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“Design and development of a low-cost underwater conductivity sensor”

TRABAJO FINAL DE GRADO

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Abstract:

Water salinity and conductivity values are always required when measurements from the sea water are needed (e.g., for water pollution, in marine fish farms, feeding industry, etc.). They can be measured directly or indirectly. In order to select the best option, three main issues should be taken into account. The first one is the periodic need of calibration because of the system wear, the second one is the cost of the components of the system, which could make to deploy an expensive device, and the third one is the accuracy of the deployed system. The existing sensors are too expensive and have a short lifespan due to the fouling, the abrasive effects caused by the suspended sediments when they are dragged by a water current, even the bites of the fauna. Also the changes of chemical conditions as acidification can cause problems in the majority of commercial sensor. In this project we are going to develop a conductivity meter able to take measure in water environments that avoid all the problems described.

Attending to the related works, we realize a first set of tests to select the best methodology to use in our developed sensor. The first one of them is composed by a solenoid and a commercial magnetic field sensor that detects the changes in the magnetic field when different materials are introduced in the center of solenoid. The second one is composed by two overlapped copper coils that, through one of them, are circulating energy, and induce in the other one. The different environments of the coils produce changes in the induced voltage in the second coil.

We decided to continue the test with the option of two copper coils. We performed a practical study comparing four models based on two coils in order to measure the water conductivity. Our test bench included several samples of salty dissolutions from which we extracted the output voltage registered in the induced coil. As we saw, there are some combinations of coils that present better sensitivity than others when differentiating the conductivity of a liquid. Gathered measurements let us determine the best combination of coils in order to implement them in low cost conductivity sensors.

Finally we made an intensive study of the best coils combination in order to determine some characteristics as their lineal ranges, using more than 30 calibrating points, the sensibility, the maximum value than can be measured. We also demonstrated that the water volume have an influence on the sensor signal. We also found the minimum volume of water needed to obtain a stable value even if the volume of water increase.

Keywords: electrical conductivity; Hall sensor; inductive coil; magnetic field; conductivity sensor

Resumen:

Los valores de salinidad y conductividad del agua son siempre importantes cuando se necesitan mediciones del agua de mar (por ejemplo, en la contaminación del agua, en las granjas de peces marinos, la industria de alimentación, etc.) Estos valores se pueden medir directamente o indirectamente. Con el fin de seleccionar la mejor opción, se tienen que tener en cuenta tres cuestiones principales. La primera de ellas es la necesidad periódica de calibración debido a la desgaste del sistema, la segunda es el coste de los componentes del sistema, lo que podría hacer despegar el precio del dispositivo, y la tercera es la precisión del sensor desarrollado. Los sensores actuales son demasiado caros y tienen una vida útil corta debido al fouling, los efectos abrasivos causados por los sedimentos en suspensión cuando son arrastrados por una corriente de agua y hasta los mordiscos por la fauna. También los cambios de las condiciones químicas como la acidificación pueden causar problemas en la mayoría de sensores comerciales. En este proyecto vamos a desarrollar un sensor de conductividad capaz de tomar medidas en ambientes acuáticos que pueda evitar todos los problemas descritos.

Atendiendo a las obras relacionadas realizamos una primera serie de ensayos para elegir la mejor metodología a utilizar en el desarrollo de nuestro sensor. La primera, compuesta por un solenoide y un sensor de campo magnético comercial que detecta los cambios en el campo magnético cuando se introducen los diferentes materiales en el centro de solenoide. La segunda, compuesta por dos bobinas de cobre superpuestas que, a través de una de ellas, circulan energía y inducen en la otra. Los diferentes entornos de las bobinas producen cambios en la tensión inducida en la segunda bobina.

Como decidimos continuar la prueba con la opción de dos bobinas de cobre, realizamos un estudio práctico que compara cuatro modelos con dos bobinas, con el fin de medir la conductividad del agua. Nuestro banco de pruebas incluyó varias muestras de disoluciones salinas de donde se extrajo el voltaje de salida registrado en la bobina inducida. Como vimos, hay algunas combinaciones de bobinas que presentan una mejor sensibilidad que otros cuando la diferenciación de la conductividad de un líquido. Las medidas nos han permitido determinar cuál es la mejor combinación de bobinas con el fin de implementarlo en sensores de conductividad de bajo costo.

Finalmente realizamos un estudio intensivo de la mejor combinación de bobinas. Determinamos algunas características como sus rangos lineales, con más de 30 puntos de calibración, su sensibilidad, y el valor máximo que puede medir. También hemos demostrado que el volumen de agua tiene una influencia en la señal del sensor. Y encontramos que el volumen mínimo de agua necesario para obtener un valor estable, incluso si el volumen de agua aumenta.

Palabras clave: conductividad eléctrica; sensor Hall; bobina de inducción; campo magnético; sensor de conductividad

Resum:

Els valors de salinitat i conductivitat de l'aigua són sempre importants quan es necessiten mesuraments de l'aigua de mar (per exemple, en la contaminació de l'aigua, a les granges de peixos marins, la indústria d'alimentació, etc.) Aquests valors es poden mesurar directament o indirectament. Per tal de seleccionar la millor opció, s'han de tenir en compte tres qüestions principals. La primera d'elles és la necessitat periòdica de calibratge a causa de la desgast del sistema, la segona és el cost dels components del sistema, el que podria fer enlairase el preu del dispositiu, i la tercera és la precisió del sensor desenvolupat. Els sensors actuals són massa cars i tenen una vida útil curta a causa del fouling, els efectes abrasius causats pels sediments en suspensió quan són arrossegats per un corrent d'aigua i fins les mossegades per la fauna. També els canvis de les condicions químiques com l'acidificació poden causar problemes en la majoria de sensors comercials. En aquest projecte anem a desenvolupar un sensor de conductivitat capaç de prendre mesures en ambients aquàtics que pugui evitar tots els problemes descrits.

Atenent a les obres relacionades vam realitzar una primera sèrie d'assajos per triar la millor metodologia a utilitzar en el desenvolupament del nostre sensor. La primera, composta per un solenoide i un sensor de camp magnètic comercial que detecta els canvis en el camp magnètic quan s'introdueixen els diferents materials al centre de solenoide. La segona, composta per dos bobines de coure superposades que, a través d'una d'elles, circulen energia i indueixen en l'altra. Els diferents entorns de les bobines produeixen canvis en la tensió induïda en la segona bobina.

Com se va decidir continuar la prova amb l'opció de dues bobines de coure, realitzem un estudi pràctic que compara quatre models amb dues bobines, per tal de mesurar la conductivitat de l'aigua. El nostre banc de proves inclogué diverses mostres de dissolucions salines d'on es va extreure el voltatge de sortida registrat a la bobina induïda. Com hem vist, hi ha algunes combinacions de bobines que presenten una millor sensibilitat que altres quan la diferenciació de la conductivitat d'un líquid. Les mesures ens permeten determinar quina és la millor combinació de bobines per tal d'implementar en sensors de conductivitat de baix cost.

Finalment realitzem un estudi intensiu de la millor combinació de bobines. Determinem algunes característiques com els seus rangs lineals, amb més de 30 punts de calibratge, la seva sensibilitat, i el valor màxim que pot mesurar. També hem demostrat que el volum d'aigua té una influència en el senyal del sensor. I trobem que el volum mínim d'aigua necessari per obtenir un valor estable, encara que el volum d'aigua augmenta.

Paraules clau: conductivitat elèctrica; sensor Hall; bobina d'inducció; camp magnètic; sensor de conductivitat

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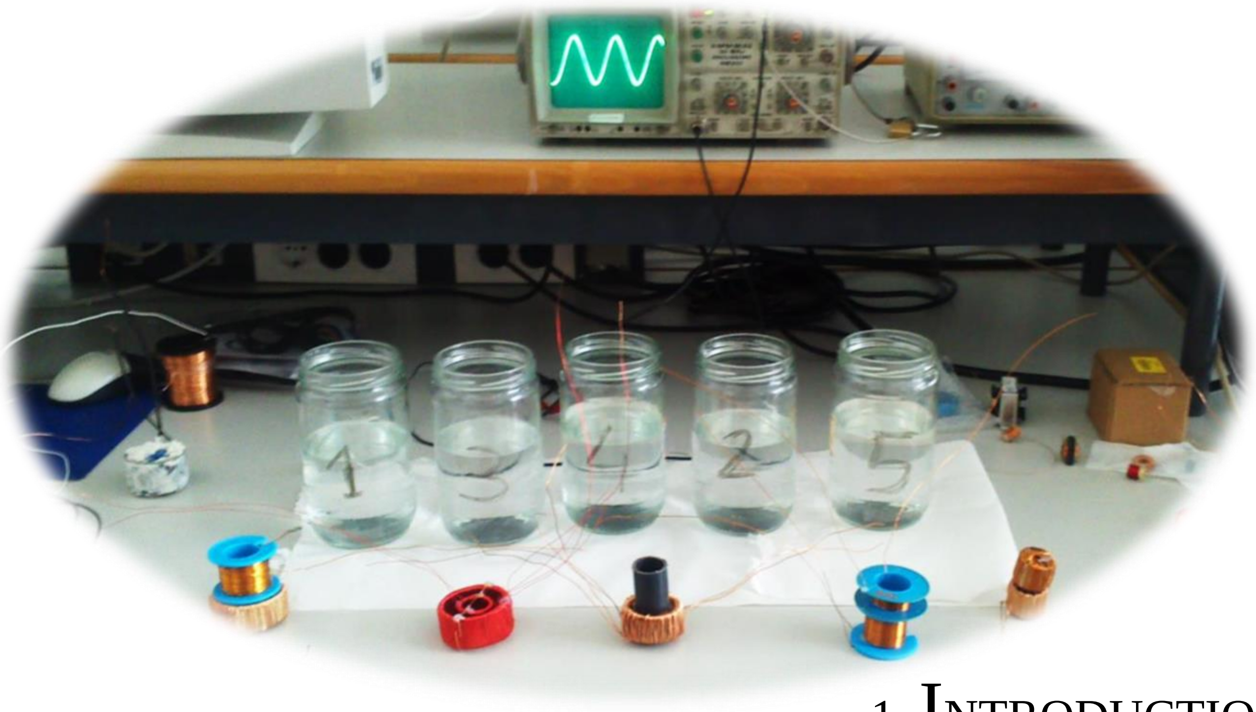


1. INTRODUCTION

1.1. INTRODUCTION

1.1.1. WHAT IS THE ELECTRICAL CONDUCTIVITY AND HOW WE CAN MEASURE IT IN LIQUIDS

The conductivity is defined as the capability of a matter or medium to permit the pass of electricity through it. It is measured in Siemens/centimeter (S/cm) or microhoms/centimeter (μΩ/cm) (USA [1]. Electric conductivity is also defined as the natural property of each body which represents how ease the electrons can pass through it. The electrical conductivity of liquids is related with the presence of salts, which generates positive and negative ions, because they are able to carry electric energy through the solution. Those ions are called electrolytes or electrolytic conductors. The electrical conductivity depends on the temperature of the solution. Because the temperature changes, it can also change the values of the ions, solubility, and solution viscosity among other issues [2].

There are different ways to measure the electrical conductivity of the water. The traditional one is to measure the conductivity or resistance offered by the water. It can also be measured by using diamagnetic and paramagnetic proprieties of the water with different concentration of salty ions. The paramagnetic substances increase the value of the magnetic field. Moreover, the diamagnetic substances drive down the magnetic field. Generally, each material has both kinds of behaviors, but predominates one of them.

The magnetic fields are composed of electrical charges, which react with the environment. Those charges can attract or repel themselves and their behavior depends on the chemical or physical forces of the environment. Electric and magnetic charges represent different aspects of the same event. When there is no electric or magnetic charge, the electron's loads are not agitated. When an attractive force is applied, the electron's loads are agitated and begin to move in the direction of the applied force. In the case of water, its chemical composition determines the effects in the magnetic field. The interaction occurred between the electrical charges and the water molecules can cause that some atoms lose their electrons, those atoms are ionized or charged. As a result, these atoms attempt to recover the missing electrons. The combination of the ionized atoms and the magnetic fields causes the formation of an electric current in the water.

When an electromagnetic field pass through a material or medium, the measurement of the changes of the electromagnetic field can bring information about some of its proprieties. In the water medium, the measurement of electric conductivity can bring information about water quality and the quantity of dissolved salts.

1.1.2. WHEN DO WE NEED TO MEASURE THE ELECTRICAL CONDUCTIVITY?

When we are working with water samples, it is common to take water conductivity measurements for defining the amount of salts dissolved in the water. The measure of electrical conductivity in water samples is very important in so many areas such as water management, agriculture, aquaculture or groundwater supplies.

In the case of agriculture, it is essential to know the salinity of the water used in the irrigation process; because when the soil is irrigated with water that contains high concentration of salts can produce salinization of the irrigated soils in the long term this is called secondary salinization. This salinization can produce that this soils are not productive. It is estimated that 50% of cultivated fields are suffering this kind of salinization [3]. In the case of aquaculture in fresh or sea waters, changes in salinity can cause the death of the cultured species, causing huge economic losses. Moreover, saline intrusion is causing great damages in the groundwater supplies, which would lead to obtain not drinkable waters with the time. Unpolluted fresh water is becoming a limiting resource in some regions, so the saline intrusion in the aquifers of those regions must be controlled to ensure the availability of the water quality.

