



EXPLORING CORROSION BEHAVIOR IN DIFFERENT ENVIRONMENTS USING A PASSIVE MICROSTRIP SENSOR

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ABSTRACT

A design for a microstrip sensor is proposed in this paper. The stub structure technique was used to contribute to the miniaturization of devices. His parametric study is described in detail, and it has been optimized using the HFSS simulator. The objective of this study is to find a way to determine the corrosion rate in order to apply appropriate protective measures, knowing that once this rate exceeds the threshold, the component becomes faulty. The corrosion sensor is a preventive solution to industrial corrosion. The corrosion sensors have shown considerable strengths, which leads us to privilege them. Furthermore, these promising results provide an in-depth exploration of corrosion behavior in various environments, highlighting the effectiveness of the passive microstrip sensor.

Keywords: Uniform; Corrosion; Corrosion Sensor; Performance; Corrosion rate.

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1. INTRODUCTION

Corrosion poses significant economic and environmental challenges, impacting a wide range of structures, especially those composed of metallic materials. Corrosion is a major factor in the degradation and failure of most structures and equipment. The process is influenced by a variety of factors that are intricately connected, such as the type and properties of metals, the chemical makeup of the surrounding environment, temperature, and other elements.

Corrosion manifests as the intricate physicochemical interplay between a metal and its environment, thriving in aggressive settings that foster the degradation of metallic materials. This aggressive environment represents, in our study, the water of the sea and the water of the rain. The sea water and rainwater represent the aggressive environment in this study.

Rainwater is composed of sulfate, sodium, calcium, and ammonium. It even contains trace amounts of nitrate. The concentration of rainwater components varies according to the geography (urban or rural area), the coastal environment, and environmental characteristics of the site. In a coastal front region, normal rainwater is very weakly acidic, and the PH is close to neutral.

Sea water is salt water from the seas and the earth's oceans. It is composed of water, salts, and small quantities of different substances such as chloride, sodium, magnesium ion, sulfate, calcium, potassium ion, bicarbonate, carbonate, and fluoride. The rain water had a PH of 6.5, while the sea water had a PH of 8.5. Corrosion can be influenced by both environmental and inherent factors, leading to significant variations in its behavior. These include high ion concentrations (like chloride, sulfate, nitrate, ammonium, carbonate), dissolved oxygen levels, pH balance, aeration, and the flow dynamics of the surrounding environment.

Due to its high resistance to corrosion, copper is one of the most frequently used metals. However, it is not entirely resistant, and pitting corrosion is a common issue. The damage caused by corrosion to many installations, the shutdown of some, increased operational costs, and the risk of water contamination when used in piping, justify the ongoing efforts to prevent and combat the deterioration of metallic materials.

In this context, monitoring the corrosion process in real time is crucial. Indeed, the corrosion problems and the miniaturization of the components are more and more taken into account, proving a great technological advancement using radiofrequency functions inserted in a chipless RFID architecture like that proposed by Preradovic and Karmakar [1], [2], [3]. The RF wireless sensors were sensitive to the degradation of materials that can be deployed on networked structures. This work is part of this problem.

2. BACKGROUND AND RELATED RESULTS

All materials are sensitive to environmental chemical attack, and so they are subjected to long-term corrosion processes according to specific mechanisms. It is therefore crucial to determine their resistance to corrosion and to detect and quantify precisely the evolution of corrosion by using corrosion sensors in civil engineering and marine sectors.

In this context, corrosion control can be achieved by several methods, such as:

1. Electrochemical method [4] that requires the measurement of potentials and electric currents
2. Eddy current method [5], [6].
3. Acoustic emission [7]: This non-destructive detection method captures the elastic energy released in the materials.
4. Automated Ultrasonic Testing [8]: The system has the capabilities to apply basic pulse echo corrosion mapping,
5. Magnetic Flux Leakage [9]: A non-destructive method used for the detection of corrosion and pitting (localized corrosion) on steel structures, such as storage tanks.

There exist various types of sensors designed for monitoring or detecting corrosion, including:

- Electrochemical sensors [10]
- Acoustic emission sensors [11]
- Optical fiber chemical sensors [12].

