Abstract: - Changes of salinity in a water medium can generate important damages in flora and fauna. Salinity can also provoke material damages as corrosion or deterioration of instruments. Water salinity is directly related to the conductivity. When a liquid contains dissolved salts, the amount of ions in the medium increases. In this situation, if a magnetic field is located in the medium, its magnitudes will be affected by the ions movements. In this paper, we are going to present a practical study which compares four models based on two coils in order to measure the water conductivity. Our test bench includes several samples of salty dissolutions from which we will extract the output voltage registered in the induced coil. As we will see, there are some combinations of coils that present better sensitivity than others when differentiating the conductivity of a liquid. We will determine in this paper what the best combination of coils is to implement low cost conductivity sensors.

Key-Words: - Conductivity sensor, inductive coils, solenoid, toroid, magnetic field.

1 Introduction

The conductivity measurement is very important factor in several areas such as, oceanography, agriculture, aquaculture or industry. The spatial and temporal monitoring of this parameter can be an important factor to prevent possible damages in fauna and flora or material damages. In some cases, it is necessary a great number of sensors to perform a correct monitoring. When high spatial resolution is required, the number of sensors should be calculated according to the needs of the installation and their purpose. The increase of the number of sensors entails major installation cost. If we want to extend the use of these devices in wireless sensor networks for monitoring, for example, industrial processes [1], we need to develop more economic sensors maintaining the required quality and accuracy [2].

The most conductivity sensors are based on the measurement of an electric signal trough a liquid. We can also find sensors based on the alteration of a magnetic field. Sensors based on electromagnetic fields can be isolated from the samples of water which are sensed. This avoids the sensor degradation due to the negative effects such as foiling, abrasive effects of suspended solids or corrosive environments. This is possible because, this kind of sensors can be put inside a capsule without disturbing the flow of electromagnetic field. In one of our previous papers [2], we proposed two conductivity sensors based on the alteration of magnetic field by the ions presents in water. In one of them, we measured the output signal in an induced coil. The results were promising and for this reason, we wanted to improve these studies.

In this paper, we are going to perform a comparative analysis of four models composed by 2 coils. Our main goal is to check what combination of coils offers the best results and sensitive. We will also extract the best working frequency and the relation between conductivity and the output signal of our models.

The rest of paper is structures as follows. Section 2 shows some previous works where authors use coils to measure the conductivity of a fluid. The models used in our test bench are presented in Section 3. Section 4 presents the results of our tests. After that, we compare the best result of four models in Section 5. Finally, Section 6 exposes our conclusion and future works.
water conductivity using coils [2]. In order to be able to perform all of these measurements, it is important to characterize the coils and their interaction with the medium.

We can find several papers where authors try to measure the water salinity and conductivity using different kinds of coils. However, it is complicated determining which coil configuration presents better efficiency and results.

A. L. Ribeiro et al. [6] presented an inductive conductivity cell to measure the electrical conductivity of the salty water. The sensor is constructed as a double transformer to be utilized to measure the water salinity in the sea and estuaries. Authors used two toroidal cores provided with one single winding which have equal number of turns. The coils were stacked within a plastic container. The electromotive forces developed in the water give rise to electrical currents which act as the secondary currents of one transformer and the primary currents of the other. The intensity of these currents is related to the electric conductivity of the medium. Authors used the electric current in the water to provide the magneto motive force necessary to magnetize a second ferromagnetic core, inducing a voltage in the secondary winding which is correlated to the conductivity of the water.

H. M. Geirinhas et al. presented in [7] a four electrode cell without metallic grids on the tops for water quality monitoring in estuaries and oceans. It is formed by a plastic tube, with two ring-shaped electrodes inside, and two metallic tips to measure the output voltage. Authors were also carried out the experimental characterization of the cell versus frequency, temperature and salt concentration. As results show, the temperature is not an influent factor in the conductivity measurements and the geometry of conductivity cell was found as an independent factor for conductivity measurements.

S. P. Natarajan et al. measured the fluid conductivity using the radio frequency (RF) phase detection. [8]. The sensor is formed from two 1.5 mm thick toroidal coils of area 1 sq. inch and a separation between them of 3mm. The feed coil and the sense coil are connected to the sensor electronics using phase stable RF cables. One of the coils is fed with an input RF signal of known frequency while the second coil acts as a sensing coil and receives the coupled signal. Authors calculated the conductivity by converting a phase change between two signals to an output voltage. The results show that it is possible to define four lineal ranges which as a function of the conductivity fluid.

