obtain absolute methods, this measurement has recently undergone a critical revision [1], systems for traceable measurements are being developed [2] and the research for the best conductivity cell is always a goal for scientists and experimentalists [3-6]. In this paper the attention is focused on the electrical behaviour of a low-cost in-situ four electrode conductivity sensor for water quality monitoring in estuaries and oceans.

Conductivity is an intrinsic property of seawater from which salinity and density may be derived. Although water itself is a poor conductor of electricity, the presence of ionic species in solution increases the conductance considerably. The conductance of such electrolytic solutions depends on the concentration and nature of the ions present. Conductivity is calculated from conductance, defined as the reciprocal of the resistance, measured by a sensor.

2. ELECTRODE CONDUCTIVITY SENSOR

This paper presents a conductivity sensor that includes the implemented cell presented in Fig. 1 with four electrodes and a plastic tube [7-9].

Two electrodes are ring shaped and stand inside the tube and the other two are metallic tips to measure the output voltage. The tube is closed on the two ends with metallic grids to achieve field confinement in the cell. The electric field becomes fully internal and proximity effect is eliminated. The physical dimensions are:

$$d = 45\ mm\ ;\ \varnothing_{int} = 16\ mm\ ;\ \varnothing_{ext} = 20\ mm\ ;\ l = 180\ mm$$

where d represents the distance between the rings, l the cell length and $\varnothing_{int}$ and $\varnothing_{ext}$ the internal and external diameter of the glass tube.

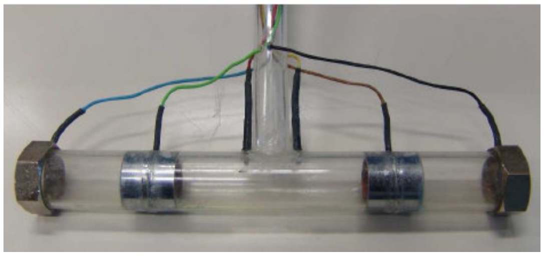

Fig. 1. Photo of the implemented four electrode cell

Figure 2 presents the block diagram of the cell and part of the implemented circuit.

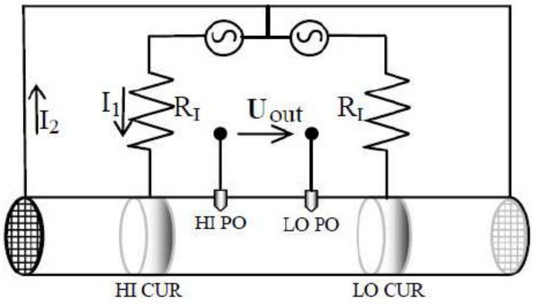

Fig. 2. Block diagram of the cell and part of the circuit implemented on the board.

The cell is connected to a printed circuit board with all signal conditioning circuitry whose output is connected to a data acquisition board to digitize data to be processed by the computer. In Fig. 3 a photo of the printed circuit board designed for the sensor is presented. The board when connected to a ±15 V power supply can generate two symmetric alternating voltages with a frequency of 1 kHz (to obtain more precise results) due to a quadrature oscillator and a phase opposition circuit. Each voltage is applied to one of the ring-shaped electrodes so that current is injected inside the cell. There are two fixed resistors, each one connected to one of the electrodes to measure the injected current. The two metallic tips that measure the output voltage are also connected to the board.

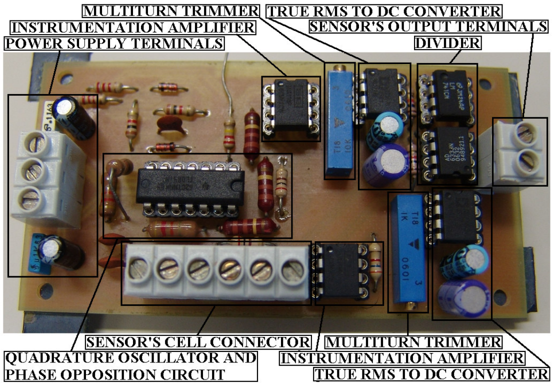

Fig. 3 – Photo of the printed circuit board implemented.