All these problems can be prevented and corrected using the proper control. Sensor networks, where sensor nodes are sensitive to conductivity changes, can bring an early warning signal, which allows applying the necessary measures to prevent harmful effects. In order to develop this sensor network, the first step is to develop a physical sensor able to measure the conductivity, which must be as cheap as possible, because, for example, to measure the environment of an aquaculture installation many sensors are needed. Low maintenance is also required for the sensors, so the contact between the water and the sensor should be minimized.

If we want to extend the use of these devices in wireless sensor networks for monitoring, for example, industrial processes [4], we need to develop more economic sensors maintaining the required quality and accuracy. 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.

Depending on the area to be monitored and the sensor coverage, the amount of devices to be used can be very high. Existing conductivity sensors are too expensive, so it is not appropriate when using large amount of devices. They also present a short lifetime due to the aggressive environmental factors. A good way to measure the spatial and temporal changes is the use of wireless sensor networks (WSN). These kinds of networks allow us to monitor bigger areas.

1.2. PRECEDINNGS AT EPSG

We have found very few works related with the topic of this project. Next we are going to cite some of them.

In December 2009 Juan Manuel González Legidos, realized a design of a sensor node that measures physico-chemical parameters in underwater environments in his project "DISEÑO E IMPLEMENTACIÓN DE UN NODO SENSOR PARA LA MEDIDA DE PARÁMETROS FÍSICO-QUÍMICOS EN PISCINAS CLIMATIZADAS".

In the Project "DISEÑO E IMPLEMENTACIÓN DE UN SENSOR DE HUMEDAD DE SUELO BASADO EN SENSORES DE CAMPOS MAGNÉTICOS GMR", presented in June 2010, Carlos Bonache Bañuls used the changes in the magnetic field to measure the humidity of the soil

In September 2010, Samuel Renard Montagud presented the project "DISEÑO E IMPLEMENTACIÓN DE UN SISTEMA DETECTOR DE OBJETOS METÁLICOS BASADO EN SENSORES GMR",, which uses the magnetic field to detect metallic objects.

1.3. OBJECTIVES

The main objective of this project is to develop a new conductivity sensor, which must have the following characteristics:

- Cheaper than the current ones
- Minimize the contact between the sensor and the environment
- Reduce the maintenance and the need to continuous calibration
- No need too much high sensibility

The most common conductivity sensors measure the conduction of an electric current through the water. However, there are sensors that use the inductive properties of the water as the alterations of the magnetic field caused by the ions of the water. Bearing in mind this premise we are going to develop a conductivity sensor based on the alterations of the magnetic field. We decide to use this methodology because it covers our needs; we can isolate the sensor from the environment, avoiding any contact between sensor and environment. To develop this sensor we need to choose the best methodology to detect changes on the magnetic field. In order to achieve this goal, we are going to make some tests using two different methodologies, based on a Hall sensor and based on an inductive coil. In both cases, we performed the following tests:

- Measure with different salinity conditions
- Measure at different electric conditions (AC, AD, different frequencies, different voltages)

We observed that the best way to measure the conductivity is using inductive coils. So, we propose these new objectives:

- Select the best electric conditions to realize the measures and find out if each coil has different behavior
    - In order to achieve this goal we realized measures with different coils and different saline samples
- Perform a comparative test with different types of coils
    - Use different coils with different wire diameter, different sizes and different structure
    - Find the best frequency to realize the measures
    - Compare the working range, lineal range and slope of the calibrate done and best frequency
- Characterize the best one of them
    - Perform a better calibration with several points to find the lineal ranges with more accuracy
    - Find the maximum value of conductivity that can measure
    - Find the sensibility of the coil at each lineal range
    - Find out if the volume of the water container have a relation with the sensor signal
- Finally, perform some measures with water samples obtained from the field, with freshwater and sea water

1.4. OUR PROPOSE

If we only want to detect big changes in salinity, for example, when the water change surround the sensor change from freshwater to seawater we do not need to much sensibility. Moreover, in some cases, the most important issue is to reduce the maintenance of the sensor as much as possible and try to eliminate the need for periodic calibration. The goal in these cases is to place the sensor during long periods of time.

The aim of this paper is to develop two new conductivity sensors but with the purpose of having low manufacturing costs and low maintenance cost, which can be applied to different areas. For this we will create a magnetic field and make it pass through the water with different conductivities. It will allow us to detect if the changes in the magnetic field are correlated with the changes of the electrical conductivity.

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 fooling, 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

1.5. STRUCTURE

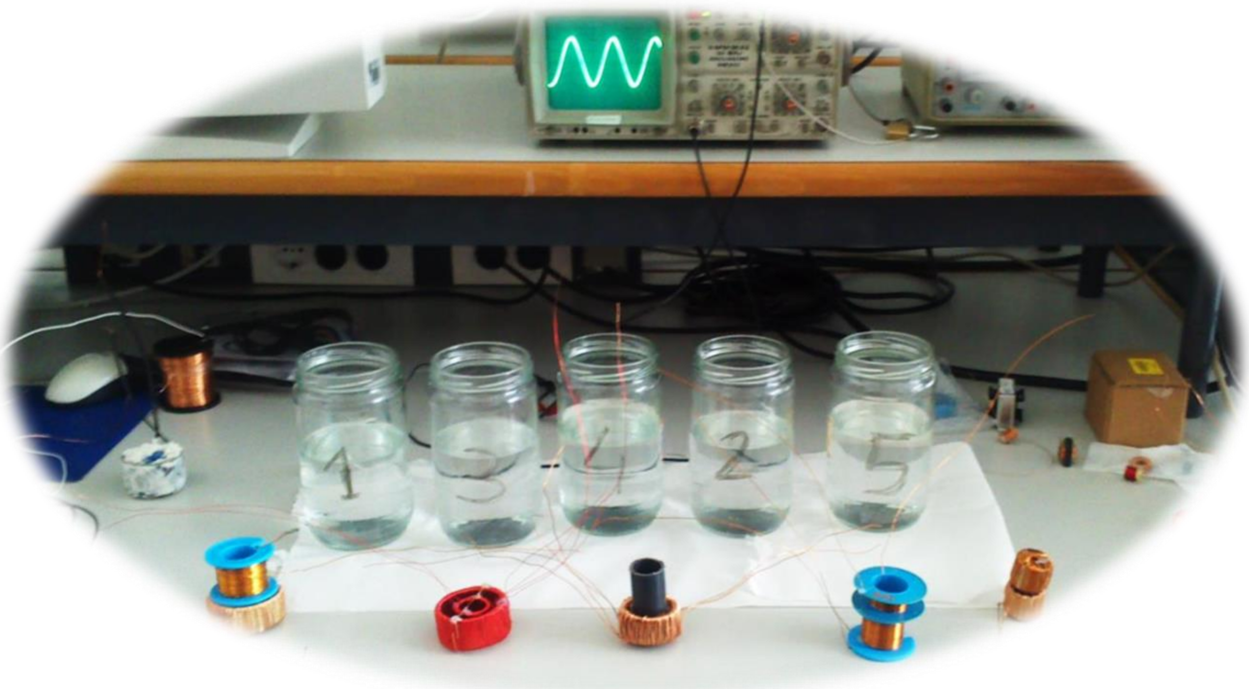
The rest of the memory is structured as follows. In Chapter 2 we show the state of the art of conductivity sensors based on conductive or inductive process. Moreover, we present other application areas where measuring of the magnetic field can be applied. Finally we propose to use the developed sensor in the study of estuarine environments.

Chapter 3 resumes the tests performed for choosing the best methodology to be used in the sensor deployment. The possible use of a Hall sensor to measure directly the magnetic field, or the use of an inductive coil. We perform several measures with different water samples which present different conductivity. We use, in the case of Hall sensor, DC and AC at different frequencies and voltages. In the case of inductive coil, we use different coils where we measure only in AC for different frequencies. Both systems can be used to deploy our sensor. We also realize a comparison of prices between the existing conductivity sensors or conductivity meters and our sensor. However, the tests realized with the Hall sensor presented more problems than the test with inductive coil. So, we decided to use an inductive coil.

We present the comparison of different coil combinations in Chapter 4. We describe the used coils such as power coil or inductive coil with their characteristics. We propose 4 models or combinations. We also perform several analyses using water with different conductivities at AC at different frequencies. This was aimed to ascertain the optimum frequency for each configuration. Later, in this chapter, we compare the calibration line obtained at the best frequency. To close the chapter we present a table that summarizes the values and shows possible applications for each one of the coil combinations.

In Chapter 5 we choose one of the coil configurations used in the previous chapter and make further tests. We analyze the lineal ranges that appear when we represent sensor signal and the water conductivity. We also describe for each range, the mathematic equation that predicts its behavior, the slope, the minimum and maximum values and the sensibility. We also make some tests to ascertain if the volume of water in where the coil is introduced affects to the signal value. Moreover, we perform a verification process using some samples from different points (sea, irrigation channel and tap water). After taking these measurements we find a drift when our sensor takes samples from the field. However, this drift can be corrected using a mathematic equation.

Finally, we present our conclusions and further investigations in Chapter 6.



2. Related work

2.1. DEVELOPMENT OF CONDUCTIVITY METERS

There are some works in the related literature where the authors develop conductivity meters. This section presents a review of those works.

In first place, an example of some work where the authors create a conductivity meter based on the traditional methodology, the pass of an electric current through the water sample.

In 2007, M. Medrano et al. [5] developed their own conductivity meter for liquids with low electrical conductivity (measuring directly the conductivity of the water). The minimum value that they were able to measure was 200pSm^{-1}, with an error of 10%. They measure with different distances between both electrodes (0.5 to 2.5 mm) and different voltages (-10 to 10V). Y. Wei at al. [6] proposed in 2010 a new seawater conductivity sensor (also based on the capacity of water to transmit the electricity), which uses a bipolar pulse to avoid the effect of electrode polarization. They also propose a temperature composition with different formulas for 3 ranges of temperature 1 ºC to 10 ºC, 10 ºC to 20 ºC and 20 ºC to 30 ºC. The sensor is able to self-compensate and self-tuning. H. Ramos et al. [7] created a low cost in-situ four electrode conductivity cells in 2006. It is suitable to take measurements from estuarine waters.

As far as we know, the use of the interaction in the electromagnetic field has not been used to measure the water conductivity yet (at least in the published works). Moreover, there are few papers describing the process that occurs when an electromagnetic field passes through water with different electrical conductivities and how to use it as an electrical conductivity sensor. However, there are some commercial sensors, that use two coils to measure the induction, but they present higher prices.

There are several application fields where it is possible to measure some environmental parameters as a function of magnetic field interaction. We can find works related to astrophysics where magnetic fields are used to characterize stars [8], in medicine where they are used to disease diagnostic [9] or in agriculture to measure the soil electric conductivity [10]. The use of the alteration on the magnetic field used to measure the conductivity is used also in the study of saline soils [11] and [12]. In those works two coils are used, the energy passes though one of them and a charge to the other coil which is induced. The charge on the second coil depends on the salinity of the soil.

In order to be able to perform all needed 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 complicate determining which coil configuration presents better efficiency and results.

A. L. Ribeiro et al. [13] 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 [14] 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 [15]. 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 [16] 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 kwon, 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.

2.2. EXAMPLE OF APPLICATION:

Now we analyze the advantages that can bring the use of the developed sensor in one specific area. Then, we will compare the changes when a new conductivity sensor is introduced.

Estuaries are places where the water conductivity presents big changes along the space and time. They are places where the freshwater of the rivers arrive to the sea. Depending of several factors such as river flow, tidal, wind or river bed, these waters can be mixed. If waters do not mix, it appears a stratification called picnocline. This effect is registered in rivers with large flows like Ebro River [17], in Spain.

In tropical places, the estuaries are important areas because they have a huge biodiversity. They also present some important species like mangroves which grow there. In last years, the decrease of the mangrove is becoming an important research topic. The change of land use, the increasing population, global warming, etc., make rivers to not carry too freshwater. For this reason, in estuaries there is a salt water domain. This generates that some species, which live in mangrove forests and tolerated certain levels of salt, have now many problems to survive. One of the main causes of this decrease is the increase of salinity in the environments where the mangroves grow [18]. So, it is very important to monitor the salinity and its changes in those areas.

Related to this topic, we can find several works where authors measure the water conductivity and the presence of salt in mangrove forests.

K. Kathiresan studied in [18] some parameters such as pH, conductivity, temperature, metals among others, to explain the main causes of the mangrove degradation. He concludes that the most common factors are the high salinity, the low level of available nutrients and poor microbial count.