Finally, H. Cui et al. presented in [9] an inductive level sensor based on a cylinder vessel wound by electric coils outside with magnetic fluid. In this case, authors used this sensor for detecting level and small inclination angles against horizontal plane. The composition of this sensor allows magnetic fluid used as a variable inductance core to detect level and small tilt of a body against horizontal plane. Authors analyzed the operation of their sensor depending on different pumping frequency. They concluded that the sensitivity of this level sensor is proportional with magnetic susceptibility of magnetic fluid, with the peak current as well as with the pumping frequency through the driving coil. They added that the sensitivity of this level sensor is independent with the value of tilting angle against horizontal plane.

As far we known, there is no works which analyze different coil configurations to measure the water conductivity. For this reason, we cannot define the best configuration for our conductivity sensor.

3 Laboratory assays
In order to check what coil configuration present the best performance, we have used different sensor models formed by two coils. In this section, we are going to present 4 models. Each model has been physically characterized taking into account its size, number of spires, diameter of enameled copper wire and kind of coil.

3.1 Description of coils models
When a wire conducts an electric current, it is generated a magnetic field wrapped around the cable. Furthermore, when a cable is introduced into a magnetic field, the wire begins to conduct an induced electric current.

All models are formed by two coils where the coil with lowest number of spires is powered by a sine wave of 8Volts peak to peak amplitude. This coil induces a current on the second coil. The output voltage is proportional to the magnetic field interaction with the fluid of the medium. The magnetic field is affected by the amount of dissolved salts in the liquid. Table 1 shows the models used in our tests and their features.

3.2 Testbench
To perform our test, we have prepared 5 dissolutions with different amount of dissolved salts. In order to prepare our samples, we have use common salt (NaCl) and tap water. Table 2 shows the value of TDS and the conductivity of each sample (measured with a calibrated device).
Table 1: Models of coils used in our tests.

<table>
<thead>
<tr>
<th>Model</th>
<th>Powered Coil</th>
<th>Features of Powered Coil</th>
<th>Induced Coil</th>
<th>Features of Induced Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solenoid</td>
<td>- Wire Diam.: 0.6 mm</td>
<td>Solenoid</td>
<td>- Wire Diam.: 0.6 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Coil Diam.: 29.6 mm</td>
<td></td>
<td>- Coil Diam.: 29.6 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Coil High: 13.8 mm</td>
<td></td>
<td>- Coil High: 27 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Nº of Spires: 21</td>
<td></td>
<td>- Nº of Spires: 45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Core: Nonferrous</td>
<td></td>
<td>- Core: Nonferrous</td>
</tr>
<tr>
<td>2</td>
<td>Toroid</td>
<td>- Wire Diam.: 0.4 mm</td>
<td>Toroid</td>
<td>- Wire Diam.: 0.4 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Inner Coil Diam.: 19.6 mm</td>
<td></td>
<td>- Inner Coil Diam.: 39.8 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Outer Coil Diam.: 26.4 mm</td>
<td></td>
<td>- Outer Coil Diam.: 51.2 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Coil High: 24.9 mm</td>
<td></td>
<td>- Coil High: 24.9 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Nº of Spires: 77</td>
<td></td>
<td>- Nº of Spires: 304</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Core: Nonferrous</td>
<td></td>
<td>- Core: Nonferrous</td>
</tr>
<tr>
<td>3</td>
<td>Solenoid</td>
<td>- Wire Diam.: 0.6 mm</td>
<td>Toroid</td>
<td>- Wire Diam.: 0.8 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Coil Diam.: 27.2 mm</td>
<td></td>
<td>- Inner Coil Diam.: 30.6 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Coil High: 17.8 mm</td>
<td></td>
<td>- Outer Coil Diam.: 44.7 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Nº of Spires: 31</td>
<td></td>
<td>- Coil High: 22.3 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Core: Nonferrous</td>
<td></td>
<td>- Nº of Spires: 132</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Core: Nonferrous</td>
</tr>
<tr>
<td>4</td>
<td>Toroid</td>
<td>- Wire Diam.: 0.8 mm</td>
<td>Solenoid</td>
<td>- Wire Diam.: 0.8 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Inner Coil Diam.: 23.2 mm</td>
<td></td>
<td>- Inner Coil Diam.: 25.3 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Outer Coil Diam.: 56.5 mm</td>
<td></td>
<td>- Outer Coil Diam.: 33.6 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Coil High: 26.9 mm</td>
<td></td>
<td>- Coil High: 22.6 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Nº of Spires: 81</td>
<td></td>
<td>- Nº of Spires: 324</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Core: Nonferrous</td>
<td></td>
<td>distributed in 9 layers.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Core: Nonferrous</td>
</tr>
</tbody>
</table>