The board's sensor output is connected to a computer through a multifunction data acquisition board from National Instruments. The ADC has 16 channels, each one having a 16-bit resolution, 250 kS/s maximum sampling rate and input voltage range programmable per channel from ±0,2 V to ±10 V.

3. MEASUREMENT METHOD

Error! Reference source not found. shows the full internal field in the cell obtained with a simulation model. The voltages applied to the current electrodes and the top grids are anti-symmetric. This geometry assures that the current inside the cell (in the region between the two electrodes) equals the current that flows from the current electrodes to the metallic grids on the top ends of the cell. That leads to $K_c = 50\ \mathrm{m}^{-1}$. This value results from the fact that the current flowing in the water cylinder confined by the tube and the voltage electrodes is half the current measured in the current electrodes.

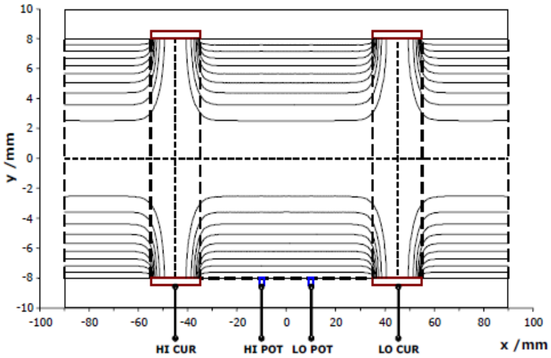

Fig. 4 – Current lines in the cell.

The measurement principle used derives from Ohm's law and thus the current, I, passing through a given body of solution is proportional to the applied potential difference, V. Theoretical results of conductivity, σ, are determined from the conductance, $1/R$, measured by the sensor using a geometric coefficient or cell constant, K_c, which depends on the cell shape

$$\sigma = K_c \frac{1}{R} \tag{1}$$

A conductivity measurement using a flow through type cell is disturbed by several electrochemical processes such as double-layer capacitance, electrolysis and concentration polarization that are sources of considerable errors. To minimize these effects, the measurements are performed with alternating current (AC).

Considering that conductivity can be determined from (1) and K_c is a constant, conductivity is directly proportional to the conductance, G, which is $1/R$:

$$\sigma \propto G \Leftrightarrow \sigma \propto \frac{1}{R} \tag{2}$$

Observing Fig. 4, the current injected in the current electrodes is the same between the two metallic tips (HI POT and LO POT) that measure the voltage $\overline{U_{OUT}}$. This can be determined as

$$\frac{\overline{U_I}}{R_I} = \frac{\overline{U_{OUT}}}{\overline{Z}} \Leftrightarrow \overline{Z} = \frac{\overline{U_{OUT}}}{\overline{U_I}} R_I \tag{3}$$

where $\overline{U_I}$ is the voltage measured in one of the fixed resistors R_I and $\overline{Z}$ is the impedance related with the conductivity of the solution inside the cell's tube. The admittance module is

$$\left|\overline{Y}\right| = \frac{1}{\left|\overline{Z}\right|} \Leftrightarrow \left|\overline{Y}\right| = \frac{\left|\overline{U_I}\right|}{\left|\overline{U_{OUT}}\right|} \frac{1}{R_I} \tag{4}$$

and also

$$\left|\overline{Y}\right| = \sqrt{G^2 + B^2} \tag{5}$$

where G is conductance and B is susceptance. Considering (2) and (5), conductivity can be measured through the relation

$$\sigma \propto \frac{\left|\overline{U_I}\right|}{\left|\overline{U_{OUT}}\right|} \Leftrightarrow \sigma \propto \frac{\left(\overline{U_I}\right)_{ef}}{\left(\overline{U_{OUT}}\right)_{ef}} \tag{6}$$

where $\left(\overline{U_I}\right)_{ef}$ is the effective value of voltage U_I and $\left(\overline{U_{OUT}}\right)_{ef}$ is the effective value of voltage U_{OUT}. The measurement of these values and their division are provided by the rest of the circuit included on the board of the sensor.

