Humidity in sandy soil measured by passive, wireless, and resonant sensor with bifilar coil

S F Pichorim, V A Marcis and G T Laskoski
CPGEI/UTFPR-Federal University of Technology-Paraná. Av. Sete de Setembro, 3165 CEP(ZIP): 80230-901 Curitiba, Paraná, Brazil.
pichorim@utfpr.edu.br

Abstract. In this paper a passive, wireless, and resonant (PWR) sensor for monitoring soil humidity is presented. This sensor employs a bifilar coil and it is compared with the classical PWR sensor with interdigital capacitor. Besides that, a theoretical model is developed to evaluate the influence of medium in sensor's response. A resonant circuit is used to detect the humidity variation. In a setup for 300 g of fine sand, where sensor's responses were evaluated for dry and wet sand, tests show a linear correlation of 0.7195 and a sensitivity of 252 kHz / % between resonant frequency and fresh water-to-sand mass ratio.

1. Introduction
Passive sensors, that do not require internal battery, generally are simple, small, and cheap. In general, passive sensors are wireless (communication by telemetry) and resonant (their frequency is modulated as a function of a measured parameter) using capacitive and inductive components. There are several applications for PWR (passive, wireless, and resonant) sensor, for example, pressure, humidity, gas concentration, pH, elasticity, radiation, and food quality measurement [1]-[6]. The modulated resonant frequency of PWR can be detected remotely by a simple excitation coil and reading circuit [7]-[8].

Humidity PWR sensors have the ability to detect water content, where it can be used in civil engineering, environmental biology, or agriculture to investigate the drying rate of seeds, wood, sand, concrete or soil [9]. The soil humidity is also important in estuarine and coastal environment, where the amount of sand and water is significant. These regions are characterized by high concentration of nutrients, temperature gradients, variable salinity and other physical-chemical parameters (including humidity) that are very important for the breeding and feeding of most species that inhabit the oceans [10]. Therefore, PWR sensor for humidity is important in bioimpedance area to characterize bacterial growth in presence of water [6], biological environment behavior [10], wood drying quality, plant properties and soil quality [11].

Ong et al. developed a PWR sensor to measure the water content (or moisture content) in sand and concrete [9]. This recent work was fundamental to the development of this sensor for sandy soils. Thus, it is described in more details and its results will be compared to the sensor proposed here. The sensor (see figure 1a) is made of a single-sided printed circuit board with square spiral inductor with 7 turns (inner and outer lengths of 25 and 40 mm, respectively). An interdigital capacitor with 19 sets of electrodes of 20 mm in length is used as sensitive element. All tracks have a width of 0.5 mm and the same spacing of 0.5 mm. This PWR sensor presented a resonant frequency of 22.5 MHz for dry sand and about of 20 MHz for sand with 21.4 % of mass ratio of water to sand [9].
2. Development

In this work, a new technique to build up a PWR sensor for humidity was developed. This new sensor employs bifilar coils, which inductors are wound with two parallel wires (i.e., bifilar coil), where higher self-capacitances were obtained [12]. In this technique, the end of first wire is connected to the beginning of the second one by a jumper wire. A PWR sensor with bifilar winding is shown in figure 1(b). It can be seen that bifilar turns work as an inductor and a capacitor, simultaneously. As a consequence of an inductor with high self-capacitance, the interdigital capacitor can be omitted in the new PWR sensor [7], [13]. This bifilar arrangement reduces the number of components in PWR sensor and increases the useful area for humidity when compared with interdigital capacitor area (figure 1(a)). For example, figures 1(a) and 1(c) show the conventional sensor and its useful area for the capacitive sensor (interdigital) in area R (purple). The area V (green in figure 1(d)) is the capacitive area of bifilar PWR sensor. Also, in area A (blue) is the useful area for the inductor in the conventional sensor compared with the area V (green), which is also the inductive element of the bifilar sensor. A larger area makes possible greater number of turns, increasing the distance for telemetry, that means a better inductive link.