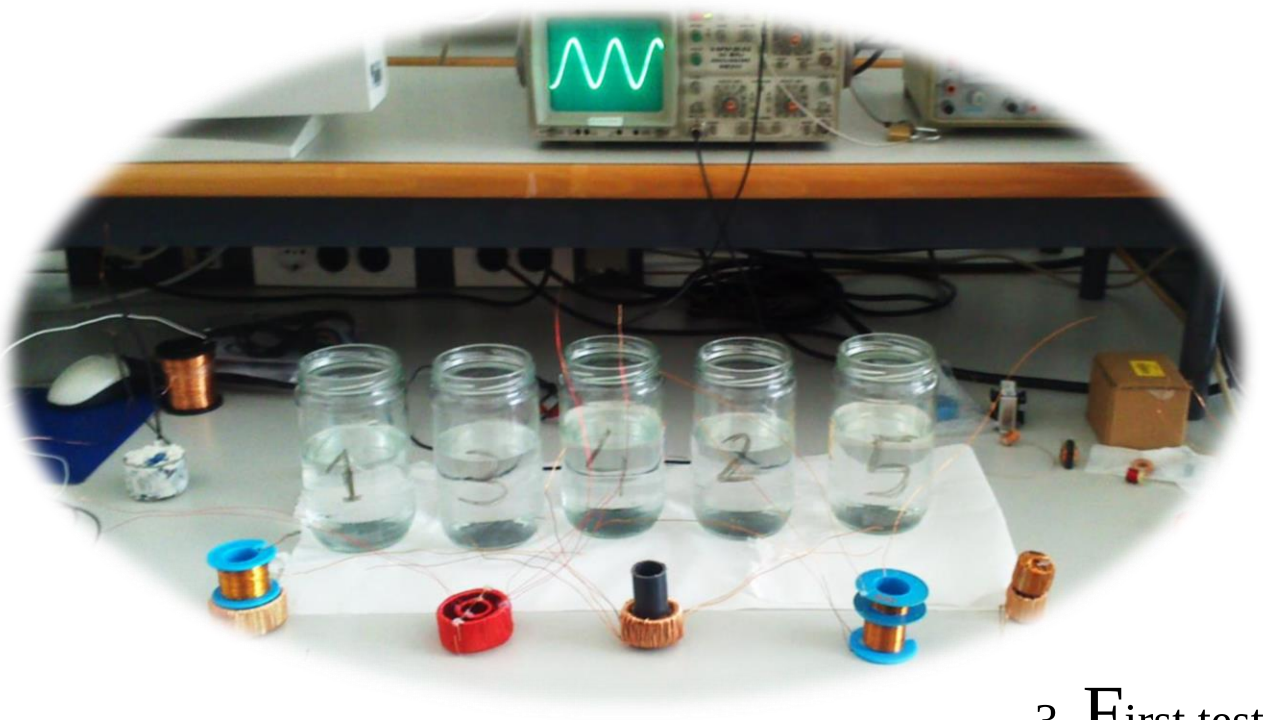
N. Suárez et al. [19] studied the effect of salt in leafs of mangrove specie (*Avicennia germinans*) in Venezuela. Authors highlighted that the high salinity periods had effects on the mangrove leafs. Their laboratory studies revealed that the high salinity in the mangrove leaf generates smaller leafs and reduces the life of plants. This contributes to reduce the plant productivity and the carbon gain.

S. Wakushima et al. [20] took seeds from the Japan mangroves and planted them in saline soils. Their conclusions suggested that growing of mangrove is regulated by the values of salinity and soil pH.

In [21], T. J. Smith worked with two species of mangrove (*Ceriops australis* and *Ceriops decandra*). Both species planted and grew under laboratory conditions changing the salinity and irradiance. They concluded that both parameters are important in the mangrove growth. However, there exist other parameters which are important and authors do not consider them in their laboratory test such as dispersal, competition or hervibory.

In [22], the seeds of *Avicennia marina* are grown in different saline concentration obtained by mixing freshwater and seawater (10, 25, 50, 75 or 100% natural seawater). After 11 month, the result showed that the optimal mixture according to mangrove growths was from 10% to 50% of seawater. The plants which received higher concentrations showed a slow develop and low level in biomass, although their appearance seemed healthy.

Our proposal of possible application is a cheap product that can be used to monitor this ambient. As far we know there is no system deployed to control the water salinity in mangrove forests with the characteristics of the one that we develop (cheap, resistant to the environment and enough sensibility). The results were promising and for this reason, we wanted to develop a conductivity sensor. The economic cost of our device is almost 50% cheaper than the commercial ones. In addition, our sensors can be isolated to protect them from the fooling, the abrasive effects of suspended solids driven by water or attacks from animals.



3. First tests

3.1. INTRODUCTION

In these firsts tests we pretend evaluate the possibility to measure the conductivity though alteration in the magnetic field. Our purpose is to detect changes of the electromagnetic field and relate it with the conductivity of the water where it is passing through. It will let us create an electrical conductivity detector. In both cases the used coils have a solenoid form.

In order to measure the electrical conductivity values, we used a commercial sensor: CM 35+. By using two different methods, we developed two different inductive conductivity sensors. The materials used in these tests are:

- Conductivity meter CM 35+
- Generator of AC
- Generator of DC
- Oscilloscope
- Hall sensor Axial Payme
- Tesalameter Phaywe
- Coil of copper of 0.8mm with empty core
- Coil of copper of 0.8mm coiled overt a plastic tube with empty core
- Copper coils from a current transformer of 0.4mm and a relation of turns of 1:36.66
- 6 assay tubes
- Salt

In these tests we obtain the preliminary data to decide on which method we will base our sensor and continue the study.

3.2. STRUCTURE OF CONDUCTIVITY SENSORS

In this section we are going to describe the structure of the conductivity sensors developed for the first tests. There are two different kinds of sensors, in both cases we generated a magnetic field using a copper solenoid powered by direct current or alternate current. There are two different systems to measure the conductivity. The first one is a sensor is based on the measures of the magnetic field directly through the use of Hall sensor. The second one measures this magnetic camp through the induced current on an inductive copper coil.

3.2.1. BASED ON A HALL SENSOR

For the first method, we prepared an assembly with a solenoid without core that generates the electromagnetic field. In the center of the solenoid, we introduced an assay tube, which is used as container for the water samples. Moreover, in the center of the solenoid (where the magnetic field is higher), inside the assay tube, we inserted a magnetic field sensor. The solenoid was powered by a direct current (DC) generator or connected to an alternative (AC) current trough a transformer from 220V to 12V, depending on the desired output measurements (in Direct Current or Alternating Current). See the explained in Figure 1.

The whole structure was fixed using a laboratory support to assure that when the solenoid and the assay tube are removed (in order to change the solution), the position of the sensor respect to the solenoid is maintained. This is very important, because when the position of the sensor over the centre of the solenoid changes, vary the values of magnetic field. This backing system is useful only for the height and the vertical movement. The horizontal movement has less importance because the width of the assay tube, the centre of the solenoid and the sensor are almost the same and that precluded the horizontal movement.

We prepared a second experience with this system (Hall sensor), a second solenoid without the assay tube, in order to avoid the potential interferences caused by the glass of the assay tube. In this solenoid the wire that generates the magnetic field envelops the exterior of a plastic tube that is used as a container for the water samples used in previous tests. The rest of the structure was the same as Figure 1 except the glass tube.

In both cases the sensor used was the Hall Axial Payme probe, connected to a Tesalameter Phaywe with a range of measurement from 0 to 2000mT.

3.2.2. BASED ON AN INDUCTIVE COIL

We also developed a second experiment to study the possibility of measure the electrical conductivity using the generated current on an inductive coil. In order to achieve this goal, we use two cooper coils, their wire has a 0.4mm diameter. Those coils were overlapped and do not have a core. The turn relation is 1:36.66. They were part of a voltage transformer that was removed previously. Both coils have a solenoid form. In one coil we introduce AC at different voltages and frequencies, always maintaining a sine wave. This is the powered coil. Meanwhile, we measure the induced current in the other coil, the inducted coil.

In the previous case, the water samples are introduced in the center of the magnetic field. In this point the magnetic field is bigger and the changes are maximum. Thus, we should take the measurements of that specific place. In this case we want to affect all the magnetic field, so the water must surround the whole space occupied by the magnetic field. So, we introduce both coils inside the water samples. In this case the water envelops the coils, the core (which is empty) and the exterior.

The coils are isolated from the environment with silicone using a silicone gun to ensure that the water does not enter inside the coils. If there is enamel cracks in contact with the water, there will be a short. Moreover, the coils had some paper protections, and their permeation can cause changes in the coil proprieties. In this case we use a generator of alternative current to power the first coil and an oscilloscope to measure the electric conductivity of the powered and the induced coil. The explained structure is show in Figure 2.

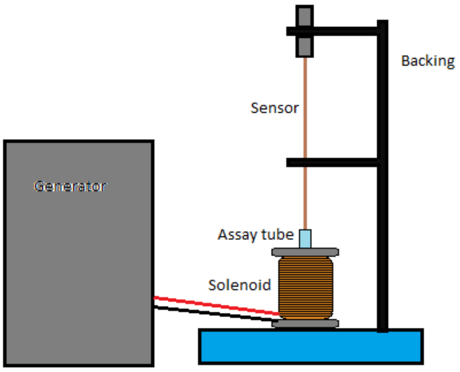


Figure 1. Structure of the laboratory test bench for Hall sensor.

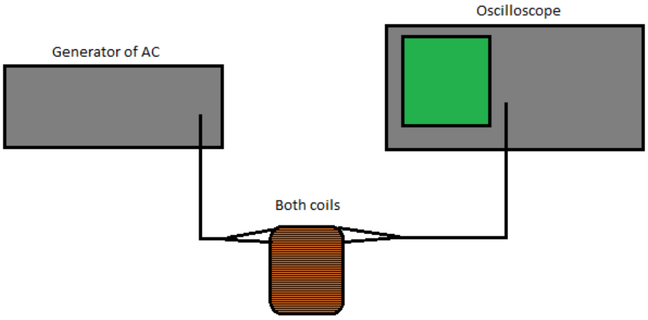


Figure 2. Structure of the laboratory test bench for Two Coils.

An initial test was performed, first the coils was in the air, so the magnetic field is completely enveloped of air, and the oscilloscope presents a fixed signal, that signal can be seen in Figure 3. When the environment changes and the coils are inside the water, the magnetic field is affected by this water. So the current induced in the inductive coil changes. The new signal can be seen in Figure 4. This change can be seen comparing Figures 3 and 4.

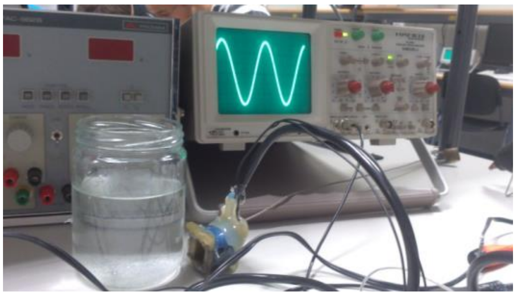


Figure 3. Laboratory set-up with the probe in the air.

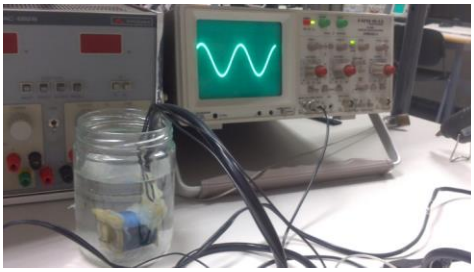


Figure 4. Laboratory set-up with the probe in the water.

3.3. LABORATORY TEST BENCH

We have done two sets of analysis, one for each methodology. The first one uses the solenoid and the Hall sensor. The purpose of these tests was to demonstrate that differences in the environment can produce alterations in the magnetic field. The second set of analysis was aimed to obtain more sensibility and the reduction of the cost of the sensor. To achieve this goal, we used an inductive coil in which we registered the induced voltage as an output signal instead of a Hall sensor.

3.3.1. BASED ON A HALL SENSOR

Our hypothesis is that we expect to be able to detect changes in the magnetic field when we vary the properties of the environment. In order to know the best point to perform the measures, we performed different tests at different electric conditions.

In the first ones, with DC current, we measured the value of the magnetic field when the generated field by the solenoid passes through different samples with different values of electric conductivity, those values are shown in Table I. We measure the changes of the magnetic field at different powering conditions; those values of used current are shown in Table II. For this experience we use the structure represented in Figure 1, with the solenoid that has a test tube inside.

Table I. Values of voltage and current used to power the solenoid in first test of DC current and sensor based on Hall sensor

Voltage (V)	5	10	15
Current (A)	0.2	0.4	0.6

Table II. Values of electric conductivity of water samples of first set of test

Sample	1	2	3	4	5
Conductivity (mS/cm)	0,002	0,405	191,4	213	285

Later, we measure those samples with AC at 12V, to confirm the different behaviour with different type of current. In this case the coil is powered using a current transformer from 220V to 12V which was connected to the electrical installation of the laboratory.

With the same purpose as before, to obtain the behaviour at different conditions, now we change the frequency of the current. This is aimed to find the best point to perform the rest of measures and obtain the most accurate correlation. The used frequencies to realize the measurements are shown in Table III.

In this case, we use the two solenoids, the first one is the same used in the DC, the solenoid with a test tube inside, see Figure 1. The second solenoid is the solenoid coiled on a plastic tube that contains the water. The purpose is to know if an attenuation of the signal due to the glass test tube exists, and if this causes a different changes behaviour, that implies less precision.

