

A Four-Terminal Water-Quality-Monitoring Conductivity Sensor

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Abstract—In this paper, a new four-electrode sensor for water-conductivity measurements is presented. In addition to the sensor itself, all signal conditioning is implemented together with signal processing of the sensor outputs to determine the water conductivity. The sensor is designed for conductivity measurements in the range from 50 mS/m up to 5 S/m through the correct placement of the four electrodes inside the tube where the water flows. The implemented prototype is capable of supplying the sensor with the necessary current at the measurement frequency, acquiring the sine signals across the voltage electrodes of the sensor and across a sampling impedance to determine the current. A temperature sensor is also included in the system to measure the water temperature and, thus, compensate the water-conductivity temperature dependence. The main advantages of the proposed conductivity sensor include a wide measurement range, an intrinsic capability to minimize errors caused by fouling and polarization effects, and an automatic compensation of conductivity measurements caused by temperature variations.

Index Terms—Conductivity sensor, measurement system, signal processing.

I. INTRODUCTION

IN INDUSTRIAL environments, water-conductivity measurements are generally used to measure the concentration of ionized chemicals in water. For water-quality assessment, conductivity measurement can be nonselective in the sense that it does not distinguish individual concentrations of different ionic chemicals mixed in water. Nevertheless, conductivity measurements are of paramount importance in water-quality-assessment systems since high or low conductivity levels, relative to their nominal values, can be used to detect environmental changes and pollution events [1]. In this paper, the attention is focused on the electrical behavior of a low-cost *in situ* four-electrode conductivity cell for water-quality monitoring in estuaries, oceans, and rivers. In these situations, water conductivity is affected by the following: 1) the presence of inorganic

dissolved solids or organic compounds in the water; 2) the geology of the area through which the water flows; 3) sea tides; and 4) temperature. These factors imply that the physical location of the measuring unit is important and that a correlation between them and the measured values must also be considered.

Generally, high conductivity levels come from industrial pollution or urban runoff. Extended dry periods and low-flow conditions also contribute to increase conductivity levels (e.g., measurements of water conductivity in lakes). However, organic compounds, such as oils, tend to lower water conductivity.

Temperature is also an important variable when conductivity measurements are concerned. Industrial discharges also have thermal effects, particularly those from power plants that cause temperature changes and reduce dissolved-oxygen concentration. Therefore, temperature is simultaneously a water-quality parameter and a variable that affects conductivity measurements [2]. For estuarine salty water, the conductivity temperature coefficient is about 20%/°C. This means that accurate conductivity measurements imply temperature measurements to compensate the conductivity for a certain reference temperature (typically, 20 °C or 25 °C).

There are two main types of conductivity sensors: electrode (or contacting sensors) and toroidal or inductive sensors [3]–[5]. Electrode sensors contain two, three, or four electrodes. The conductivity (σ) is directly proportional to the conductance ($1/R$). The proportionality coefficient (K_C) depends on the geometry of the sensor that must be designed according to the target conductivity range [6], [7]. Toroidal or inductive sensors usually contain two coils, sealed within a nonconductive housing. The first coil induces an electrical current in the water, while the second coil detects the magnitude of the induced current, which is proportional to the conductivity of the solution.

In this paper, the implementation and characterization of a four-electrode conductivity cell is presented. The main advantages associated with the designed sensing unit are its low cost, very low sensitivity to contact resistance and fringing effects, wide measurement range, and linearity that can be extended by varying the cell's excitation-voltage level.

The flexibility provided by the proposed solution can also be applied to implement a maintenance cleaning detector triggered by cell excitation voltages. This capability is of paramount importance due to the harsh environmental conditions to which these sensors are usually exposed. Besides, as the proposed solution for conductivity measurements has a linear behavior, an accurate calibration scheme using a minimal number of standard solutions can be used.