![Figure 1](image.png)

**Figure 1.** The conventional PWR (a) and bifilar winding PWR (b) sensors. Both are built on a printed circuit board. In (a), there are a square spiral inductor, the interdigital capacitor, and the jumper (red) completing the LC parallel circuit [9]. In (b), there are the bifilar inductor (two wires are painted with black and blue for clarity the explanation) and jumper (red), that completes the bifilar coil. In (c) and (d), a comparison of the useful areas for the capacitive element R (purple) and inductive element A (blue) for conventional and bifilar sensor. It is important to point out that bifilar sensor presents both (inductive and capacitive) elements in the area V (green).
2.1. Electrical model of PWR sensor

The capacitance between adjacent tracks of bifilar coil is used as a capacitive sensor. The total capacitance of sensor (figure 2) is composed by a substrate (permittivity \( \varepsilon_S \)), the medium under test (with permittivity \( \varepsilon_M \) and conductance \( \sigma_M \)), and a thin enameled layer of polyester or polyamide-imide (permittivity \( \varepsilon_E \) about 4.\( \varepsilon_0 \)), which covers the copper tracks and protects them against oxidation caused by the medium.

![Figure 2](image)

**Figure 2.** Electric fields between two adjacent tracks (a), crossing the medium (b), the substrate (c), and enameled layer (d).

The admittance of the medium \((Y_M)\) is capacitive and can be calculated by

\[
Y_M = j\omega C = j\omega K \, ,
\]

where \( K \) is a constant that represents the geometry of sensor, and \( \varepsilon \) is the complex permittivity of the medium. The electrical permittivity is complex number due to dispersive effects caused by conductivity \((\sigma_M)\), which it can be written as

\[
\varepsilon = \varepsilon_M - j\frac{\sigma_M}{\omega} \, .
\]

Applying equation (2) in (1), yields

\[
Y_M = j\omega \varepsilon_M K + \sigma_M K \, .
\]

Defining \( C_M \) and \( R_M \) as total capacitance and resistance of the medium, respectively, which can be written as

\[
C_M = \varepsilon_M K \quad \text{and} \quad R_M = \frac{1}{\sigma_M K} \, ,
\]

the admittance of the medium is
Thus, rewriting equation (5) as the impedance of the medium \((Z_M)\), a parallel association of the resistance \(R_M\) and capacitive reactance \(X_{CM}=(2.\pi.f.C_M)^{-1}\), can be written as

\[
Z_M = -jX_{CM} // R_M ,
\]

where it is possible to see that impedance of medium, due to the electric fields between two adjacent tracks, depends on capacitance and resistance of medium. As can be observed in figure 2, electric fields \(E_S\) and \(E_E\), that cross only the substrate and enameled layer, respectively, cause a constant capacitance (called here \(C_S\)), which is independent of the medium influence. The electric field thought the medium also crosses the enameled layer. The influence of this layer is represented by a serial capacitance \(C_E\). Therefore, a representation of an electrical circuit equivalent for the sensor is shown in figure 3. In this circuit, the total capacitance \((C_T)\) of the PWR sensor can be determined by

\[
C_T = C_S + \frac{C_E.C_M}{C_E + C_M} .
\]

\[\text{Figure 3. Electrical circuit for PWR sensor.}\]