Table III. Values of frequencies used at 12V

AC at 12V				
Frequency (Hz)	15	150	1500	15000

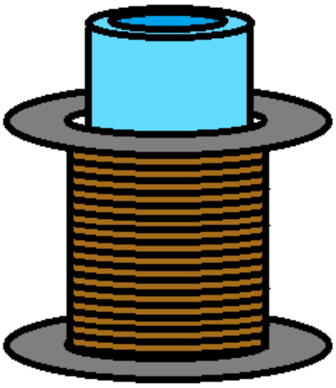


Figure 5. First solenoid of the first test, which has an assay tube in the centre.

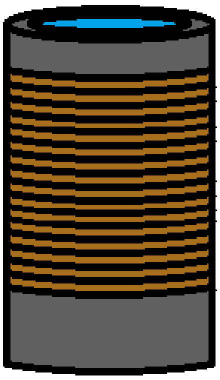


Figure 6. Second solenoid for the first test, which is coiled on a plastic tube that serves as a container.

In order to complete the first test bench, we take measurements at higher DC voltages with the first solenoid, the one that has a test tube. For this test we use different samples, which had different concentration of salts, those conductivities are shown in Table IV.

Table IV. Values of electric conductivity of water samples

Sample	1	2	3	4	5	6
Conductivity (mS/cm)	0,0028	0,378	1,087	51,2	147,9	194

3.3.2. BASED ON AN INDUCTIVE COIL

The second set of laboratory tests is performing using the two overlapped solenoids. The first one is connected to AC at different voltages, using a generator. This coil generates a magnetic field that causes an induction on the second coil. The core of those coils was removed, allowing us to use the air or water as the coil core. Then, we take measurements in both environments, air and water (in this second case we immersed both coils in a container full of water with high salinity). The measurement of the induced voltage is taken with an oscilloscope by measuring from peak to peak the sine wave. We want to relate the output voltage of the induced coil with the conductivity of the water.

First, we perform several changes of the working frequency. We observe the difference of the induced voltages in the second coil when the environment changes (air or water). This is a preliminary test aimed to find the frequency where the difference between air and water is maximum. Probably at this frequency the same coil will detect more accurately the changes between different conductivities.

The second test was also performing with different frequencies shown in Table V. But in this case the voltage of the induced coil is fixed to 2.8V in air, changing the voltage of the powered coil. Then, we introduce both coils inside a container with salty water and compare it with the obtained voltage after this change. The aim of this test is to find the point where the change of the voltage is higher when we change the environment. This point is important to be found because this will be the point where we will have the maximum precision. This frequency depends on each coil; we made some tests to use it in future tests.

Table V. Values of frequencies used in the test

AC at 2.8V of induced current in air									
Frequency (kHz)	0.5	1	2	4	5	6	7	10	20	100

3.4. RESULTS

3.4.1. BASED ON A HALL SENSOR

First, we describe the results obtained in the first set of analysis performed with the solenoid and the commercial sensor. We are going to start showing the results obtained with AC, those results are shown in Table VI. We have not appreciated any correlation between the magnetic field and the conductivity of the water at 12V at any frequency. Thus this method is not useful with the used equipment (maybe with a sensor with higher sensibility we will be able to take this measure).

We repeated the same tests with the second solenoid in order to know if the problems obtained in the previous test are caused by the influence of the glass tube. The results are show in Table VII. In this case we have not also appreciated any correlation between the magnetic field and the conductivity of the water at 12V, but we have seen a difference in the magnetic field when the environment changes (air or water) only at 15Hz and at 1500Hz.

Table VI. Magnetic field (mT) values at different conductivities and frequencies with 12V (AC) with Solenoid 1 (with the test tube).

Conductivity (mS/cm)	15Hz	150Hz	1500Hz	15000Hz
Without assay tube	269	198	26	3
0,002	269	198	26	3
213	296	198	26	3

Table VII. Magnetic field (mT) values at different conductivities and frequencies with 12V (AC) using Solenoid 2 (without the test tube.)

Conductivity (mS/cm)	15Hz	150Hz	1500Hz	15000Hz
Without water	0.17	0.18	0.16	0.03
0,002	0.16	0.18	0.15	0.03
213	0.16	0.18	0.15	0.03

Now we present the results obtained with the test when using DC. In this case we only take measurements with the first solenoid because the other solenoid has less turns so the generated electromagnetic field is lower. Also in the previous test we observed that the influence of the glass tube is not so important.

First we took measurements with 5 samples with different concentration of salt and different voltages (shown in Table I and Table V). The conductivity of the samples has 3 intervals, 1 with the lowest conductivity, 0.002mS, other with low conductivity, 0.405 mS, and 3 samples with high conductivity 192 mS, 213 mS, and 285mS. This distribution allows us to see different issues. First of all, it is possible to distinguish between very different conductivities (low values and high values). Second, it allows us to know the different sensitivities in high conductivities or low conductivities, because the sensitivity is different at different ranges for electrical conductivity.

In this case we did two series of measures at each voltage, to know the repeatability, because we have seen that in some cases there is a low repeatability. Those measures are called Test A and Test B, Test A was done before and once them are finished we started again with the measures of Test B.

The results showed us that at high voltages the sensibility increases, but, at same time, it caused some problems, because a change in the position of the sensor in the magnetic field causes variations in the lecture of the value. At high voltage values, the error committed in a single value is higher than at low voltages. It is so important when taking measurements from different ranges. The results are shown in Table VIII.

Table VIII. Magnetic field (mT) values when measuring different conductivities at different voltages with DC

Environment	Measured at 5V		Measured at 10V		Measured at 15 V	
	Test A (mT)	Test B (mT)	Test A (mT)	Test B (mT)	Test A (mT)	Test B (mT)
Air	2,89	2,90	8,66	8,72	14,89	14,51
Water with conductivity (mS/cm)						
0,002	2,91	2,93	8,68	8,71	14,86	14,56
0,405	2,93	2,96	8,69	8,89	14,82	14,66
191,4	2,93	2,98	8,69	8,89	14,81	14,64
285	2,97	3,01	8,70	8,90	14,82	14,59
213	2,96	3,00	8,73	8,92	14,78	14,62

In Figure 7, we can see the representation of the measurements obtained at 5V in test A and test B. In this case, the results show that is possible to distinguish between different conductivities. In all cases, the value of the magnetic field registered in the centre of the solenoid increases with the conductivity of the sample. In this case, it is possible to distinguish between samples with low conductivity, but with high conductivities the sensibility is lower. At low conductivity a variation in the conductivity of the water of 0.4 mS/Cm causes a variation on the magnetic field of 0.02 mT, but at high concentrations a variation of 94 mS/cm causes a variation of just 0.04 mT (examples of test A). It probes that at low conductivity values the sensitivity is higher than at high conductivity values. The changes in the magnetic field are almost the same in both tests, test A and test B, with a little increment in test B respect test A. So, at 5 V the repeatability of the measures is good.

In Figure 8 the measures obtained at 10 V for test A are shown. The behavior presented when we measure at 10 V in test A is similar to the presented and at 5V, in all cases, the value of the magnetic field registered in the centre of the solenoid, increase with the conductivity of the sample. At low conductivity a variation in the conductivity of the water of 0.4 mS/Cm causes a variation on the magnetic field of 0.01 mT, but at high concentrations a variation of 94 mS/cm causes a variation of just 0.04 mT (examples of test A). That probes that at low conductivity values the sensitivity is higher than at high conductivity values, the same that happened in test A and test B at 5 V. The results of test B was no so coherent, and did not show a correlation between magnetic field and conductivity. That can be caused because at higher voltages minimum variations in the position of the Hall sensor respect the solenoid causes bigger errors than at lower variations.

We realized also measures at 15 V of two test, but both times yield confusing results, so they are not represented. We think that they may be caused by errors in the position of the sensor respect the magnetic field or because 15 V is not a good input voltage for the sensor.

We also performed measurements at 20V with different samples of water, shown in table V. The main problem was that at these voltages the coil starts to heat up, and this heat interferes with the measures. So, is very important to realize the measures and turn of the generator that powers the coil. The results are show in Table IX and represented in Figure 9.

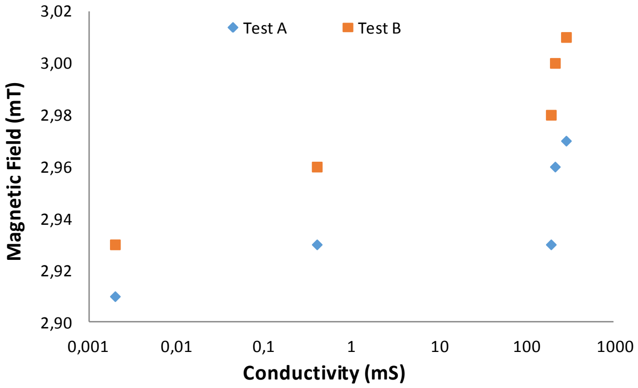


Figure 7. Representation of the data for 5V for test A and test B

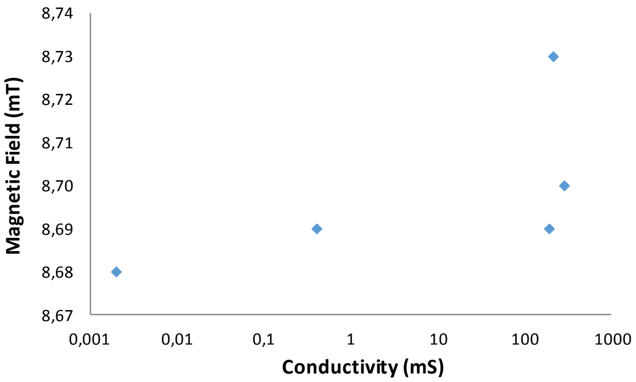


Figure 8. Representation of the data for 10 V for test A

Table IX. Measures obtained at 20 V of DC

Conductivity of samples (mS/cm)	0,0028	0,378	1,087	51,2	147,9	194
Magnetic fiel (mT)	50,4	50,2	49,8	48,5	48,2	48

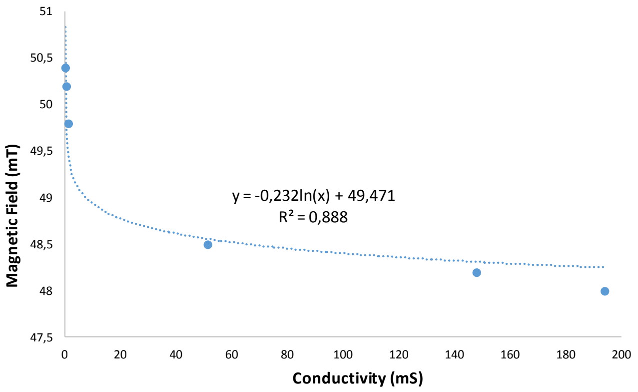


Figure 9. Representation of the data for 20V for test A

This test showed us that there is a good correlation between the changes in the magnetic field and the conductivity of the samples. The magnetic field decreased in all cases when the conductivity increased. This relation can be expressed as a logarithmic function (1). In this case, it presents higher sensibility at low values of conductivity.

$$\text{Magnetic Field } (mT) = -0{,}232 * \ln(\text{Conductivity } (mS/cm)) + 49{,}471 \quad (1)$$

The first set of tests shows us that there is a huge variability on the obtained results, and there is a good correlation in just some cases. Moreover, at high values, where the magnetic field is higher and we expect to have the major sensibility, there are a lot of problems with the heath of the coil. Furthermore, the changes of the position of the Hall sensor respect of the centre of solenoid produces errors.

3.4.2. BASED ON AN INDUCTIVE COIL

In the first test we changed the frequency and we observed the voltage in the induced coil in both environments: water and in air. The results are show in Table X and are represented in Figure 10. We observed that in the air, voltages increase until 4 kHz. Then, it is maintained until 7 kHz, and starts to decrease. Otherwise, in water it increases until 4 kHz, then it starts to decrease. Both environments have the same behaviour but different peaks. These behaviours can be interpolated with the following (2) for air and (3) for water. These results demonstrate us that it is possible to distinguish between salty water and air at any frequency, but some frequencies have higher differences.

$$\text{Voltage of induced coil } (V) = 23/(-1{,}071-0{,}01984 * \text{Frequency } (kHz)) \tag{2}$$
$$R^2=0{,}86$$

$$\text{Voltage of induced coil } (V) = 653{,}4/\text{Frequency } (kHz) \tag{3}$$
$$R^2=0{,}86$$

We need to know in which frequency the difference between environments in higher, and this is what we did in the second test. We change the frequency, but maintaining the voltage of the induced coil in air at 2.8 V. These results are show in Table XI and represented in Figure 11.