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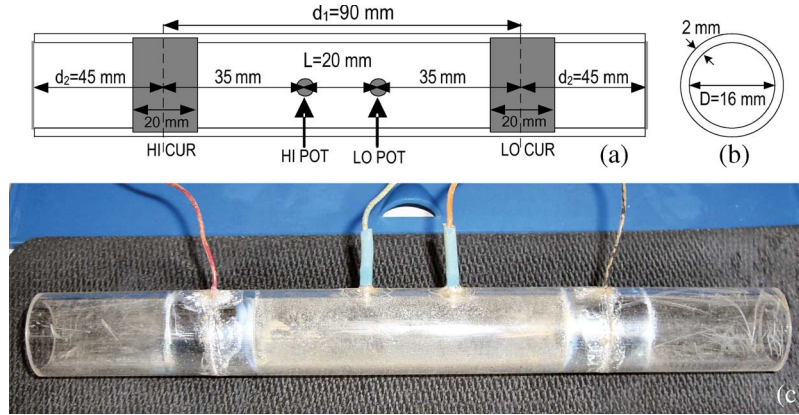


Fig. 1. Conductivity sensing unit. (a) Longitudinal sectional-view geometry. (b) Transversal sectional-view geometry. (c) Actual sensing unit.

This paper includes the system description, simulation, and experimental results of the developed prototype. Measurements for different conditions in terms of measurement frequency, solution conductivity, and temperature are also presented.

II. OBJECTIVES AND PAST WORK

The purpose of this paper is to present and characterize a prototype for water-conductivity measurements based on a four-electrode sensor. The system also includes a temperature sensor to provide compensation of conductivity measurements caused by temperature variation.

Conductivity of very dilute solutions can be calculated by the sum of the conductivity contribution of all ions in the solution

$$\sigma = \delta_w \cdot \sum_i (\alpha_i \cdot c_i) \quad (1)$$

where σ represents conductivity, δ_w is the water density, α_i is the equivalent ionic conductance of ion “i,” and c_i is its concentration. If a single-ion solution is present, its concentration can also be evaluated from the conductivity measurements. Implicit temperature dependence is included in the equivalent ionic conductance and water-density coefficients.

As far as water conductivity is concerned, several solutions have been proposed [8], [9], and many commercial types of equipment are available from many manufacturers [10], [11]. The main problems associated with water-conductivity measurements are sensitivity to external disturbances, polarization and fouling effects, measurement selectivity, and measurement dynamic range.

In previous research and development in this area, the authors developed a prototype for water-conductivity measurement based on a three-electrode cell and their application to water-conductivity measurements in estuarine zones [12]. Well-known limitations have been identified in literature [13], [14]: surface molecular water polarization and electrode fouling. This measurement solution implies a large number of calibration points due to the nonlinear effects, and repeated calibration procedures are required due to the fouling drawback.

To minimize these factors, a four-electrode cell was projected and implemented. This type of cell is like a four-terminal preci-

sion resistor: Two electrodes are used to force a uniform time-varying electric field, and the other two measure the voltage.

III. SYSTEM DESCRIPTION

A. Sensing Units

The measurement system includes two sensing units: a four-electrode conductivity sensor and an integrated temperature sensor.

In Fig. 1, the geometry of the conductivity sensing unit is shown. A tubular cylindrical structure is used to implement the conductivity-sensing unit. It is formed by a plastic tube, with two ring-shaped electrodes inside to force the electric field and two metallic tips to measure the output voltage.

The current terminals (HI CUR and LO CUR) are not on the edges of the tubular structure in order to minimize the cell’s sensitivity to external disturbance caused, for example, by the proximity of metallic materials that can be near the cell periphery. The sensing terminals (HI POT and LO POT) are located in symmetrical positions across the center of the cell and far away from the current terminals to obtain a uniform electrical field between these terminals. The electrodes are encapsulated inside a 16-mm diameter acrylic tube where the water flows.

Since the conductivity is directly proportional to the cell constant and inversely proportional to the resistance

$$\sigma = K_C \frac{1}{R} \quad (2)$$

the cell constant value must be chosen, taking into account the target conductivity range and the desired resistance values to be measured. For conductivities between 50 mS/m and 5 S/m corresponding to resistance values between 1 k Ω and 10 Ω , the desired cell constant value is 50 m⁻¹. To project the cell, some basic assumptions were considered to achieve the target value of the cell constant. Assuming that the open-water resistance is negligible when compared with the water resistance inside the sensor, the sensor dimensions ($d_1 = 2d_2$) are selected so that the current is evenly divided in each current terminal. This way, half the current flows directly toward the other current terminal inside the sensor, and the other half circulates outside. The position of the voltage terminals is determined by the selected value

