Smart oil and conductivity sensor for water quality monitoring

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Abstract – This paper presents a smart sensor designed for oil-on-water thickness and water conductivity measurements. Basically, the proposed sensing devices include a capacitive element used to measure oil thickness and a conductivity element to measure water conductivity. Temperature compensation of measured values is also provided by including an additional temperature sensor in the system. The main characteristics of the smart sensor system include pulse-width modulation of sensors' output signals, auto-calibration capability and temperature error compensation. Field applications are not restricted to environmental monitoring and can include wastewater treatment plants, oil quality measurement and measurement of oil quality in fluid systems and hydraulic components. Some experimental results are also presented in this paper.

I. Introduction and objective

Removal of free oil and floating materials in industrial wastewater-treatment processes together with conductivity measurements are two important issues in water pollution control [1-3]. Another important application of oil and conductivity measurements is in the field of water quality monitoring in rivers and estuaries especially in geographical areas nearby pollutant industrial plants. Nowadays, this subject is a major topic that affects life quality in our society.

This paper presents a measurement solution for oil-thickness and water conductivity. Oil-on-water thickness measurement is based on a capacitive sensor that takes advantage of the large difference between the dielectric constants of oil and water [4-6]. Conductivity measurement is based on a three-electrode conductivity sensor that includes a reference and a measuring sub-cell [7]. A third sensor for temperature measurements (thermistor Omega ON-400 Series) is also included in the system in order to compensate measurement errors caused by temperature variations.

Finally, it is important to refer that although this paper does not addresses in detail auto-calibration [8], sensor cleaning procedures, and choice of anti-fouling and anti-adherent electrode materials, these issues must be considered in a commercial design of the system to assure accurate measurements in aggressive environments like the ones provided by industrial polluted and contaminated waters.

II. Sensor design

Sensors are assembled together in a single structure as represented in Figure 1. The conductivity sensor includes two parts: a reference sub-cell, connected between terminals (1) and (2), and a measuring sub-cell, connected between terminals (2) and (3). The metallic plates are supported by a material with a low electrical permittivity (acrylic) in order to minimize the displacement current around the conductivity sensor. Sensor assembly assures that the conductivity cells work always under the oil thickness layer, being the maximum expected oil thickness, $(d_{oil})_{max}$, lower than dimension W represented in Figure 1.

The conductivity reference sub-cell is filled with a calibrated solution with a well-known conductivity value and is used for auto-calibration purposes and to minimize common errors that affect equally measuring and reference conductivity sub-cells (ratio measurement techniques).

The oil-on-water sensor includes a single capacitor whose dielectric is filled with two different liquids: oil and water. A low density material (fluctuant base) must be connected to the upper side of sensor's module in order to assure that the upper capacitor plate is at the liquid surface level.

In order to avoid mutual interference between conductivity and oil-on-water measurements an acrylic separator is used to reduce capacitive connections between both sensors.

The temperature sensor (Omega ON-401-PP) is a precision thermistor with an accuracy of ±0.1 ºC, a resistance value equal to 2252 Ω at T=25 ºC and a maximum temperature rating equal to 100 ºC.

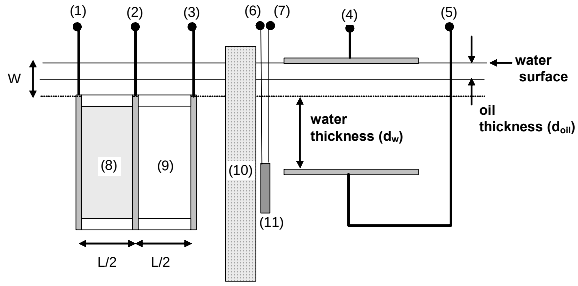

Figure 1. Sensing module: (1)(2)(3)- electrical terminals of conductivity sensor, (4)(5)- electrical terminals of oil-on-water sensor, (6)(7)- electrical terminals of the temperature sensor, (8) reference conductivity sub-cell, (9)- measuring conductivity sub-cell, (10)- acrylic separator, (11)- temperature sensor.

III. Sensors modeling

Theoretical models of each sensor will be presented in this Section to underline its working principle. However, these models are only general approximations of sensors' behavior and measurement results will be obtained using advanced signal processing techniques based on artificial neural networks (ANNs).

A. Oil-on-water sensor

The electrical model of the sensor used for oil-on-water thickness measurement is represented in Figure 2. The equivalent electrical circuit, only considering capacitive effects, is an acceptable approximation due to the low conductivity value of the oil layer and considering that $\omega R_w C_w >> 1$.

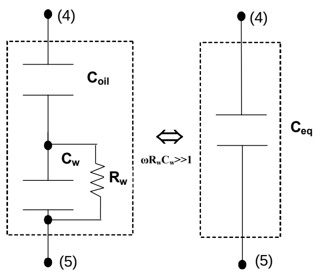

Figure 2. Equivalent electrical circuit of the oil-on-water sensor (C_{eq}- equivalent capacitor).