Table X. Induced coil voltage at different frequencies when the environment changes

Frequency (KHz)	Voltage (V) in Salty water
0,1	2,4
0,5	2,8
1	2,8
10	1,25
25	1,8
50,8	2
100	3,25
145	2,5
248	2,8
500	3,2
750	3,6

Table XI. Induced coil voltage at different frequencies when the voltage in the air is fixed at 2.8v

Frequency (KHz)	Voltage (V) measured in	
	Air	Salty water
0,5	15	3
1	18	6,4
2	18	14
4	20	17,5
5	20	13,6
6	20	11,9
7	20	10,4
10	18	8
20	15	5
100	7,6	0,6

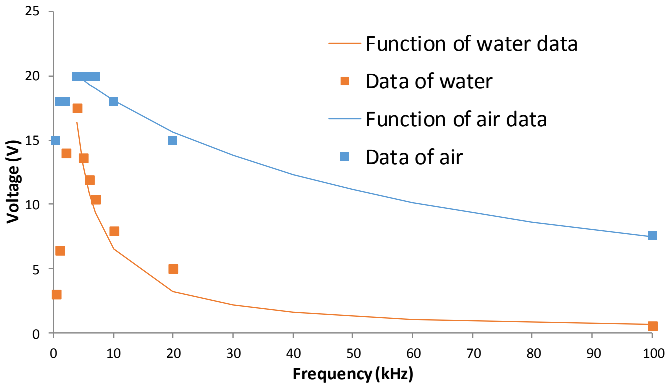


Figure 10. Representation of the data of Table V

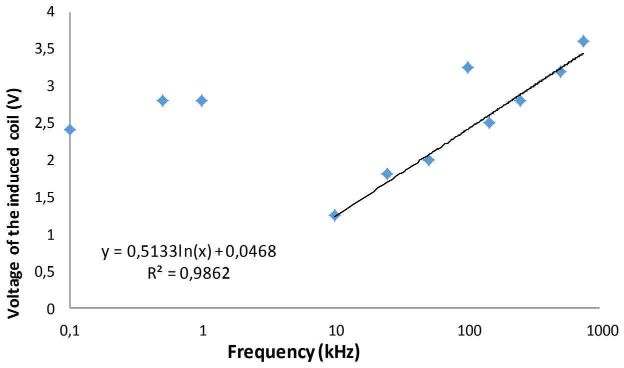


Figure 11. Representation of the data of Table VI.

In Figure 11 we can see that depending on the frequency, the effect of the change of environment can have different sign (positive sign or negative sign). So the voltage in the water can increase or decrease with respect to the voltages in the air. The value of the voltage in the induced coil was allways 2,8V. The point where the sign changes is at 248kHz. From 10kHz to 248 kHz the change of environment (air to water) makes to decrease the voltage. This change is higher at 10kHz and decreases until 248kHz where is null. From 248kHz the change of the environment makes to increase the voltage and the difference of voltage increases when the frequency increases. Part of this data (from 10 to 1000kHz have a logarithmic behaviour and follow (4):

$$\text{Voltage of induced coil (V)} = 0{,}5133\ln(\text{Freq. (kHz)}) + 0{,}0468 \qquad (4)$$

The best point to take measurements will be the point where the values have higher differences. We can find two different points to take measurements, at high voltages (1000kHz) and at medium voltages (10kHz). The maximum differences appear at 10kHz.

3.5. COMPARATIVE OF PRICES OF THE DEVELOPED SENSORS AND CURRENT COMMERCIAL SENSORS

In this section we are going to make a comparative of the princes of the commercial sensors of conductivity and the price of the final assembly of the sensors that we used in these tests. The data of the price of commercial sensors are founded on the different websites of the fabricants, shown in Table VII. Meanwhile, the prices of the proposed sensors are calculated according to the necessary materials and the electronic components needed to their assembly, shown in Table XII and Table XIII. The total price of the first model (Hall sensor + Solenoid) is 42.83€. By the other hand the total prince of the second model (Two Solenoids) is 48.19€.

Table XII. Price of the components for sensor 1 (Hall sensor + solenoid)

Component	Prize (€)
Sensor of Hall Effect	1.64
Voltage regulator +5V (1A output current)	14.50
Voltage regulator -5V (1A output current)	2.73
PIC 16f8775.39	5.39
Digital to Analog converter – 8 bits	8.57
Resistors and capacitors	3
Coil solenoid	7

Table XIII. Price of the components for sensor 2 (two solenoids)

Component	Prize (€)
Voltage regulator +5V (1A output current)	14.50
Voltage regulator -5V (1A output current)	2.73
PIC 16f8775.39	5.39
Digital to Analog converter – 8 bits	8.57
Resistors and capacitors	3
2 x Coil solenoid	14

We can see that the price can vary quite a lot from one vendor to another. The cheapest costs around 85.00 €, while the most expensive costs around $806. The new developed sensors are nearly 50% cheapest than the commercial sensors.

Table XIV. Comparative of prices of different sensors on the market.

Name	Fabricant	Physical method	Range on values	Price
WQ-COND	Global Water	Conductive	0 to 2000 mS/cm	606€
YSI 5560	YSI	Conductive	-	288€
PCE-CM 41	PCE Holding GmbH	Conductive	0 to 20 mS/cm	85 €
HI 98309	Hanna Instruments	Conductive	0,000 to 1,999 S/cm	122 €
HI 720122-1	Hanna Instruments	Inductive	0 to 2000 mS/cm	503€

3.6. CONCLUSION

In these tests we demonstrate that different environments (air, fresh water and salty water) can produce different alterations in the electromagnetic field, and these alterations can be measured by different methods.

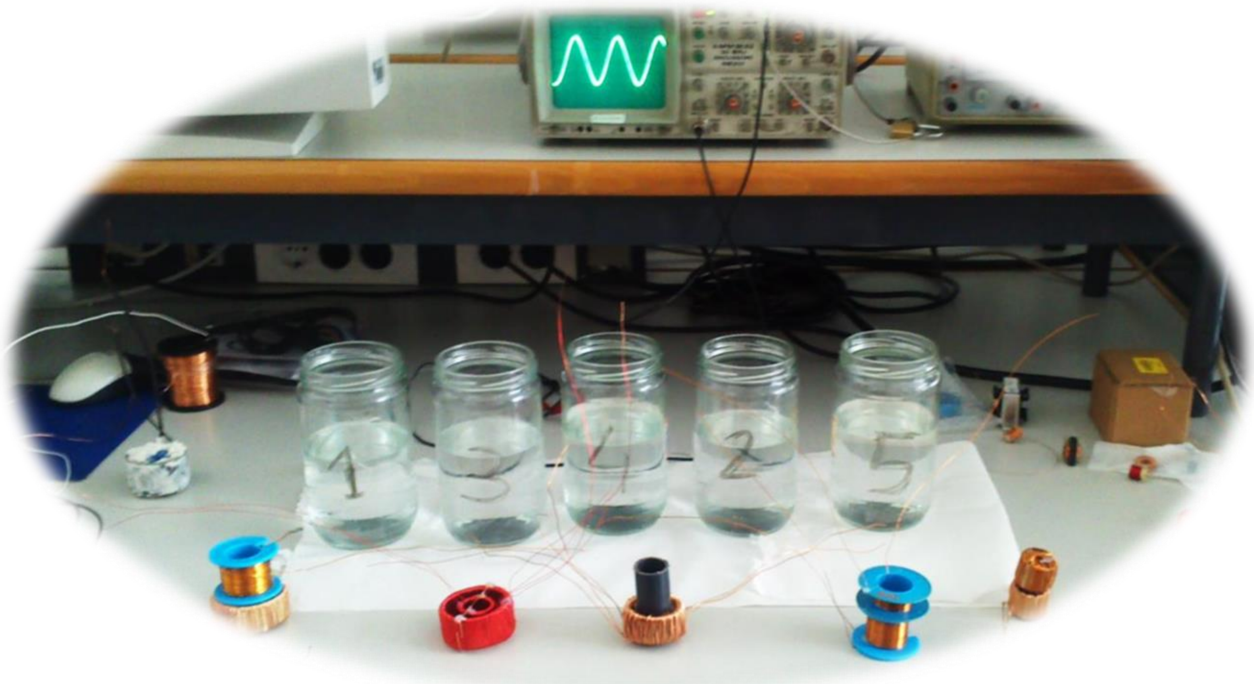
First, by using a solenoid we can measure the values of the electromagnetic field. But the sensibility of this sensor is too low and we need to increase the voltage of the solenoid in order to obtain enough sensibility in the sensor, this produces 2 problems. In the first one, the solenoid heats up and we need to turn off the solenoid between measures because this heat produces interferences (it changes the magnetic field that produces the solenoid). The second one happens because when the magnetic field increases, little changes in the position of the sensor and the solenoid produce erroneous data.

Another way to solve the problem of low sensibility was measuring the electromagnetic field through the induction of voltage in the second coil. In this case we are able to distinguish air from salty water at different frequencies. We have observed that the best frequency to measure is at 10 kHz. In some cases we have been able to distinguish water with low conductivity from high conductivity.

The advantages of these detection methods versus the traditional ones is that we do not need to put in contact the sensors (the two copper coils or the copper coil with the magnetic field sensors) with the environment. So, there is no high degradation of the sensor along the time. This is very important because it means that the sensor can be left at any place with no maintenance. Moreover, because the sensor does not have any perishable part or is not consumed during the measurement, the lifespan of the sensor only depends on the energy source.

The main problem in the first set of tests was that there are important changes in the electromagnetic field when the position of the sensor over the solenoid changes. To prevent this in future tests we propose to create a fixed container for liquids or to make it waterproof and introduce it inside the water. The problem in the second set of tests is that the coils have to be completely isolated. Any hole can make the coils started to drench.

We have several lines to research in future works. Although the highest sensitivity is given at high voltage, this range of measurement has problems. Moreover, the need of an energy source in the environment, where the sensor will be placed, makes us to continue with the tests at low voltages. We will also minimize the size of the coils used to take measurements. In order to achieve this purpose, we will introduce some electronic components that help us to obtain higher values and more sensitivity.



4. Comparison of different models of coils

4.1. INTRODUCTION

The models of sensors showed in section 2, are based on inductive coils that always use two toroid coils in the same position, one over the other. But in this section we perform a comparative study to decide which the best option is. We will use other configurations and compare the results.

For this section the material that we use are the next:

- Conductivity meter CM 35+
- Generator of AC
- Oscilloscope
- Copper coil of 0.4mm, 0.6mm and 0.8mm (See Table XV for more information)
- Nonferus materials to use for coiling surface
- Resistance of 100 Ω
- Capacitor 100nF
- 5 glass containers
- Tap water
- Salt

4.2. LABORATORY TEST BENCH

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.

4.2.1. DESCRIPTION OF COILS MODELS

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

We used to types of coils, solenoids and toroids. We made different configurations using only solenoids, only toroids or toroid and solenoid. Also we put this coils in different positions of the coils, one over the other and one inside the other.

All models are formed by two coils where the coil with lowest number of spires is the powered coil (POWC) and it was powered by a sine wave of 8 Volts peak to peak amplitude. This coil induces a current on the induced coil (INDC). 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 XV shows the models used in our tests and their features.

4.2.2. TEST BENCH

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). The first sample which presents lowest conductivity corresponds to the tap water. These samples include the conductivity values from freshwater to seawater.

Each model is submerged in the five dissolutions starting with the sample of lowest conductivity. The vessels which contain the dissolutions have a high 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 23.2ºC.

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.

Table XV. Models of coils used in tests to compare the different configurations of coils combination (S: Solenoid, T: Toroid)

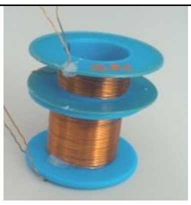
Model		**POW**	**Features PC**	**INDC**	**Features IC**
1		S	Wire Diam.: 0.6 mm Coil Diam.: 29.6 mm Coil High: 13.8 mm - Nº of Spires: 21	S	Wire Diam.: 0.6 mm Coil Diam.: 29.6 mm Coil High: 27 mm Nº of Spires: 45
2		T	Wire Diam.: 0.4 mm Inner Coil Diam.: 19.6 mm Outer Coil Diam.: 26.4 mm Coil High: 24.9 mm Nº of Spires: 77	T	Wire Diam.: 0.4 mm Inner Coil Diam.: 39.8 mm Outer Coil Diam.: 51.2 mm Coil High: 24.9 mm Nº of Spires: 304
3		S	Wire Diam.: 0.6 mm Coil Diam.: 27.2 mm Coil High: 17.8 m Nº of Spires: 31	T	Wire Diam.: 0.8 mm Inner Coil Diam.:30.6 mm Outer Coil Diam.: 44.7 mm Coil High: 22.3 mm Nº of Spires: 132
4		T	Wire Diam.: 0.8 mm Inner Coil Diam.:23.2 mm Outer Coil Diam.: 56.5 mm Coil High: 26.9 mm Nº of Spires: 81	S	Wire Diam.: 0.8 mm Inner Coil Diam.:25.3 mm Outer Coil Diam.: 33.6 mm Coil High: 22.6 mm Nº of Spires: 324 distributed in 9 layers.

Table XVI. Samples used in tests to compare the different configurations of coils combination

Sample	**1**	**2**	**3**	**4**	**5**
Amount of added salt (mg/l)	254	4020	2340	40200	57700
Conductivity (mS/cm)	0.397	6.28	36.6	62.9	90.2

4.3. 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

4.3.1. 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 Figure 12.

Figure 13 shows the output voltage for second model as a funcion of frequency. In this case, the value of output voltage (in the induced coil) decreases when the water conducivity 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 behaviuor is very irregular. It starts to be estable for frequencies from 1750 kHz. Figure 14 shows the behavior for third model.