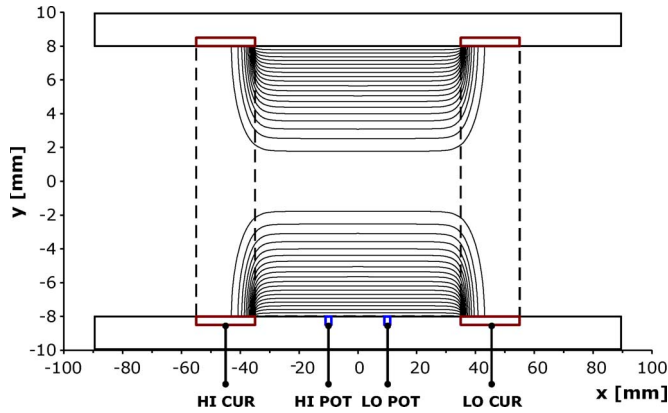


Fig. 2. Finite-element-algorithm results for the internal cell current's lines. Due to the geometrical structure of the sensor, only one quadrant of the x - y plane was simulated with a total of 1921 nodes.

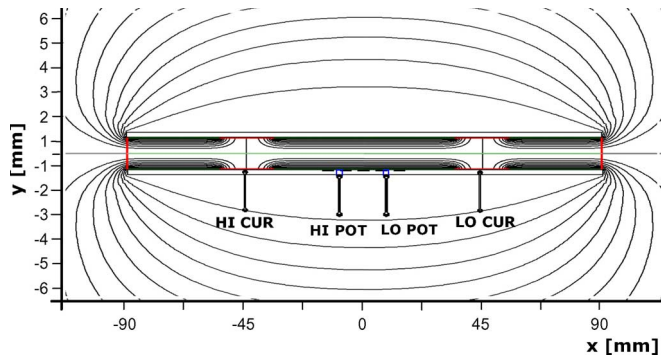


Fig. 3. Finite-element-algorithm results for the cell current's lines, including the current lines that flow in the surrounding liquid.

of K_C and the cross-sectional area ($A = \pi D^2/4$). To achieve the desired cell constant of 50 m^{-1} , the distance between the voltage terminals is approximately 20 mm ($L = 2K_C A$).

To confirm the previous assumptions, a finite-element analysis (FEA) program [15] is used. Fig. 2 shows the internal electrical-field geometry obtained with the FEA program. Besides the dimensions of the sensing unit, the program accepts the material conductivity (a variable mesh refinement), which is dependent on the model volume and on the required approximation of the solution and the boundary conditions.

The FEA program confirms that the electrical field is uniform between the sensing terminals HI POT and LO POT. Due to the fact that the sensing unit is open on both sides, some current will flow outside the cell through the surrounding liquid. In Fig. 3, the current lines obtained with the finite-element algorithm are shown when the surrounding liquid current lines are also considered.

This program can provide an adaptive refinement of cell design, minimizing prototyping-development time and improving performance results for conductivity measurements. It is very easy to simulate cell behavior for different geometries.

Temperature measurement is provided by a three-terminal semiconductor sensor from Analog Devices (TMP36) [16], whose main characteristics include the following: low self-heating; low-voltage operation (2.7–5.5 V); temperature range between -40°C and 125°C ; $10\text{-mV}/^\circ\text{C}$ scale factor; $\pm 2^\circ\text{C}$

accuracy over its temperature range; and a typical $\pm 0.5^\circ\text{C}$ linearity error.

B. Signal Conditioning and Measurement Method

The four-terminal conductivity sensor acts like a four-terminal impedance with two current terminals (HI CUR and LO CUR) and two voltage terminals (HI POT and LO POT). However, it is not possible to use commercially available impedance-measuring instruments, as in traditional impedance meters, where a zero detector and a feedback circuit are used. The impedance instruments set the current in the LO POT terminal to zero by forcing the potential in LO POT and LO CUR to zero. This is not possible in our sensor due to the potential imposed between LO POT and LO CUR. One solution that circumvents the limitations of these instruments, based on a front-end amplifier and on a set of residual correction procedures, is presented in [17]. This measurement procedure is still not suitable for implementation in our sensor conditioning circuits.