As the enameled layer is very thin, the capacitance \(C_E\) is greater than \(C_M\), but it cannot be neglected in the electrical model analysis. The humidity increases the capacitance \(C_M\) due to high relative permittivity of water (about 80) in comparison with the air or dry sand (about 4) [9]. When the PWR is inserted in a sandy soil, the capacitance \(C_M\) increases about 6.25 times, since dry sand and wet sand have relative permittivity of 4 and 25, respectively [14]. It is important point out that constant capacitances of sensor \((C_S\) and \(C_E\) according to equation 7) reduce the variation of total capacitance \(C_T\). However, the change of humidity in soil significantly modulates the capacitance \(C_M\) and \(C_T\), where it can be measured as a function of resonant frequency \((f_0)\) by the classical equation
As can be observed in figure 3, the conductivity of water in the soil can modify $R_M$ and the response of PWR sensor. Although typical fresh water is much more conductive (range of few mS/m) [14] than deionized water, the resistance $R_M$ is high enough to be neglected in sensor analysis ($R_M \to \infty$). However, the presence of sea water, which has high conductivity (some S/m) caused by its salinity, reduces drastically the resistance $R_M$, and, consequently, decreases the quality factor of resonant sensor. This effect causes a reduction in signal amplitude, getting more difficult to read remotely $f_0$. For low values of $R_M$, the sensitivity of $C_M$ is also reduced.

2.2. Sensor construction

The PWR bifilar sensors were made of a single-side printed circuit board (PCB) with 9 pairs of turns with a spacing of 0.5 mm between tracks. The figure 4 shows the sensor with dimension of $37.5 \times 40$ mm$^2$. External dimensions, track width, and track separation were chosen based on a previous work [9] to be possible comparisons. To complete the bifilar coil a jumper is soldered between points 1 and 2, resulting a spiral coil with 18 turns.

![Figure 4. The new PWR sensor with 9 pairs of bifilar turns.](image)

3. Tests and results

In general, the resonant frequency is obtained by the response frequency analysis using an RF signal generator and an oscilloscope to measure the maximum amplitude. Meanwhile, for wireless sensors, other technique must be employed. Resonant frequency ($f_0$) can be detected remotely using a dip-meter, where the absorption of an RF oscillator signal is measured by a meter pointer deflection when a resonant LC circuit is placed near to its antenna coil. In this experiment, a Leader LDM-815 dip-meter was used. However, the value of $f_0$ is shown in an analog dial with poor precision and resolution. Thus, a second coil (loop coil in figure 5) connect to a digital oscilloscope (Agilent model MSO 6034A) was used to measure, with higher precision, the oscillation frequency of dip-meter.

The sensor must be placed close to dip-meter antenna coil (few centimeters). Turning the dial of dip-meter, it changes the oscillation frequency. When the oscillation frequency corresponds to the PWR resonant frequency, there is a maximum amplitude reduction, where it can be easily measured in a pointer of dip-meter. The dip point (minimum for $f_0$) also can be observed in the digital oscilloscope.
by monitoring signal amplitude reduction. When dip point is found, the resonant frequency of PWR sensor is read with an oscilloscope.

Tests of PWR sensor for humidity measurement were made by insert the sensor in a sample of sandy soil with a volume of water. The sand was collected in Pontal do Paraná beach, where it was verified a particle size distribution with 82% of fine sand, about 10% of medium sand, about 7% of very fine sand, and 1% of fine sediments (silt and clay). The sand was inserted in a box with dimensions of $90 \times 50 \times 75 \text{ mm}^3$. A procedure to dry and wet the sand changes the humidity values, where the weight of water was used to determine the humidity of sample soil. Initially, the sample of sand was heated up to 200°C for two hours, and a mass of 300 g was measured with a precision weighing balance (iPlena with resolution of 1 g). This dry sample is denominated as $m_d$. Afterwards, the sample was saturated with the addition of fresh water and it was obtained the mass of wet sand mass, denominated $m_w$. The drying process was natural evaporation of water. Some hours were necessary to complete the process. Periodically, the $f_0$ of PWR sensor was measured and the sample weighed to determine the new mass of water in soil ($m_w$). This process was repeated until the mass of sand is equal to initial value ($m_d$). The humidity of soil was related with mass ratio of water to sand ($h$), calculated by

$$h = \frac{m_w - m_d}{m_d} \times 100\% .$$

Figure 5. Setup for experiment.

In figure 6 is shown the relation between resonant frequency of sensor and the water-to-sand mass ratio (soil humidity). Frequencies of about 19 MHz and 14 MHz were measured for dry and wet sandy soil (dots), respectively. A linear-curve fitting measured points was calculated, presenting a slope of 190.9 kHz per each percent of mass ratio and coefficient of determination about 0.7195.