Last model presents two frequecies 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. Figure 15 shows the measurement results for fourth model.

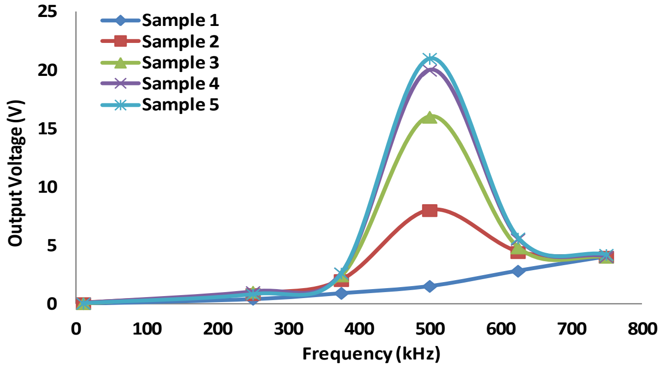


Figure 12. Output voltage for first model.

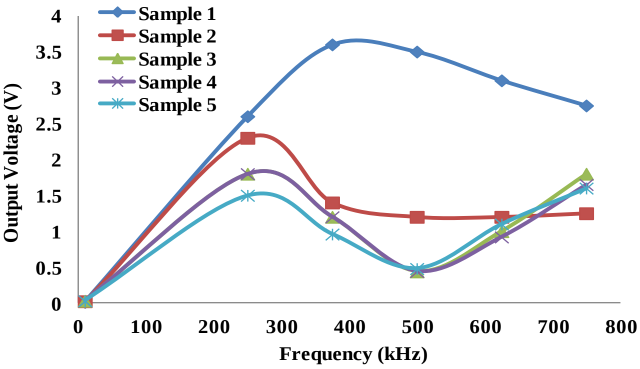


Figure 13. Output voltage for second model.

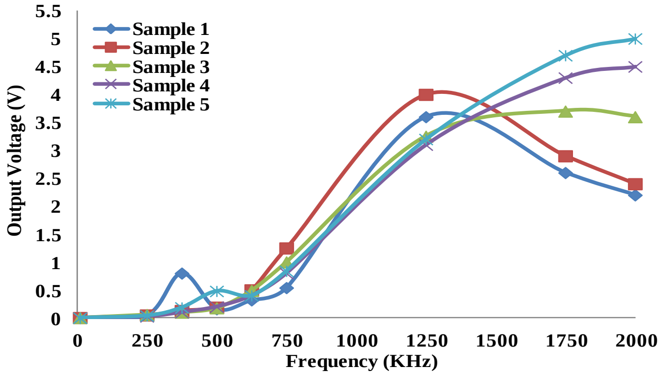


Figure 14. Output voltage for third model.

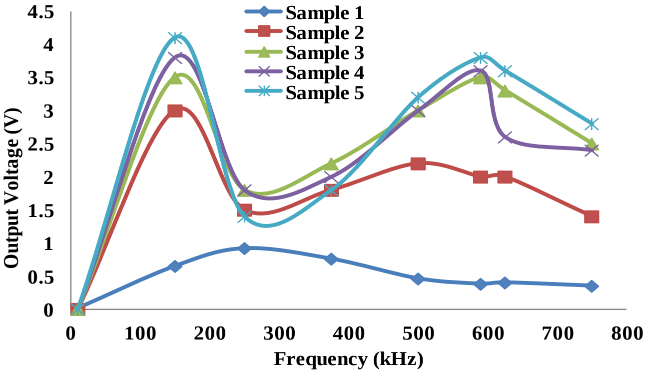


Figure 15. Output voltage for fourth model.

4.3.2. 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 Figure 16). We can use (5) to model its behavior. Model 1 presents a correlation coefficient of 0.9903.

$$V_{out} = 4.653 \cdot \log(0.9833 + \mathrm{C}) \qquad (5)$$

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 Figure 16, 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.

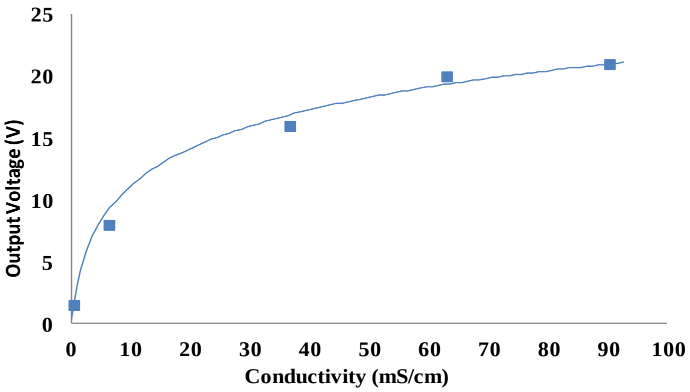


Figure 16. Relation between water conductivity and output voltage for Model 1 at 500kHz.

Figure 17 shows the relation of output voltage as a function of the water conductivity for Model 2. Eq. (6) represents the mathematical model for this configuration of coils.

$$V_{out} = 2.446 \cdot \mathrm{C}^{-0.3877} \qquad (6)$$

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. In this case there is not a linear clear linear range.

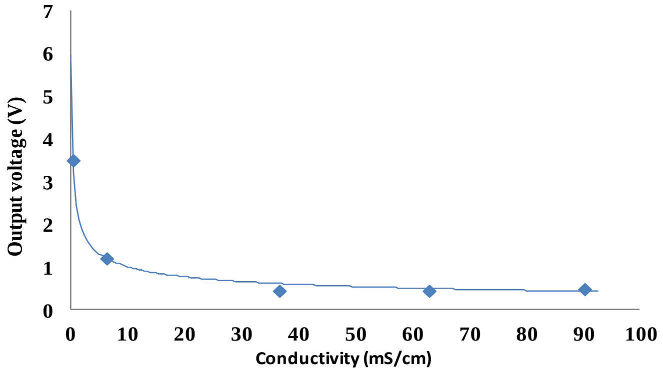


Figure 17. Relation between water conductivity and output voltage for Model 2 at 500kHz.

The third model shows a lineal behavior at 2000 kHz (See Figure 18). In this case, the relation between induced output voltage (V) and conductivity (mS/cm) can be expressed as (7) where the correlation coefficient is 0.9826.

$$V_{out} = 0.0324 \cdot \mathrm{C} + 2.2675 \qquad (7)$$

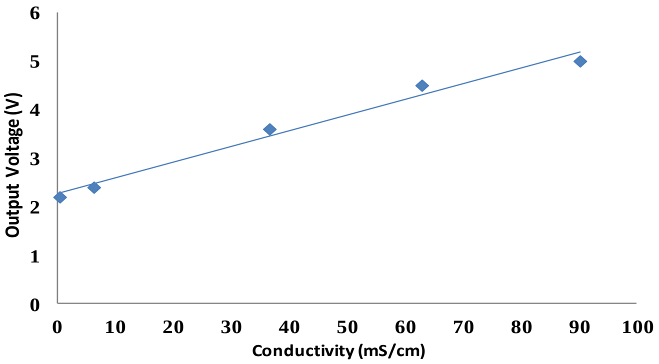


Figure 18. Relation between water conductivity and output voltage for Model 3 at 2000kHz.

Finally, Figure 19 shows that Model 4 presents a clear lineal behavior from 6.28 mS/cm. to 90.2mS/cm. Eq. (4) show its mathematical expression where $\mathrm{V}_{\mathrm{out}}$ is the output voltage induced in the second coil in Volts and C represents the water conductivity in mS/cm. The correlation coefficient for (8) is 0.9888

$$V_{out} = 0.013 \cdot \mathrm{C} + 2.9637 \qquad (8)$$

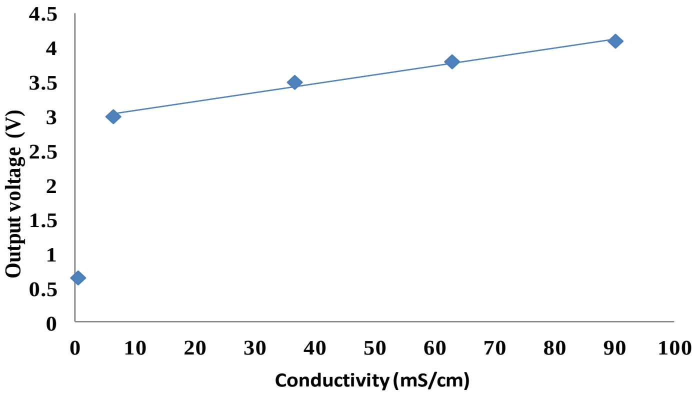


Figure 19. Relation between water conductivity and voltage registered in the Model 4 at 150kHz.

4.4. 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 XVII 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 lineal 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 lineal 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 lineal working range but we can approximate its operation as 3 lineal working ranges as a function of conductivity. Finally, Model 2 can also be approximated by 3 lineal 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.

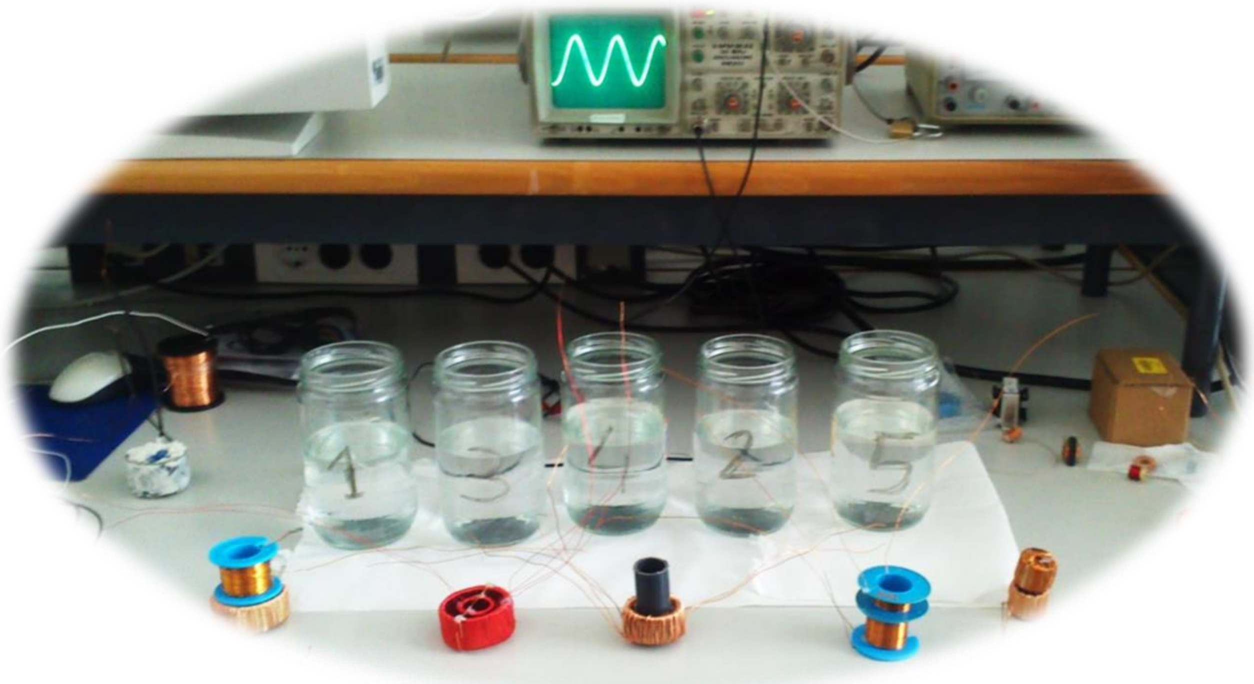
Table XVII. Comparative of best results for four models.

				Possible camps of applications			
	Lineal range (mS/cm)	**Slope**	**Optimal frequency (kHz)**	**Estuarine environments**	**Saline wedges**	**Irrigation water**	**Saline environments**
Model 1	-	-	500	✓	✓	-	-
Model 2	-	-	500	-	-	✓	-
Model 3	0,397 - 90,2	0,0324	2000	✓	✓	✓	✓
Model 4	6,28 - 90,2	0,013	150	✓	✓	-	-

4.5. CONCLUSION AND FUTURE WORKS

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 abrupt changes in any parameter could mean the death of animals [23].



5. Characterization of the conductivity sensor Model 4

5.1. INTRODUCTION

In the previous section we analyzed the results of the measures of different configurations of coil combinations. We concluded that Model 4 is the one that gave best results. It had the wider range to take measurements, from freshwater to seawater. Then, we realized further research with this prototype. In this test we are going to characterize that sensor and find some important data such as the minimum cell volume, linear range and sensibility.