The equivalent capacitor value (C_{eq}) is then given by:

$$C_{eq} = \frac{S}{\frac{d_{oil}}{\varepsilon_{oil}} + \frac{d_w}{\varepsilon_w}} \tag{1}$$

where d_{oil} and d_w represent the oil-on-water and water thicknesses, and ε_{oil} and ε_w represent the oil and water electrical permittivity values, respectively. Typical values of relative permittivity ($\varepsilon/\varepsilon_0$) for oil and water are between 1.9 and 2.1 and between 80 and 81, respectively, being $\varepsilon_0=8.85\cdot10^{-12}$ F.m^{-1} the vacuum absolute electrical permittivity.
Expression (1) represents a non-linear relation between C_{eq} and d_{oil}, which means that a non-linear relationship between the capacitive value (C_{eq}) and the measurement variable (d_{oil}) exists even when non-linear effects, like the ones caused by temperature variations, are considered.

B. Conductivity sensor

The electrical model of the sensor used for conductivity measurements is represented in Figure 3. In this case, the equivalent electrical circuit, only considering resistive effects, is an acceptable approximation due to the high conductivity value of water. Assuming that the testing frequency is low ($\omega R_w C_w << 1$) the capacitive effects of the cell are negligible.

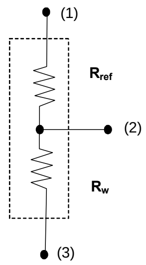

Figure 3. Equivalent electrical circuit of the conductivity sensor (R_{ref}- reference resistance, R_w- water resistance).

In this case, the ratio between resistance values is given by:

$$\frac{R_w}{R_{ref}} = \frac{\sigma_{ref}}{\sigma_w} \cdot \frac{k_w}{k_{ref}} \tag{2}$$

where σ_{ref} and σ_w represent the reference and water conductivity values and k_{ref} and k_w represent the correspondent geometrical factors for each sub-cell whose ratio is theoretically unitary:

$$\frac{k_w}{k_{ref}} = \frac{S_{ref}}{S_w} \cdot \frac{L_w}{L_{ref}} = 1 \tag{3}$$

It is also important to refer that the considered equivalent model is valid as long as capacitive effects, always present, are very small compared to resistive effects. To minimize polarization of the cell and double layer effects conductivity measurements are performed with alternate voltage or current sources. In our case the working frequency used for conductivity measurements is equal to 12.5 kHz being the modeling error lower than 1% of full-scale measuring range.

C. Temperature sensor

The electrical model of the thermistor used for temperature measurements can be expressed by the following relationship:

$$R(T) = R_0 \cdot e^{B\left(\frac{1}{T} - \frac{1}{T_0}\right)} \tag{4}$$

where R(T) is the resistance for a given temperature (T) and R_0 is the resistance for the reference temperature (T_0). The coefficient B is the characteristic temperature of the thermistor and depends on its building material. Figure 4 represents experimental and modeled data of the Omega ON-401-PP thermistor. The coefficient B, obtained by using a least mean square minimization algorithm (MATLAB function fmins), is equal to 3870.4 ºK and the maximum relative deviation between modeled data and experimental results is equal to 0.24 %.

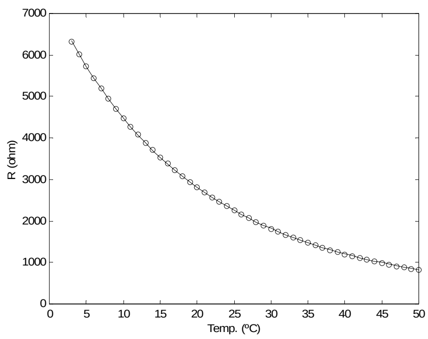

Figure 4. Thermistor characteristic for a temperature variation between 3ºC and 50 ºC.

IV. Conditioning circuit and signal processing

A. Conditioning circuit

Signal conditioning circuit is based on an Universal Transducer Interface (UTI) [9] whose main characteristics are: measurement of multiple sensor types, resolution and accuracy up to 16 bits, continuous auto-calibration of offset and gain, PWM output signal compatible with most microcontrollers, suppression of 50/60 Hz interference, power down mode and a large temperature operating range, between -30ºC and 70 ºC. Figure 5 represents the internal block diagram of the UTI whose main elements include: an input multiplexer, an amplitude current-voltage divider, a voltage to period converter, a frequency divider and a logic control circuit.