In [18], an impedance-measurement system based on two simultaneously acquiring ADC channels and sine-fitting algorithms was presented. This system can be used to measure the four-terminal conductivity sensor, since the current is imposed by the sine generator, and there are separate terminals for the voltage measurements (without current). Sine-fitting algorithms best fit (by minimizing the least squares error) the measured records with generic sine signals, estimating the sine amplitude, phase, dc component, and frequency. Since the fitting algorithms must be applied to the two records (one sampling the voltage across a well-known impedance—indirectly, the sensor current—and the other sampling the voltage terminals of the sensor) and they are nonlinear iterative algorithms, they will result in slightly different frequencies for the two records (due to different signal-to-noise ratios and different input ADC voltage range). To prevent this, an improved fitting method was presented in [19]. This method uses the data from both channels to estimate the sine amplitudes, phases, dc components, and common frequency, reducing the uncertainty of the estimated parameters. With the sine amplitudes and the well-known impedance magnitude, the sensor impedance (or admittance) magnitude can be easily determined, as shown in [18]. The sensor impedance angle is determined from the phase difference of the two sine signals and the phase of the well-known impedance at the measured frequency.

Implementation of the two data-acquisition channels and sine-fitting algorithms requires a DSP-based system like the one presented in [20]. For the conductivity-sensor conditioning circuit, a DSP kit from Analog Devices with a BF533 DSP was used. It includes 64 MB of external memory and a codec (AD1836) with ADCs for data acquisition and DACs for data generation. The ADCs have a sigma-delta architecture with differential inputs, 24-b resolution, 96-kS/s sampling rate, and input-voltage range of $\pm 3.08 \text{ V}$. The ADC data records are transmitted to the DSP by an SPI connection. One of the DACs in the AD1836 is used to generate the sine stimulus for the impedance-measurement circuit. The DAC has 24-b resolution and a maximum amplitude of 5.6 Vpp . The sine

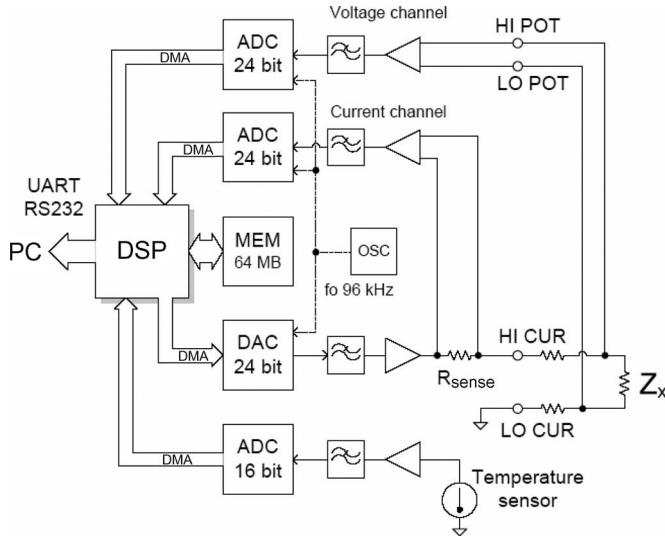


Fig. 4. Diagram block of the conductivity-sensor conditioning circuit.