The material used in this section is is the following one:

- Conductivity meter CM 35+
- Generator of AC
- Oscilloscope
- Model 4, see Figure 20
- Resistance of 100 Ω
- Capacitor 100nF
- 5 glass containers
- Different containers (See Table XIX for more information)
- Tap water
- Salt

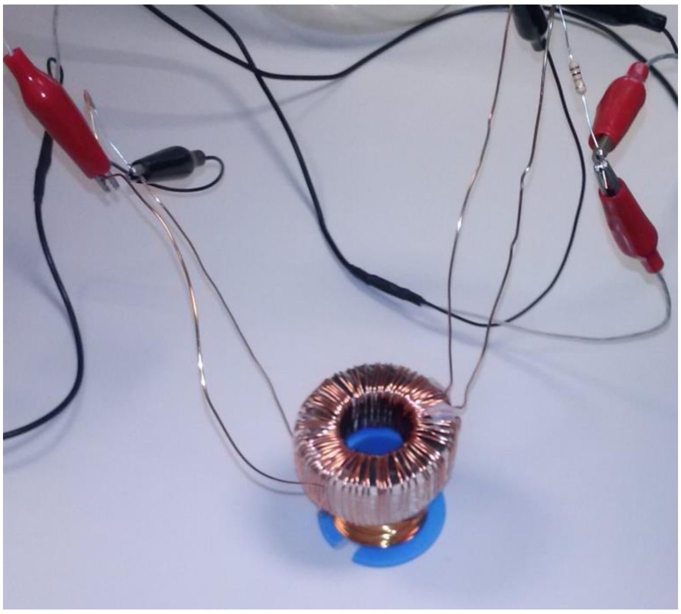


Figure 20. The conductivity sensor Model 4 with the components.

5.2. LABORATORY TEST BENCH

There are some characteristics that we need to know about our sensor before using it in the real environment. In this section we are going to establish the laboratory procedures to obtain this data. Moreover, we will explain why is so important to ascertain this characteristics.

When our system is used in an open environment, the volume of the water that envelops the coils is infinite. But in the laboratory test, it’s not possible to measure infinite containers. Therefore, the first measure should define the minimum cell volume.

The other important factor to bear in mind is the measurement limitation of our sensor and its mathematical model.

5.2.1. MINIMUM CELL VOLUME

One of the parameters to take into account is the dependence of the results with the cell volume.

When we are performing laboratory tests, it is usually used small containers. Due to the container size, the measurements can be modified due to interferences, changes of the medium and reflections in the container walls. Measurements in natural environments are not affected by these effects. We use small containers in order to avoid the waste of water, because bigger containers imply bigger volumes of water and salt.

As Figure 21 shows, when we have a container too small, the lines of the magnetic field would spread out of the container. In addition, our measurements could be affected by external interferences. However, when our container has a size which can contain the lines of the magnetic field generated by the feed coil, the measurement will be independent of the container volume.

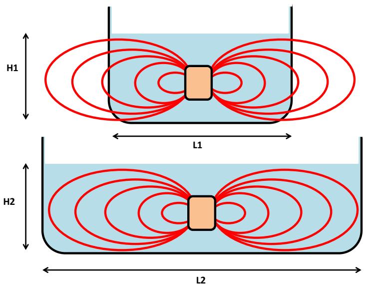


Figure 21. Possible scenarios of measurement attending to the size of container

Figure 21 shows the two possible scenarios where we can take the measurements. Magnetic lines are represented in red and H1, H2, L1 and L2 are the dimensions of each container.

This test will be composed by two measurements. The first one will be about the measures dependence with the water depth. With this, we will check if covering the sensor is enough to take the correct measurements or if we need to add more water to have accurate measurements. The second test will check if the surface of water around the sensor affects significantly the results. For a sample with a fixed conductivity, we will increase the size of the container, keeping the water level. Simultaneously, we will take measures of the output voltage in the induced coil. The minimum cell volume will be the one, which registers a stable value of output voltage in spite of increasing the size of the container.

5.2.2. ANALYSIS OF LINEAL WORKING RANGES AND MEASUREMENT LIMITATIONS.

Before using our sensor, it is important to define its working ranges. This implies to determine the minimum and maximum values of water conductivity where our sensor is able to show a correct correlation between water conductivity and the output signal. In our previous tests, we saw that at higher salt levels the conductivity values of all devices, the commercial ones and our proposal, present unstable values. For this reason, we need to define our working range.

In our experiments, we use tap water to prepare our samples. The sample with lowest conductivity is tap water and the highest value of conductivity will be the one registered before this effect appears.

On other the hand, the entire working could be approximated by a mathematical expression or by multiple lineal ranges. In some occasions, when the device behavior is approximated by some lineal ranges, we can obtain better correlation. In order to measure it, we have prepared 35 samples with conductivity values between 0.397 mS/cm and 88.3 mS/cm. Each conductivity value provides us a voltage value. With these values, we will be able to model the behavior of our sensor. Measurements have been performed at 22 ºC.

5.3. TEST BENCH AND MEASUREMENT RESULTS

This section shows the results of our test bench. First of all, we are going to analyze the dependence of the measurements with the volume of the container.

After that, we are going to see the relation between the water conductivity and the output voltage of our sensor. Finally, in order to determine the accuracy of our device, a verification process with unknown samples will be performed.

The samples are prepared with tap water and common salt (NaCl). The conductivity of each sample is measured with a commercial conductivity meter CM 35 by Crison Instruments.

Finally, the toroid is powered by a signal generator. It is used a sine wave of 8 V peak to peak amplitude. The induced signal in the second coil (solenoid) is measured by an oscilloscope where both signals can be visualized easily.

5.3.1. MINIMUM CELL VOLUME

In order to check the minimum value of the cell volume, we have taken the container of 4cm of diameter and, progressively, we have added water to increase the height of water. The first value, 7.1cm, is the minimum height because it is the level of water that covers entirely the sensor. Table XVIII shows the output voltage for each level.

Table XVIII. Height of water (cm) in the test of minimum cell volume and the output sensor signal (V)

Height (cm)	Output sensor signal (V)
7.1	0.7
7.5	0.7
8.1	0.7
8.7	0.7
9.5	0.7

As we can see, the value remains constant in all tests. Then, we can conclude that measurements will be independent to the water level.

The second step shows us the dependence of measures with the surface of container. In order to achieve this goal, we have prepared 4 containers with the same dissolution and the same water level. For each container, we have measured the output voltage value. Table XIX shows the results of this test.

Table XIX. Diameter of the container (cm) in the test of minimum cell volume and the output sensor signal (V)

Diam. or sides (cm)	Kind of container	Area (cm^2)	Cell Volume (l)	Output sensor signal (V)
8,6	Round	48.8	0.35	0.7
14,5	Round	165.1	1.17	0.54
18*27	Square	486.0	3.45	0.46
25,5*25,5	Square	650.3	4.62	0.43

As we can see, the changes in the container surface affect the value of the output sensor signal. This test confirms our hypothesis about the dependence of the cell volume and the conductivity measurements. As Figure 22 shows, the increase of the area produces an increase of the output sensor signal.

We can model this effect by (9) in order to apply the appropriate correction of the measurements in smaller containers. The correlation coefficient of this expression is 0.9772.

$$V_{out} = 0.4332 + \frac{0.09254}{\text{Vol}} \qquad (9)$$

Where V_{out} are the signal of the sensors and Vol is the Volume of the container full with water.

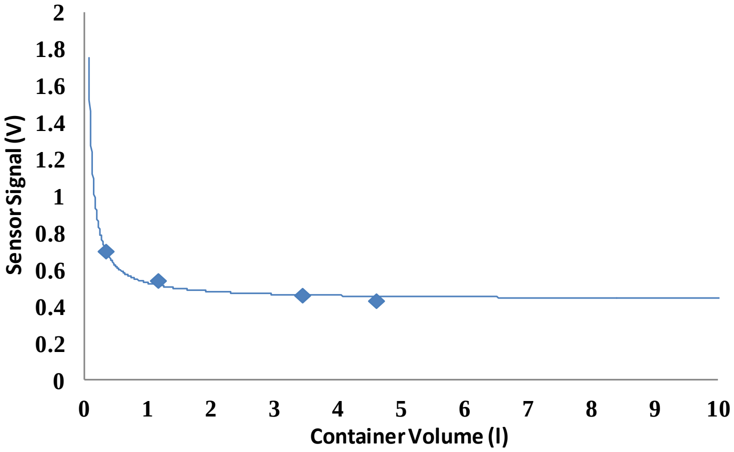


Figure 22. Dependence of the Sensor signal with the volume of water obtained in the test of minimum cell volume

As Figure 22 shows, for 7.845 liters the value of the output sensor signal is stable in 0.43 V. Then, we can conclude that our measures will be independent of the container for volumes higher than 7.845 liters. If we assume a height of 7.1cm, the minimum size of a square container will have a side of 33.24cm. If our container is circular, its radius will be 18.75 cm.

As this sizes are too big to use them in laboratory we are going to use a containers of smaller size (0.35L), and use the equation 9 to convert the sensor output signal if we need to use the sensor in the field.

5.3.2. LINEAR RANGES AND SENSIBILITY

This section shows the relation between the water conductivity and the output voltage of our sensor. We are going to present the linear ranges and the sensibility of each one.

The methodology that we use is starting with tap water we add salt, shake it until stabilize value of conductivity, measure the conductivity with the commercial conductivity meter and introduce the sensor inside the water container.

As in the previous tests we saw that the slope of the calibration line had a change, see Figure 19, we want to be sure that we have enough points to represent the behavior of the two linear ranges (or more). Also we know that at low values of conductivity the slope is bigger so that, at low values of conductivity we are going to perform a lot of points. And when we see that slope changes we will reduce the number of points. Figure 23 shows the behavior of our sensor. It relates the output voltage with the water conductivity.

Once we represent the results we can see that there are three linear ranges, the first from 0.397 to 6.56 mS/cm, the second from 6.56 to 22.6 mS/cm, and the last one from 22.6 to 76 mS/cm. The values of voltage registered for this test varied from 0.02 to 7.6V. The slope of each linear range is different. The most sloped is the range that correspond to the lower conductivity values.

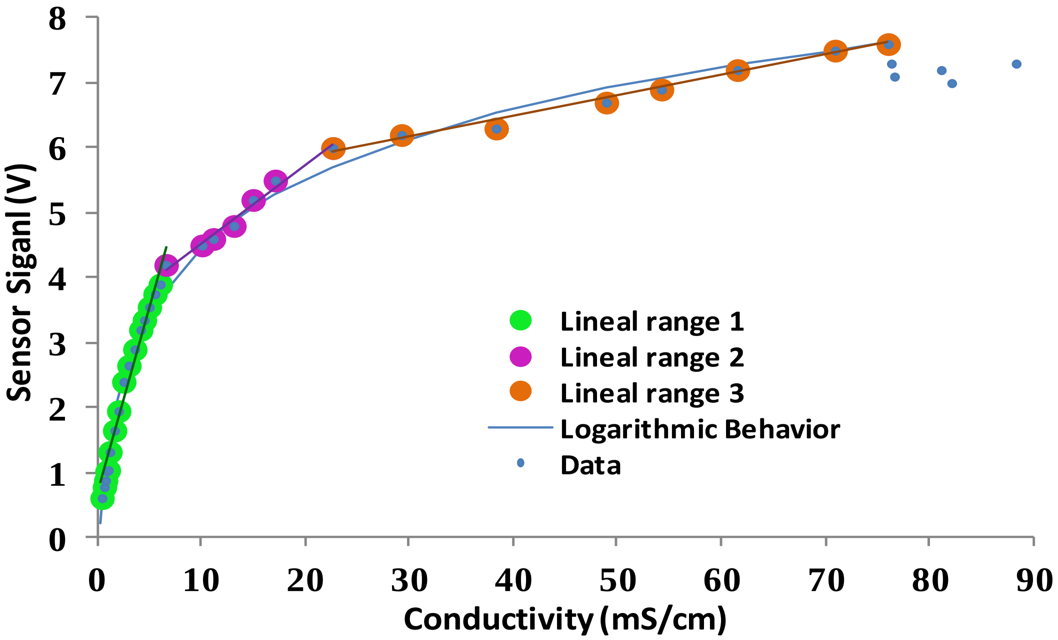


Figure 23. Correlation between the water conductivity and the Sensor signal Model 4 at the working frequency.

In the lineal range 1, Eq. (2) can be applied for conductivity values from 0.397 mS/cm to 6.56 mS/cm. These values correspond to output sensor values from 0.2 to 4.2 V. Eq. (10) represents the expression of first lineal working range with a correlation coefficient of 0.9751.

$$V_{out} = 0.5894 \cdot \mathrm{C} + 0.6037 \qquad (10)$$

Where V_{out} is the output voltage of sensor in V and C represents the conductivity in mS/cm.

The second lineal working range is expressed by Eq. (11) with a correlation coefficient of 0.9813. Eq. (11) should be applied for values of conductivity from 6.56 mS/cm to 22.6 mS/cm. These values correspond to output sensor values from 4.2 to 6 V.

$$V_{out} = 0.1193 \cdot \mathrm{C} + 3.3457 \qquad (11)$$

Where V_{out} is the output voltage of sensor in V and C represents the conductivity in mS/cm.

The third lineal working range is applied from from 22.6 mS/cm to 76 mS/cm. The output voltages which correspond to these values are ranged between 6 V to 7.6 V. Eq. (12) represents the expression for the third lineal working range. Its correlation coefficient is 0.9872 and V_{out} is the output voltage of the sensor in V and C represents the conductivity in mS/cm.

$$V_{out} = 0.0313 \cdot \mathrm{C} + 5.23 \qquad (12)$$

Where $\mathrm{V}_{\mathrm{out}}$ is the output voltage of sensor in V and C represents the conductivity in mS/cm.