Between the terminals of the board's sensor that measures U_I and U_{OUT} and the board's output that shows the result of the division between $\left(\overline{U_I}\right)_{ef}$ and $\left(\overline{U_{OUT}}\right)_{ef}$, there is a conditioning circuit with instrumentations amplifiers and multiturn trimmers that allow to adjust the values of both voltages to obtain better results.

4. EXPERIMENTAL CHARACTERIZATION

Tests take place in an automated temperature controlled bath using tap water as the solution whose conductivity is to be determined [10]. Sodium chlorite is used to increase water's conductivity in order to study sensor's output changes. The block diagram of the automated temperature controlled bath used to test the sensor is shown in **Error! Reference source not found.**. The bath has a maximum capacity of 14 litres. The temperature is controlled with a heating/cooling thermoelectric pump based on Peltier Modules and a PID controller implemented in LabVIEW is used. The temperature is set to be always at 25 ℃. A full description of the testing system can be found in **Error! Reference source not found.**.

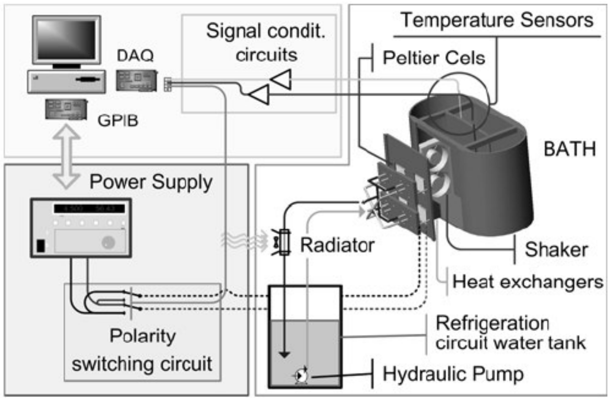

Fig. 5 – Block diagram of the automated temperature controlled bath.

The calibration of the conductivity value of the solution is performed with a commercial sensor from Hanna Instruments, HI 255-01. In **Error! Reference source not found.** a photo of this laboratory bench meter is presented.

Fig. 6 – Photo of laboratory bench meter.

At a first stage measurements are taken to adjust multiturn trimmers included in the conditioning system to their optimal value which is the one that leads to a minimal error for the desired range of conductivities to be measured. Fig. 7. presents the results obtained for $P_1 = 0.25\ \Omega$ and $P_2 = 4.65\ \Omega$ being 20% the worst relative error.

5. EXPERIMENTAL CHARACTERIZATION

At a first stage measurements are taken are not only to confirm that current flows in the tap water and the voltages needed to determine the conductivity are being acquired but also to adjust multiturn trimmers, P_1 and P_2, included in the conditioning system to their optimal value which is the one that leads to a minimal error for the desired range of conductivities to be measured.

To confirm if the voltage measured by the sensor and detected at the board’s output is according to liquid conductivity, the liquid conductivity relative error is calculated by

$$\varepsilon_{\tilde{\sigma}} = \frac{\left|\tilde{\sigma} - \sigma\right|}{\sigma} \qquad (8)$$

where $\tilde{\sigma}$ is the voltage value measured by the sensor and σ is the liquid conductivity value measured by the laboratory bench meter. The range of electrolytic conductivities varies from 0,025 S/m, typical value for tap water, to 5 S/m, typical value for sea water.

Several tests were done, setting P_1 and P_2 with different values. The best results are obtained when P_1 = 0,25 kΩ and P_2 = 4,65 kΩ and are shown in **Error! Reference source not found.**. It presents the sensor’s output voltage as a function of the water conductivity measured by the laboratory bench meter at 25 ℃. The worst relative error for the estimated liquid conductivity is 20%.