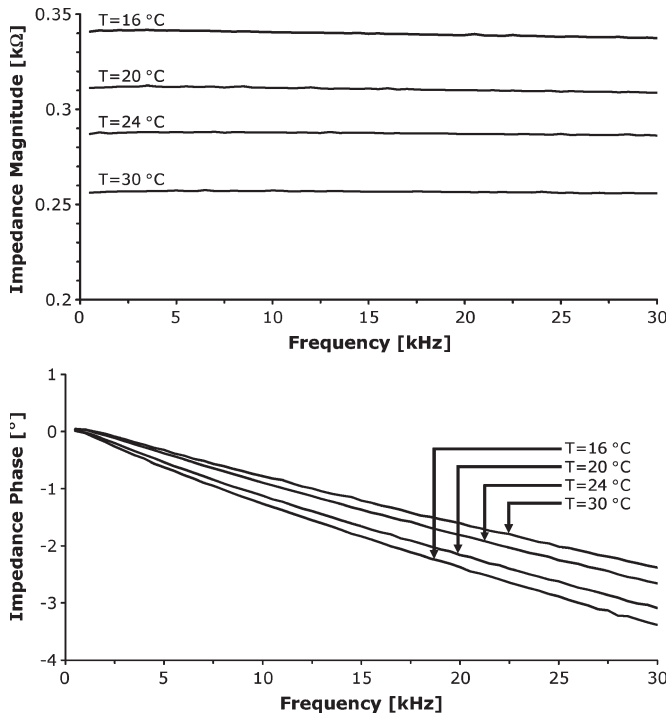


Fig. 5. Conductivity-sensor impedance magnitude and angle.

signal is sampled at 96 kS/s. The DAC output-voltage level can be digitally controlled with 1024 steps of linear attenuation.

To measure the temperature, the TMP36 temperature sensor is used, together with a AD974 16-b ADC. The temperature measurements are taken at 100 ms each.

The block diagram of the developed and implemented prototype is presented in Fig. 4.

C. Experimental Results

The first sensor tests are related to the temperature and frequency dependence of the sensor impedance. In Fig. 5, the impedance amplitude and angle are shown as a function of the applied sine frequency and the controlled water temperature for

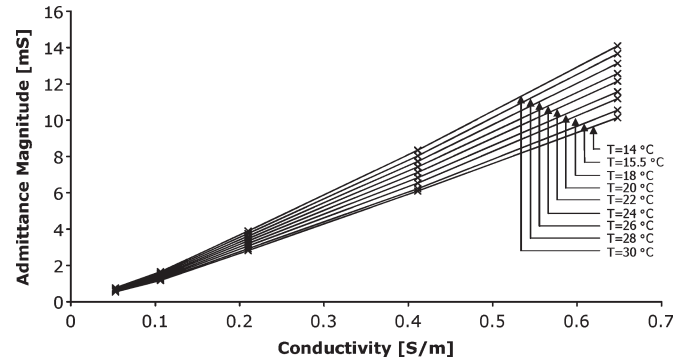


Fig. 6. Conductivity-sensor admittance magnitude as a function the electrolytic conductivity for different values of temperature.

$\sigma = 210$ mS/m. It is clear from these experimental results that, for frequency values below 20 kHz, the stray capacitances are still very low.

The system that controls the liquid temperature was presented in [21]. It consists of a bath with a maximum capacity of 14 L. The temperature is controlled with a heating/cooling thermoelectric pump based on Peltier modules and a PID controller implemented in LabVIEW. The temperature range was specified to be in the 0 °C to 35 °C interval.

Since the impedance amplitude is inversely proportional to the liquid conductivity, it is the admittance that is directly proportional to the conductivity. In Fig. 6, the conductivity-sensor admittance amplitude is shown as a function of the liquid conductivity at 1 kHz. For this frequency, the impedance angle is approximately zero, and thus, the admittance amplitude is proportional to the conductivity.

Electrical conductivity of all electrolytic solutions is strongly dependent on temperature. A solution at a higher temperature will present a higher quantity of dissociated ions, which leads to a higher concentration of electric charges, and as consequence, the conductivity will rise.

The measurements for different concentrations of NaCl confirm the linear variation of the conductivity with temperature

$$\sigma_t = \sigma_{\text{ref}} [1 + \alpha(t - t_{\text{ref}})] \quad (3)$$

where σ_t is the conductivity at any temperature t (in degrees celcius), σ_{ref} is the conductivity at the reference temperature t_{ref} (in degree celcius), and α is the temperature coefficient of the solution at t_{ref} . The amplitude admittance measured as a function of temperature for different values of the solution conductivity is presented in Fig. 7. From the values depicted, a temperature coefficient of $\alpha \simeq 2.21\%/^{\circ}\text{C}$ at 20 °C was estimated. For each conductivity value of the solution, the conductivity was measured for a range of temperatures.

With this result, data obtained at different temperatures can be converted to a standard reference temperature, allowing a better comparison of measurements taken at different locations and times. Since the conductivity sensor is to be used for estuarine-water monitoring, a temperature value of 20 °C is chosen as the temperature reference.