Until now we use linear ranges, with linear equations but we also can adjust the behavior of all our interval of measures to a logarithmic equation by an expression followed by Eq. (14). To obtain this equation we use a mathematic program Eureqa Formilize.

$$V_{out} = 0.6714 + 0.7999 \cdot \ln(\mathrm{C} + \mathrm{C}^2) \qquad (14)$$

Where $\mathrm{V_{out}}$ is the output voltage of sensor in V and C represents the conductivity in mS/cm.

Computationally, it is much easier the process of a lineal function than a logarithmic function. For this reason, we can consider the option of modeling the behavior of our sensor as a set of lineal equations.

For conductivities higher than 76 mS/cm, the sensor presents unstable values of voltage. For this reason, we have limited the use of our sensor for conductivity values up to 76 mS/cm.

The sensibility of our sensor will depend on the lineal working range. Its sensibility will also depend on the electronic circuit used to amplify the output signal. In our case, it is easy to get sensibilities of mV. Thus, according to both factors, the sensibility should be 0.002mS/cm for the first lineal range, 0.008mS/cm for the second lineal range and 0.03mS/cm to the third lineal range.

Finally in Table XX we show a resume of the characteristics of the linear ranges

Table XX. Characterization of the linear ranges of the sensor Model 4

Linear range	Formula	R^2	Slope	Interval range (mS/cm)	Interval range (V)	Sensibility (mS/cm)
1	$V_{out} = 0.5894 \cdot \mathrm{C} + 0.6037$	0.9751	0.5894	0.397 - 6.56	0.2 - 4.2	0.002
2	$V_{out} = 0.1193 \cdot \mathrm{C} + 3.3457$	0.9813	0.1193	6.56 - 22.6	4.2 - 6	0.008
3	$V_{out} = 0.0313 \cdot \mathrm{C} + 5.23$	0.9872	0.0313	22.6 - 76	6 – 7.6	0.03

5.4. VERIFICATION PROCESS

Once we have obtained the correlation equation we should verify it. In order to achieve this goal, we have taken some samples of water from the natural environments. Two of these samples are from two different irrigation channels. The third sample is from the sea (seashore) and other one is from tap water. These samples have an unknown conductivity value.

Samples do not suffer any treatment. We put them in 1.5 liters plastic bottles and we kept them in the refrigerator during the time that they were stored (less than 8 hours). Before performing the measurements, we have homogenized the samples by shaking the bottles.

The first step is to verify the correct behavior of our sensor; we have measured the output voltage of each sample (See Table XXI).

Table XXI. Output Voltage for unknown samples.

	1	***2***	***3***	***4***
Output Votlage	0.86 V	1.14 V	2.40 V	6.50 V

Estimating the conductivity values by using Eq. 2, Eq. 3, and Eq. 4, we have calculated the results of the water conductivity. In order to compare the estimated conductivity values with the measured values, and the error for the four samples, we provide Figure 24.

Figure 24 compares our conductivity measurements and the values of conductivity obtained by a commercial conductivity meter. From Figure 24, we can extract the value of correction of our measures. Eq. (14) shows the expression which relates the actual conductivity measure and the value of conductivity measured with our sensor.

$$C_{correct} = 0.7157 \cdot C_{measured} + 0.0224 \qquad (14)$$

Where $C_{correct}$ is the conductivity in mS/cm gave by the commercial sensor, and $C_{measured}$ in the value of conductivity gave by or sensor using Equations 10, 11 or 12 to transform the signal of voltage on value of conductivity.

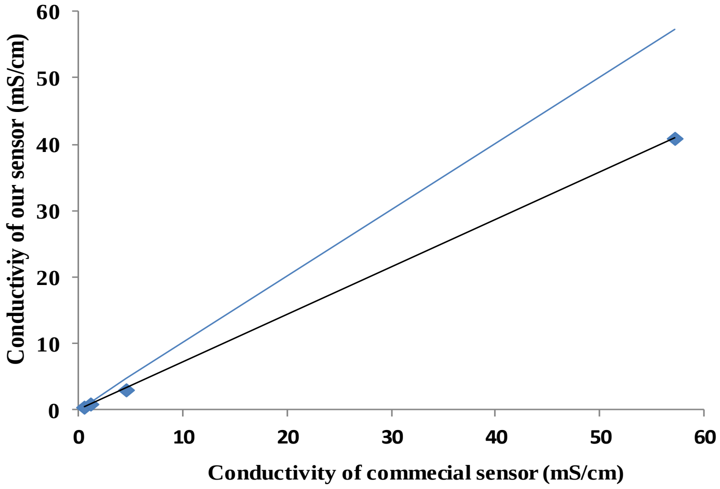
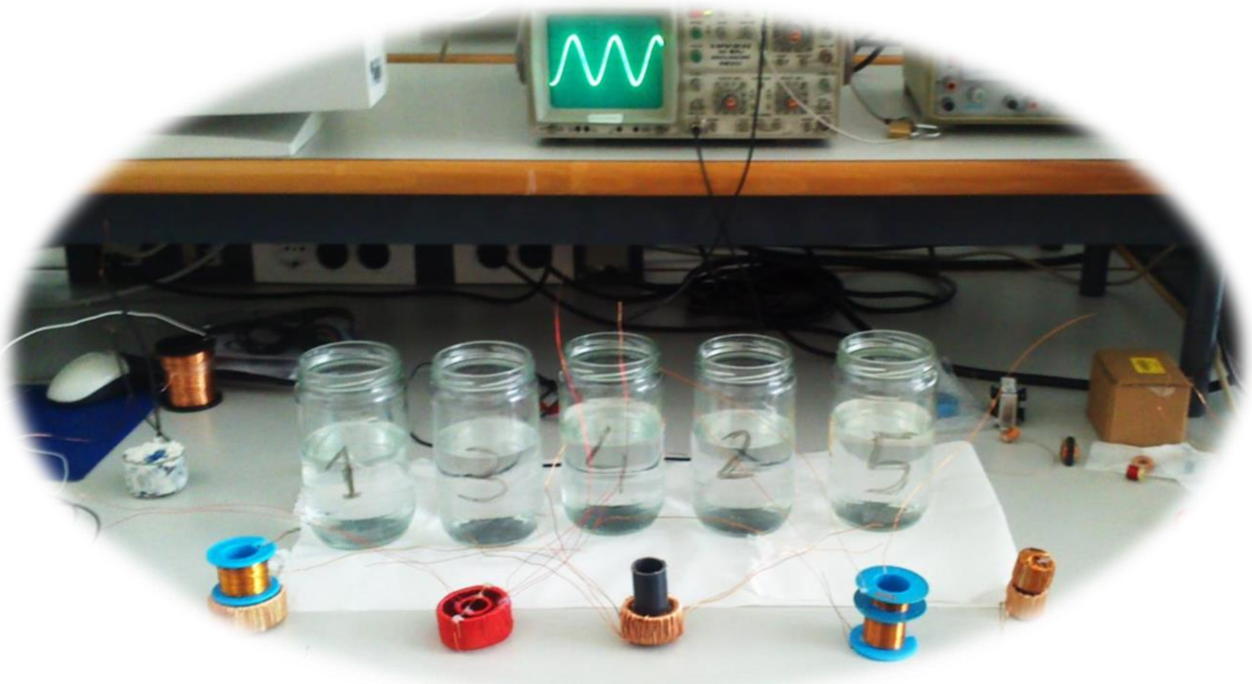


Figure 24. Conductivity of our sensor vs. Conductivity of commercial device.

We discover that we have some kind of error that produce that the signal of our sensor is lower than the signal of the commercial sensor. But using (14) we are able to convert the value of our sensor into real value.

5.5. CONCLUSION AND FUTURE WORKS

In this Master thesis, we have presented an economic conductivity sensor. In addition, we have performed several tests in samples with different water conductivity to model and to calibrate the operation of our conductivity sensor. Our results have shown that the minimum volume of container to measure the conductivity is 7.845 l. Finally, we have analyzed the accuracy of our sensor compared with the results of a commercial one. As Fig. 5 shows, we have an error between 20-30% which can be corrected by Eq. (6). In a future work, we want to encapsulate our conductivity sensor with its correspondent electronic. Finally, we also want to adapt our sensor to measure the salinity in marine fish farms, in those installations abrupt changes in any parameter could mean the death of animals and cause economic losses for the factory [23].



6. Conclusions and further investigations

6.1. FULFILLMENT OF THE OBJECTIVE

Our main objective was to develop a new low-cost, low-maintenance conductivity sensor without contact with the water, reducing the need of continuous calibration and reducing as less as possible the sensibility. It has been achieved successfully.

In the first tests we demonstrated that different environments (air, fresh water and salty water) can produce different alterations in the electromagnetic field, and these alterations can be measured by different methods. But we detect some problems when we are using the Hall sensor. The sensibility of the senor is too low for our purposes. So, we needed to increase the voltage of the solenoid in order to obtain enough sensibility. This causes a heater of the solenoid that changes the value of the magnetic field when the position of the Hall sensor changes a little.

We choose to measure the alteration of the magnetic field through the changes of the current registered in an inductive coil. We use four different combinations of coils (solenoids and toroids) with different wire diameter and sizes to make a comparison. We saw that each configuration has different optimum frequencies. This frequency can distinguish between different salinities, but not all of them work in the same way. One of them was able to distinguish water samples with low conductivities, however when the conductivity increases the values of sensor signal is the same. So this coil was good to use it in control of irrigation water, but not for our purpose. The others are capable to distinguish freshwater from seawater and different conductivities between them. To decide with one use in the final tests we pay attention at the working frequency, because at lower frequencies, the electronic components needed and the circuit are cheaper. Thus, we chose Model 4 to perform the final test.

In those final tests, we realize some investigations in this sensor. We analyze some factors as the lineal ranges, their sensibility or the minimum cell volume. We saw that there are three lineal intervals with different sensibilities, from 0.002mS/cm to 0.03mS/cm. Moreover, we demonstrate that the volume of the water that surrounds the coils is very important. The high of water needed to use the sensor is just the level of water that covers completely the sensor. However, the surface of water is very important because the magnetic field must be enclosed by water. In the case of our sensor the surface of water needed to realize the measures is 18.75 cm radius.

Finally we perform some measures with samples obtained from the field, with no one treatment, and we identify a drift in our sensor. We have found an analytical relation between the real value and the obtained values by our sensor, and, by using this equation, it is possible to correct the value of conductivity.

6.2. DIFFICULTIES FOUND DURING THE PROCESS

One of the main problems when we start the measures is the great variations of behavior that we found at different frequencies. Until we do not finalize the first set of tests we do not know how big the options to continue our test are.

The use of two cooper coils submerged under the water was an issue that caused us many problems and made us lose a lot of time. In the first coil that we use, that was part of a current transformer exist thin layers of paper between the layers of copper wire. When this paper gets soaked, the behavior of the coil changes, and we cannot continue the test until the coil dries up. So, we decided to isolate the coil with silicone. But this only retains the water out of the coil for a few period of time. Once the water was inside the coil, we must to remove all the silicone, because with the silicone the coil does not dry up.

Finally, we decided to stop the use of this coil and create our own coils with fewer layers and do not use any other material than the wire of copper. So, the behavior of the coil does not change even if we introduce the coil inside the water for long terms of time.

6.3.PERSONAL OPINION

When I decide to realize my master thesis with a research group with a completely different background that mine I was nervous because I knew that there would be some problems in the working procedure. Once I started to work with my tutor and his research group those problems become nothing. I have learned how important is the mixture of knowledge from different areas, and how, different point of view can see the same thing with different eyes. Moreover, I learned how to work in an interdisciplinary group where everyone contributes with their knowledge to achieve a common goal. Now I am in charge of the environmental part inside the research group.

6.4.PUBLICATIONS

During the process of this project we have published three papers in different conferences. Those papers and their conferences a showed below.

L. Parra, S. Sendra, V. Ortuño, and J. Lloret, **Two New Sensors Based on the Changes of the Electromagnetic Field to Mesure the Water Conductivity**, in proceedings of SENSORCOMM 2013, August 25 - 31, 2013 - Barcelona, Spain.

L. Parra, S. Sendra, V. Ortuño, and J. Lloret, **Water Conductivity Measurements based on Electromagnetic fields**, in proceedings of CSE 2013, August 6 - 8, 2013 - Valencia, Spain.

L. Parra, S. Sendra, V. Ortuño, and J. Lloret, **Low-cost Conductivity Sensor Based on Two Coils**, in proceedings of CSE 2013, August 6 - 8, 2013 - Valencia, Spain.

6.5.FUTURE RESEARCH AND APPLICATIONS

In further investigations we want to try to avoid that drift, because we think that possibly it is caused by the suspended sediments. Those sediments can interact with the magnetic field but does not interact with the pas of electricity. So, in the next tests we want to measure the turbidity using another developed sensor in other paper [24]. We decide to use it instead of a commercial sensor because this turbidity meter is also a low cost sensor, and one of our objectives is to obtain a low cost sensor.

Also we want to implement this sensor completely with the electronic circuit needed and use this sensor in fishfarms, where changes in the water conductivity can produce huge economic loses.

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