Other measurements were done to evaluate the electrical model of sensor (figure 3). When the PWR sensor was removed from soil, its $f_0$ and self-inductance $L$ were measured by precision vector impedance analyzer (Agilent model 4294A). Using measured values of $f_0$ and $L$, the electrical model of PWR sensor could be solved by equation 7, yielding the capacitances $C_S$, $C_E$, and $C_M$. These capacitances values are presented in table 1.
Figure 6. Resonant frequency of PWR bifilar sensor as a function of mass ratio of water to sand (dots) and a linear-curve fitting measured points.

Table 1. Measured parameters of PWR bifilar sensor and capacitances of electrical model obtained by equation 7.

| Parameter | Situation           | Value       |
|-----------|---------------------|-------------|
| $f_0$     | Air                 | 19.6 MHz    |
| $f_0$     | Dry sand            | 18.94 MHz   |
| $f_0$     | Wet sand            | 13.9 MHz    |
| $L$       | at 1 MHz            | 6.58 $\mu$H|
| Sensitivity| Full range        | 252 kHz / % |
| $C_S$     |                     | 8.6 pF      |
| $C_E$     |                     | 62 pF       |
| $C_M$     | Dry sand            | 2.2 pF      |
| $C_M$     | Wet sand            | 13.7 pF     |

4. Discussion and Conclusion

In this work the development and implementation of a PWR sensor for monitoring soil humidity was presented. The developed sensor employs a bifilar coil that presents a high self-capacitance. This intrinsic capacitance changes as a function of medium and it is used to monitoring the humidity. The main advantage of this sensor is that bifilar arrangement reduces the components and increases the useful area for humidity when compared with the PWR with interdigital capacitor. Besides that, it increases the useful area for the inductor, improving the inductive link between PWR sensor and
reading circuit. In this work it was obtained 123% of more inductance (6.58 μH versus 2.95 μH[9]) than a PWR sensor with interdigital capacitor, same dimension, and similar humidity sensitivity.

The theoretical model shows that sensor's capacitance presents an impedance that depends on capacitance and resistance of medium. In this work, a resonant circuit was used to detect the variation of capacitance as a function of the humidity of medium. However, it is necessary to ensure that medium presents a low conductivity due to the dependence of the resistance between the PCB tracks in capacitor's response.

In a setup for 300 g of fine sand, tests shows a linear correlation between resonant frequency and fresh water content. Analyzing figure 6, the points below 17% for mass ratio present a better linear correlation (R²=0.8548) and a sensitivity of 90 kHz/%. However, including the points of mass ratio up to 21%, the sensitivity increases to 190.9 kHz/%, but linear correlation is reduced (R²=0.7195). This sensitivity is higher than obtained by Ong et al. (114 kHz per each percent of mass ratio)[9]. The problem of non-linearity may be related to the sand drying process. During the process it was observed that some regions of soil sample were drier than others. It means that balance measured total mass of water and sensor analyzed the humidity in its neighborhood. For greater volumes of soil the problems of sand drying could be reduced. Thus, for dry and water-saturated sand, the water distribution is more homogeneous and these values of humidity and resonant frequency are more reliable. Thus, the full range sensitivity of 252 kHz / % can be accepted.

The electrical model of sensor developed in equation 7 and figure 3 could describe the behavior of total capacitance of sensor with the influence of medium humidity, and could be used to predict, with acceptable precision, the resonant frequency of PWR sensor.

Future works can be developed to improve sensor's response (linearity and sensitivity). Besides that, it is possible to analyze sensor with other dimensions and frequencies. Despite of the good response of theoretical model, it must be improved to verify the influence of medium. Especially in medium with high conductivity. Finally, the sensor may have its application extended to other areas, such as monitoring of moisture in the soil for agriculture, construction, farming, and other possible applications.

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