In Fig. 8, the dotted lines represent the measured uncompensated conductivity as a function of the water temperature for different values of the solution conductivity. The full lines

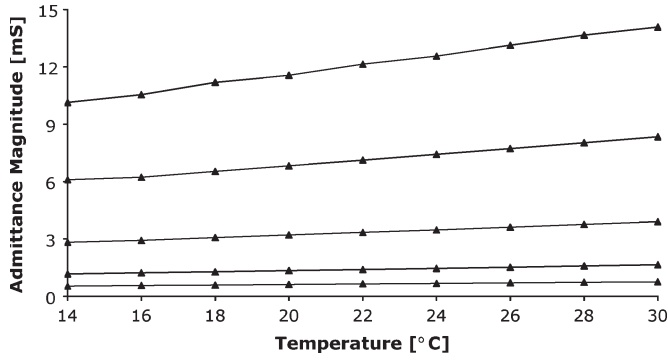


Fig. 7. Admittance magnitude of the conductivity sensor for different values of electrolytic conductivity, as a function of temperature.

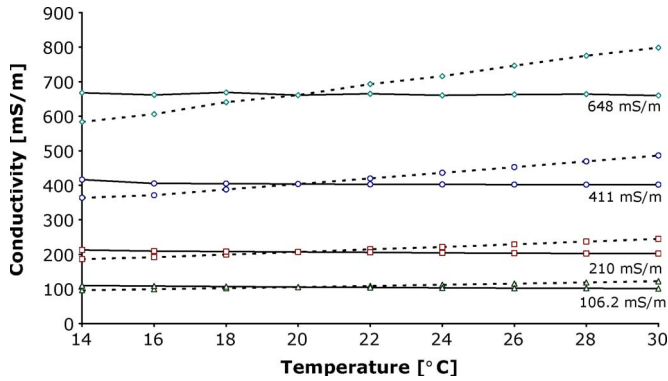


Fig. 8. Compensated and uncompensated values of the conductivity for different values of electrolytic conductivity as function of temperature.

correspond to the compensated conductivity values. This figure clearly shows the need for temperature compensation. The reference temperature is also visible (at this temperature, the compensated and uncompensated values of the conductivity are the same).

D. Discussion

The simulation results obtained using the FEA program when the conductivity sensing unit is submitted to a solution conductivity of $\sigma = 1$ S/m, and an excitation voltage applied between current terminals (HI CUR and LO CUR) of 2 V show that the current inside the cell (I_{INT}) and the cell external current (I_{EXT}) are

$$\begin{aligned} I_{INT} &= 5.5 \text{ mA} \\ I_{EXT} &= 4.9 \text{ mA} \end{aligned} \quad (4)$$

and the voltage measured between the potential terminals is

$$U_{HI \text{ POT}} - U_{LO \text{ POT}} = 0.54 \text{ V}. \quad (5)$$

The resistance between the sensing terminals is

$$R_{\text{sensing terminals}} = \frac{U_{HI \text{ POT}} - U_{LO \text{ POT}}}{I_{INT}} \cong 99.5 \Omega. \quad (6)$$

The resistance measured by the system considers the total current (I_{TOTAL}) that goes through the sensing resistor, which

means that the resistance value that would be obtained by the conditioning circuit is

$$R_{sm} = \frac{U_{HI \text{ POT}} - U_{LO \text{ POT}}}{I_{TOTAL}} \cong 52.5 \Omega. \quad (7)$$

Using the definition of the cell-geometry factor, the cell geometric constant obtained from simulation (K_{CS}) is

$$K_{CS} = R_{sm} \times \sigma = 52.5 \text{ m}^{-1} \quad (8)$$

which is very close to the value used as a design target.