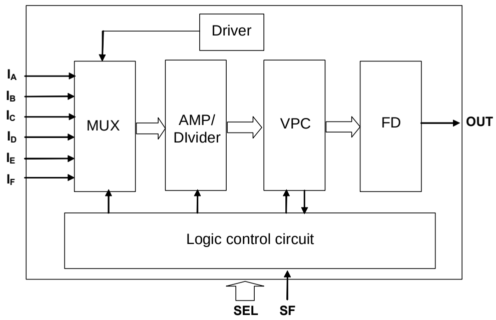

Figure 5. Internal block diagram of the UTI integrated circuit (MUX- multiplexer, VPC- voltage to period converter, FD- frequency divider, I_i- sensor connections, OUT- output, SEL- selection bus, SF- slow/fast mode selection pin).

The selection bus, connected to a microcontroller, contains 4 lines that are used to select one of the 16 operating modes of the UTI. For the oil-on-water measurement the operating mode 4 is selected (SEL_{1234}=0100). In this mode, capacitive elements up to 300 pF with a common electrode can be measured. The measurement range (0-100 pF) was set above the maximum expected capacitive value, obtained for d_{oil}=0, and the extra capacitive terminals were connected to a pair of reference capacitors, C_{reff1}=10 pF and C_{reff2}=100 pF, respectively. The slow-fast mode pin (SF) is used to adjust testing frequency for capacitive (fast mode) and conductive (slow mode) measurements.

For the conductivity and temperature measurements the operating modes 5 and 6 of the UTI are selected, respectively (SEL_{1234}=0101/0110). In these modes, a ratio measurement of resistive values is performed and used to obtain water conductivity value (2) and temperature. Figure 6 represents sensors connections for each measurement mode.

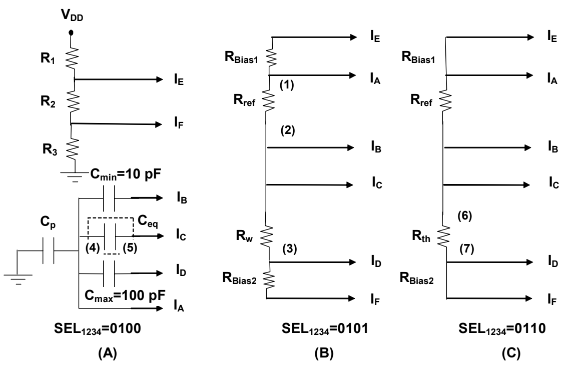

Figure 6. Sensors connections: (A) oil-on-water measurement, (B) water conductivity measurement, (C) temperature measurement ($R_{1,2,3}$- measurement range adjustment of capacitive measurements, C_P- cable parasitic capacitance, I_i- UTI sensors connections, R_{th}- thermistor resistance).

A switch block based on Siemens V23100 reed relays, driven by a microcontroller (PIC16F877) digital input-output port (PORTB) is used to select sensors connections.

The electrical driver signal for the sensing elements, generated by the driver sub-block, is chopped at ¼ of the modulator frequency (50 kHz). This type of exciting signals has three main advantages: reduction of low-frequency disturbing signals coming from power supply, cancellation of parasitic thermocouple junction effects and reduction of polarization errors associated with the conductive cell measurements.

A programmable interface controller (PIC[10]) is used to acquire and process the output voltage signal from the UTI. The use of a PIC is particularly efficient for frequency and duty-cycle modulated signals. One of the main advantages of the proposed signal processing solution include: easy analogue-to-digital conversion, low-cost, low-power consumption (power-down mode) and enough processing capabilities for sensors' data processing [11-12].

B. Signal processing

The main signal processing tasks performed by the microcontroller include time measurement of the output signal driven by the UTI, offset and gain errors compensation, and evaluation of oil-on-water thickness and water conductivity. The output signal of the UTI is a three-phase periodic modulated signal. During the first phase, the offset of the overall system is measured (T_{off}). In the second phase, a reference element, generally associated with full-scale amplitude (FS), is used to obtain the reference period value, T_{FS}. Finally, during the last phase, the signal itself is measured (T_x). All these phases are automatically controlled by the UTI. After each measurement cycle the offset and gain compensated variables are given by:

$$X_c = \frac{N_x - N_{off}}{N_{FS} - N_{off}} \cdot FS_x \qquad (5)$$

where X_c represents the offset and gain compensated measurement, N_{off}, N_{FS} and N_x, represent the number of PIC internal clock cycles contained in T_{off}, T_{FS} and T_x, periods, respectively.

Compensation of temperature effects in conductivity and oil-on-water thickness measurements are obtained using ANN structures whose weights and biases are previously evaluated during ANN training phase. The ANN architecture, represented in Figure 7, includes two identical modules with the following main characteristics: multiplayer perceptron type (MLP), 3 layers (input, hidden and output layers), hyperbolic tangent sigmoid activation function for the hidden layer neurons and linear activation function for the output neuron of each ANN.