. Following measurements are done after adding some portions of salt so that it is possible to reach the conductivity values of sea water.

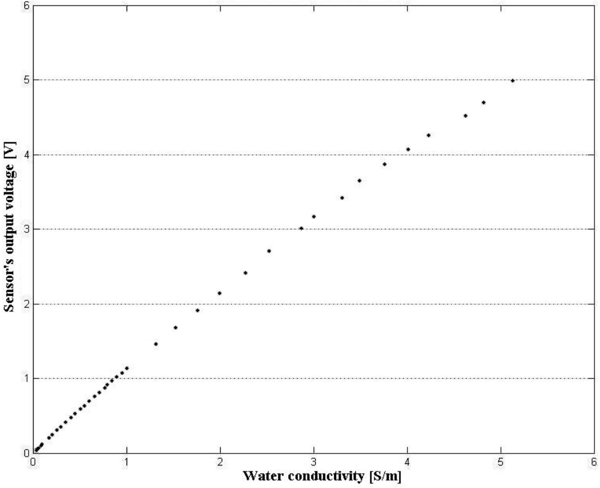

Fig. 7 - Sensor’s output voltage as function of the water conductivity with P1 = 0,25 kΩ and P2 = 4,65 kΩ.

An algorithm to determine the value of the liquid conductivity from the output sensor voltage is implemented. The algorithm is based in three vectors: one with the values of the liquid conductivity measured by the laboratory bench meter, other with the values of the voltage detected at the sensor’s output and a third one which is a test vector that begins with the value of the lowest voltage measured by the sensor and ends with the value of the highest voltage measured by the sensor. A certain number of points can be determined inside this range. With a linear interpolation, an estimated conductivity is calculated and related to all the points of the test vector based on the values measured by the sensor and laboratory bench meter. Applying another linear interpolation to the test vector it is possible to obtain the liquid conductivity estimated for any voltage measured by the sensor and whose corresponding liquid conductivity is not known. In Fig. 8, the liquid conductivity estimated is shown as function of the voltage detected at the sensor’s output.

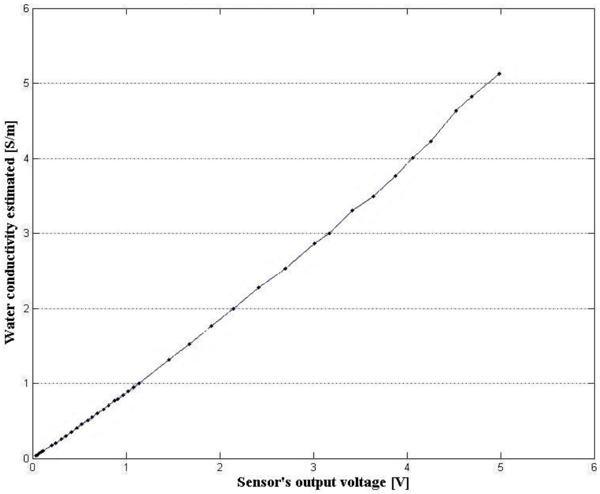

Fig. 8. Liquid conductivity estimated as a function of the sensor's output voltage.

5. CONCLUSIONS

The proposed prototype is an attractive solution for water quality measurement systems in estuarine zones. Main characteristics of the proposed prototype include the metallic grids at the ends of the cell that create a geometry where the electric field is internal and no current paths spread out of the sensor which avoids any perturbations caused by the proximity of external objects. This leads to a low sensitivity to disturbances caused by electrolytic polarization, double layer and fringe effects.

The printed circuit board allows a measurement system's conditioning signal circuit while the data acquisition board makes it possible for digital signal processing and the implementation of algorithms that assure a large conductivity measuring range and improve the measurement accuracy, reducing the difference between the values measured and the real values of conductivity.

An agreement between simulation and experimental results can be improved with the implementation of more developed algorithms but still validates the theoretical assumption of the prototype's model. And the immunity of the proposed prototype to external disturbances caused by polarization and fouling effects.

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