Recently, RFID (radio-frequency identification) technology has been applied to monitor and evaluate corrosion in concrete infrastructure. The conception of miniature autonomous wireless sensors is essential. Our main objective has been to address the two points described above, namely to propose an inspired corrosion sensor using RFID technology.

3. DEVICE CONSTRUCTION

This paper presents the design and implementation of passive sensors based on microstrip line technology, which are used to detect corrosion in metals caused by rainwater and seawater.

The originality of this study lies in the simplicity of the realized structures that enable lower manufacturing, which is reflected in the miniaturization of components.

Corrosion may manifest as either uniform or localized corrosion [13], [14]. Uniform corrosion is characterized by consistent destruction being spread evenly across the entire surface of the metal. It is expressed as an average thickness loss ($\text{mg}/\text{cm}^2/\text{year}$) or penetration into the metal (mm / year).

In this work, we focus on uniform corrosion. In order to monitor the corrosion, our work consists of constructing two RF structures sensitive to corrosion : One sensor, which has been soaked in rainwater, and another sensor, which has been soaked in seawater, are compared. An effective method for miniaturizing components is the use of microstrip line technology.

The microstrip sensors, based on a one-stub resonator or two-stub resonators, allow the corrosion process to be followed by frequency variation. This can be carried out in a relatively small frequency band.

4. PROPOSED SENSOR

Figure 1 illustrates the proposed sensor along with its dimensions; it has a thickness of $35\ \mu\text{m}$ and is mounted on an FR4 substrate with a permittivity of 4.5 and a thickness of 1.6 mm. To achieve a design suitable for 50 W, the width of the access line is set to 2.9 mm. Figure 2 displays the top-view layout of the sensor.

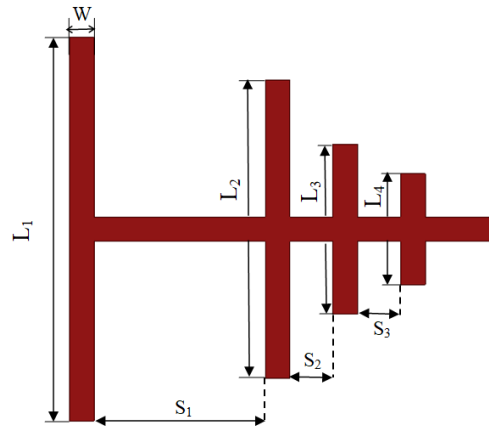


Fig.1. 2D illustration of the proposed sensor, with $W= 2.9\ \text{mm}$, $L_1= 5\ \text{mm}$, $L_2= 4\ \text{mm}$, $L_3= 3\ \text{mm}$, $L_4= 2\ \text{mm}$, $S_1= 1.5\ \text{cm}$, $S_2= 0.5\ \text{mm}$, $S_3= 0.5\ \text{mm}$.

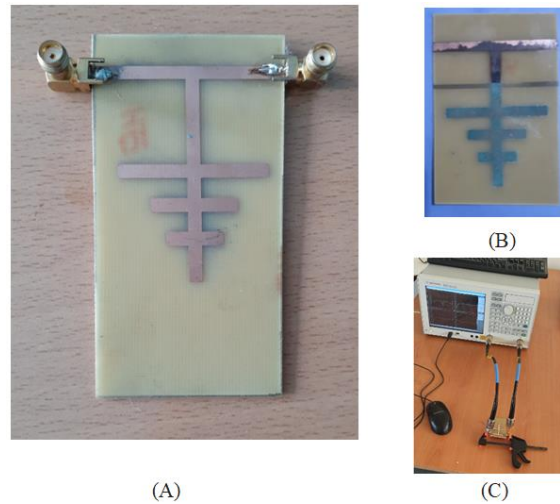


Fig.2. (A), Photograph of the fabricated proposed sensor; (B) corroded sensor; and (C) a network analyzer E5071C being used for S-parameter measurement and excitation of the sensor.

5. SIMULATION AND EXPERIMENTAL RESULTS

The lower portion of the sensor, up to 0.8 cm of the S1 section, is exposed to corrosion. During this exposure, the protected area stays the same, while the exposed part develops green spots on the surface. This color change reflects the conversion of metallic copper into active corrosion products. From an electrical perspective, corrosion causes a shift in the resonant frequency, which is captured by the S parameters on the vector analyzer, as shown in Fig. 3.