From the experimental data represented in Fig. 6, the relationship between admittance measurements and conductivity values, for $\sigma > 50$ mS/m, can be obtained by linear regression at the temperature reference ($t = 20^\circ\text{C}$)

$$|Y| = -6.7 \times 10^{-4} + 1.867 \times 10^{-2} \times \sigma \quad (9)$$

where Y represents admittance, and σ is the liquid conductivity (in siemens per meter). The experimental value of the cell geometry can be determined from (9) by $1/1.867 \times 10^{-2} = 53.6 \text{ m}^{-1}$. The linear regression minimizes the square distance of all points to the straight line. Since the last experimental point has much higher admittance amplitude, the linear regression will tend to favor this point instead of the lower conductivity measurements. The conductivity is estimated by

$$\hat{\sigma} = \frac{|Y| + 6.7 \times 10^{-4}}{1.867 \times 10^{-2}} \quad (10)$$

after the admittance amplitude has been determined by the sine-fitting algorithms. The liquid conductivity relative error for the measurements is

$$\varepsilon_{\hat{\sigma}} = \frac{\hat{\sigma} - \sigma}{\sigma} \quad (11)$$

where $\hat{\sigma}$ is the liquid conductivity estimated by the prototype using (10), and σ is the actual liquid conductivity. For the five measured conductivities at $t = 20^\circ\text{C}$ (shown in Fig. 6), the highest relative error is for the lowest conductivity value and reaches 7.8%.

Instead of a standard linear regression, a least squares method was implemented that determines the straight-line parameters that minimize the worst relative error of the estimated conductivity after the amplitude admittance is measured. With this method

$$\hat{\sigma} = \frac{|Y| + 5.97 \times 10^{-4}}{1.839 \times 10^{-2}}. \quad (12)$$

$K_{CE} = 1/1.839 \times 10^{-2} = 54.37 \text{ m}^{-1}$, and the worst relative error for the estimated liquid conductivity is 1.86% (again, for $\sigma > 50$ mS/m). To improve this result, more conductivity measurements are required at different temperatures, and a refined calibration of the impedance-measurement system is also necessary. The results show good agreement between simulation and experimental results, validating the theoretical assumptions of the prototype's model.

Table I summarizes the metrological parameters of the conductivity-measurement system. The main advantages of

TABLE I
METROLOGICAL PARAMETERS OF THE
CONDUCTIVITY-MEASUREMENT SYSTEM

Sensor type	4 terminals
Cell constant	54.37 m ⁻¹
ADC Resolution	24 bit
Relative Error	1.86 % (worst case)
Maximum Experimental Uncertainty (Type A, 2 σ)	0.53% of reading
Measurement Range	0.05-5 S/m
Operating Frequency	1 kHz

the proposed conductivity sensor include a wide measurement range and an intrinsic capability to minimize errors caused by fouling and polarization effects; a flexible solution for data acquisition and signals processing; the capability to generate the stimulus signal with different amplitudes; an automatic compensation of conductivity caused by temperature variation; and a low-cost solution that is essential for environmental distributed monitoring networks. In addition, a total maximum experimental uncertainty (Type A, at 2 σ) of 0.53% reading was obtained by repetitive measurements for different conductivities.

IV. CONCLUSION

The proposed prototype is an attractive solution for water-quality measurement systems in estuarine zones. Main characteristics of the proposed prototype include an automatic temperature compensation of conductivity measurements and low sensitivity to disturbances caused by electrolytic polarization, double layer, and fringe effects. The measurement system's conditioning signal circuitry and digital signal processing assure a large conductivity measuring range, good measurement accuracy, and an easy implementation of telemetric solutions. Testing voltage amplitudes can be automatically adjusted by the DSP according to the conductivity range under measurement. This autorange capability improves the measurement system's accuracy, particularly for applications where large conductivity variations are expected. The prototype can also include a dirty detector based on the voltage drops between cell terminals.

Experimental impedance results of the conductivity cell, and its variation with frequency and temperature, confirm theoretical expectations. A good agreement between simulation and experimental results validates the theoretical assumptions of the prototype's model and confirms the expected immunity of the proposed prototype to external disturbances caused by polarization effects.

The developed system consists of a prototype to demonstrate the proof of concept of the sensor structure, as well as the signal conditioning and signal processing algorithms. As far as power consumption is concerned (a very important parameter for stand-alone instruments and field measurements), the pro-

totype consumes about 200 mA at 9 V, but a great part of this power is used to supply the DSP kit subsystems that are not used in the sensor-conductivity prototype. Several solutions can be considered to assure an extended system's autonomy. An interesting powering solution for a complete monitoring station could be the use of renewable power sources.

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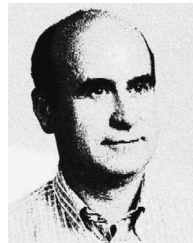
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