Table 2: Samples used in testbech

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of added salt (mg/l)</td>
<td>254</td>
<td>4020</td>
<td>2340</td>
<td>40200</td>
<td>57700</td>
</tr>
<tr>
<td>Conductivity (mS/cm)</td>
<td>0.597</td>
<td>6.28</td>
<td>36.6</td>
<td>62.9</td>
<td>90.2</td>
</tr>
</tbody>
</table>

The first sample which present lowest conductivity corresponds to the tap water. These samples include the conductivity values of freshwater and seawater.

Each model is submerged in the five dissolutions starting with the sample of lowest conductivity. The vessels which contain the dissolutions have a height of 14 cm., but the liquid level is 7.5 cm. The containers have a diameter of 7.9 cm. In all cases the coils are entirely covered by the dissolution.

For each model and sample, we are going to perform a frequency scan between 0.1KHz to 800 KHz. because in this range we detect at least a point in the frequency range where we can measure the water conductivity. The third model is measured for a range of 0.1 kHz to 2000 kHz. The water temperature was 23.2°C.

The results of our test will be a voltage value proportional to the current induced in the second coil due to the interaction of the magnetic field with the aqueous medium. From our results, we will be able to determine the best working frequency for each configuration and if it is possible to define a lineal working range. The best working frequency will be that which present higher differences in output voltage for each sample. From the results of each model, we will extract the mathematical expression which will relate the conductivity and the output voltage.

4 Measurements results

This section presents the measurement results for our four models. On the one hand, we are going to show the behavior of each model as a function of frequency. After that, we will analyze the relation between water conductivity and output voltage for each model for the frequency of best results.

4.1 Frequency scanning

The first model presents similar values of output voltage depending on the frequency. For frequency range of 400 kHz to 600 kHz, this coils combination present different output voltage as a function of
water conductivity. The frequency with highest differences between samples is 500 kHz where we have registered 1.5 V for water with lowest conductivity and 21 V for the sample with the highest concentration of salt. The behavior of first model is shown in Fig. 1.

Fig. 2 shows the output voltage for second model as a function of frequency. In this case, the value of output voltage (in the induced coil) decreases when the water conductivity increases. In addition, we can see that the output voltage is very similar for water with any salt concentration.

Finally, this model does not present any significative peak in the signal behavior. The optimal frequency for second model is registered at 500 kHz where we can distinguish between salt water and freshwater.

The third model combines a solenoid and a toroid. This model shows significant results at high frequencies (2000 kHz). In medium and lower frequencies, the registered behavior is very irregular. It starts to be estable for frequencies from 1750 kHz. Fig. 3 shows the behavior for third model.

Last model presents two frequencies which can be used for measuring the water conductivity. The first one is registered at 150 kHz with output voltages of 0.65 V for tap water and 4.1 V for water with highest conductivity. Fig. 4 shows the measurement results for fourth model.

4.2 Optimal working frequencies

Once we have found the best working frequency for each model, we can analyze the operation of each model showing their response in volts as a function of the water conductivity.

In order to analyze the relation of conductivity and output voltage, we are going to take into account two factors:

- Correlation between conductivity and output voltage registered in the induced coil.
- Slope in the lineal range.
- If there is a lineal working range.

We are only going to consider a lineal range when, at least, 4 point are contained in this range and the value of correlation coefficient is higher than 0.95.

For first model, we have analyzed the relation between output voltage and water conductivity at 500 kHz (See Fig. 5). We can use (1) to model its behavior. Model 1 presents a correlation coefficient of 0.9903.

\[
V_{out} = 4.653 \cdot \log (0.9833 + C) \quad (1)
\]

Where \(V_{out}\) is the output voltage induced in the second coil in Volts and C represents the water conductivity in mS/cm.

As we can see in Fig. 5, the lineal range of this model is not clear. The behavior of this combination of coils fits to a logarithmic function and we do not have enough points to approximate this behavior to a lineal range with enough accuracy.
Fig. 5. Relation between water conductivity and output voltage for Model 1 at 500kHz.

Fig. 6. Relation between water conductivity and output voltage for Model 2 at 500kHz.