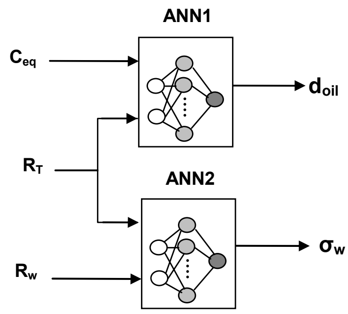

Figure 7. ANN block diagram.

The structure of each ANN includes two inputs and one output and a number of hidden layer neurons optimized to reduce the testing set error during the ANN training phase. The input values of the ANNs are the normalized amplitudes of the compensated parameters (5) delivered by the conductivity, oil-on-water and temperature transducers (R_w, C_{eq} and T) and the output values of ANN1 and ANN2 are the temperature compensated values of oil-on-water thickness and water conductivity, d_{oil} and σ_w, respectively .

V. Experimental results

In order to evaluate the performance of the measurement system, several measurements of oil-on-water thickness and water conductivity for different temperature values were performed. The temperature values were included in the [5,25] ºC interval, the oil-on-water thickness varied between 0 and L/2 (3 cm) and a set of conductivity standards (KCl standards with ±1% accuracy at 25 °C from Oakton) with conductivity values equal to {84, 447, 1500, 2764, 80000} uS/cm were used to collect data for the ANN training phase.

An impedance meter [13] with GPIB interface and a commercial conductivity probe [14] were also used to verify the measured data obtained with the UTI. For the oil-on-water tests it was used a mineral oil (Technol US 3000P) with the following electrical characteristics: dielectric losses (tg δ) lower than 0.15 %, resistivity at 100 ºC higher than 10^{14} Ω and a relative electrical permittivity in the range 2.2±0.1. Figure 8 represents the experimental impedance values of the oil-on-water sensor when the frequency varies between 1 kHz and 100 kHz. The minimum equivalent capacitive value (C_{eq}), associated with d_{oil}=L/2, is equal to 8.46 pF and the maximum relative deviation between modeled data, presented in Section 3A, and experimental data is 0.58 %.

Results of ANN1 training are also presented in Figure 8. The training set includes 124 measurements of C_{eq} and T for oil-on-water thicknesses in the range 0,L/2 (3 cm) and temperature values equal to {15, 20, 25, 30} ºC. The relative errors of oil-on-water thickness measurements obtained for a testing set with 31 measurements are lower than 0.25 %.

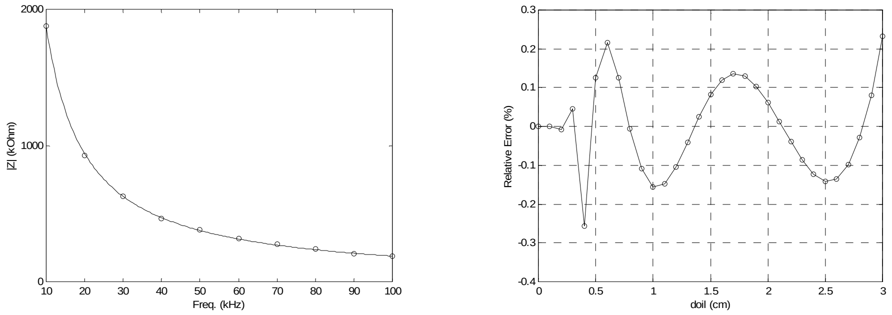

Figure 8. Experimental results: (a) impedance values of the oil-on-water sensor when frequency varies between 10 kHz and 100 kHz (d_{oil}=L/2), (b) ANN relative errors associated with the testing set for the oil-on-water sensor.

VI. Conclusion

The paper presents a smart measurement system that can be used for oil-on-water and water conductivity measurements. The main applications of the proposed measurement system can be found in industrial environments (e.g. wastewater-treatment processes) or in water quality monitoring of rivers or estuaries.

The multiplexed solution used for signal conditioning together with the flexible characteristics of the UTI circuit and associated PIC enables a compact and robust solution for data acquisition. Signal transmission between the UTI and the microcontroller uses PWM modulated signals that are particularly adapted for an easy analogue-to-digital conversion.

The measurement system also assures a low sensitivity to external noise and resistive attenuation of the transmission paths. The proposed modulation technique enables two different measurement parameters, oil-on-water thickness and water conductivity, to be transmitted over a single pair of wires. Usage of ANN signal processing techniques seems to be an adequate choice in the present case due to the multiple non-linear effects caused by frequency variation, double layer effects and temperature influence, among others.

Acknowledgements

The present work was supported by Portuguese Science and Technology Foundation (FCT) PRAXIS XXI program, FCT/BPD/2203/99 and also by FCT Project PNAT/1999/EEI/15052.

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