Fig. 7. Relation between water conductivity and output voltage for Model 3 at 2000kHz.

Fig. 8. Relation between water conductivity and voltage registered in the Model 4 at 150kHz.

Fig. 6 shows the relation of output voltage as a function of the water conductivity for Model 2. Eq. \( (2) \) represents the mathematical model for this configuration of coils.

\[ V_{out} = 2.446 \cdot C^{-0.3877} \]  \( (2) \)

Where \( V_{out} \) is the output voltage induced in the second coil in Volts and \( C \) represents the water conductivity in mS/cm. The correlation coefficient for \( (2) \) is 0.9952.

The third model shows a linear behavior at 2000 kHz (See Fig. 7). In this case, the relation between induced output voltage (V) and conductivity (mS/cm) can be expressed as \( (3) \) where the correlation coefficient is 0.9826.

\[ V_{out} = 0.0324 \cdot C + 2.2675 \]  \( (3) \)

Finally, Fig. 8 shows that Model 4 presents a clear linear behavior from 6.28 mS/cm to 90.2mS/cm. Eq. \( (4) \) show its mathematical expression where \( V_{out} \) is the output voltage induced in the second coil in Volts and \( C \) represents the water conductivity in mS/cm. The correlation coefficient for \( (4) \) is 0.9888

\[ V_{out} = 0.013 \cdot C + 2.9637 \]  \( (4) \)

5 Comparison of models

As previous sections show, it is possible to use several combinations of coils to measure the water conductivity. However, Section 4 has shown that some combinations of coils present better performance to measure this parameter. In this section, we are going to compare the results of four models that we have tested. We will also discuss about the possible applications of each model.

Table 3 shows a summary of best results shown by each model. As we can see, each coil presents different behavior. On the one hand, Model 3 and Model 4 have a linear working range. A low value of slope means that a high variation in the conductivity value generates high variations in the output voltage in the induced coil. The linear range of Model 3 presents higher slope than the one offered by Model 4. However, the optimal frequency for Model 3 is 2000 kHz meanwhile the fourth model places its optimal frequency in 150 kHz. This would be the best option because the cost (economical and energetic) of a prototype with lower frequency is lower. Model 1 does not have any linear working range but we can approximate its operation as 3 linear working ranges as a function of conductivity. Finally, Model 2 can also be approximated by 3 linear working ranges. The specific applications for this model must be focused for freshwaters areas because at higher values of conductivity, we cannot define a correct value of voltage.
6 Conclusion

In this paper, we have analyzed 4 configurations of coils to measure the water conductivity. These models combine toroids and solenoids with nonferrous cores. As our measures show, models which present best results are Model 1, Model 3 and Model 4. Previous works have shown other coils combinations. All of them are coils located one after another. But, we have also checked configurations of coils which contains other coils. Finally, we have not used ferrous cores although these avoid the expansion of magnetic field. Nonferrous cores are more susceptible to magnetic interferences but allow greater frequency range and higher sensitivity. But in future works, we want to include them. In future works, we want to focus our efforts in improving the tests of Model 4 because it presents the lowest working frequency. In addition, we would like to integrate it to implement a low cost conductivity sensor. We want also include an analysis of temperature dependence and if the flow of liquid through the coils can improve the measurements.

Finally, we also want to adapt our system to measure the salinity in marine fish farms where where abrupt changes in any parameter could mean the death of animals [10].

Acknowledgements

This work has been partially supported by the “Ministerio de Ciencia e Innovación”, through the “Plan Nacional de I+D+i 2008–2011” in the “Subprograma de Proyectos de Investigación Fundamental”, project TEC2011-27516, and by the Polytechnic University of Valencia, though the PAID-05-12 multidisciplinary projects.

References:


Table 3. Comparative of best results for four models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Linear range (mS/cm)</th>
<th>Slope</th>
<th>Optimal frequency (kHz)</th>
<th>Detect plume of rivers in the sea</th>
<th>Control of saline wedge</th>
<th>Control of irrigation water</th>
<th>Little variations of salt in the sea water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>-</td>
<td>-</td>
<td>500</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Model 2</td>
<td>-</td>
<td>-</td>
<td>500</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Model 3</td>
<td>0.397 - 90.2</td>
<td>0.0324</td>
<td>2000</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Model 4</td>
<td>6.28 - 90.2</td>
<td>0.013</td>
<td>150</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Possible Applications

- Detect plume of rivers in the sea
- Control of saline wedge
- Control of irrigation water
- Little variations of salt in the sea water