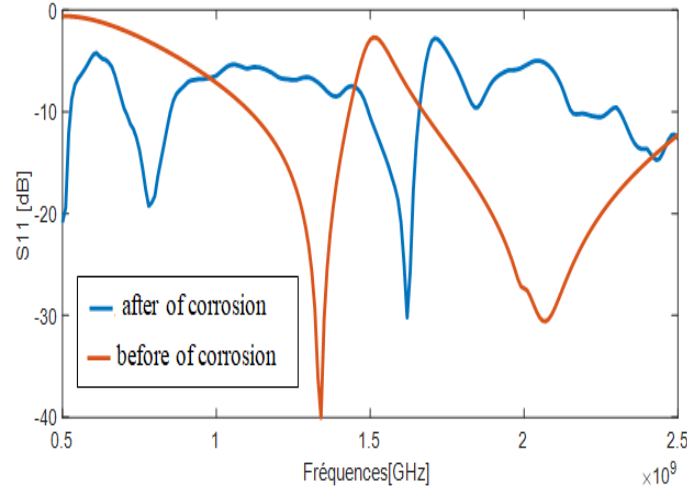


Fig.3. Change in resonant frequency due to corrosion.

$$L_{stub} = \frac{\lambda}{4} = \frac{C}{4 \times F_r \times \sqrt{\epsilon_{eff}}} \text{ (cm)} \quad (1)$$

Where L_{stub} signifies the length of the stub, λ is the wavelength, C is the speed of light, F_r is the frequency at resonance, and ϵ_{eff} represents the effective permittivity of the medium, which is 3.4 for FR4.

As shown by the blue curve, the measurement of the sensor's signal transmission after copper corrosion indicates a frequency shift to $F_{r2} = 1.7$ GHz.

We present in Fig. 3, the evolution of the resonant frequency during one year and 8 months to have the phenomenon of corrosion in the water of the rain and the sea.

The processor for corrosion in rainwater is very slow compared to seawater.

In the case of rainwater, the frequency shift is not observed.

We have not added products to accelerate the corrosion process.

After one year, a frequency shift is observed. The results obtained in real time are shown in Fig. 4. It is clear that there is a resonant frequency offset from 1.3 GHz to 1.7 GHz with an increase in the reflection parameters at port 1 S11 from -40 dB to -30 dB.

The corrosion rate is a function of several parameters, which depend on the metal and the environment. This corrosion rate is determined using (3). This speed is very slow in rainwater compared to sea water, as shown in the Fig. 4 below.

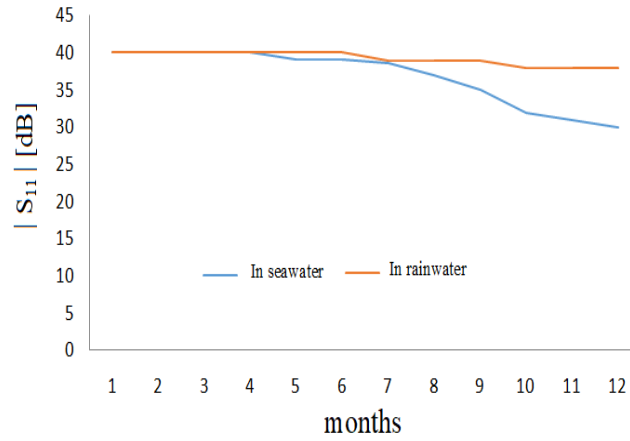


Fig.4. Acceleration of the corrosion process.

6. PRESENTATION SPECIFICATIONS AND MODELING

To address the needs of users of corrosion sensors, we have developed a communication support system. This system functions similarly to an embedded system designed specifically for corrosion monitoring. This system consists of a corrosion sensor and a microcontroller. The data will be sent via Bluetooth and displayed on the screen of a smartphone as a percentage. Regarding the material components and to facilitate the study, the corrosion rate display system will be broken down into three main blocks shown in Fig. 5: the entry, processing, and output blocks.

1. The input block, or sensor block, contains the main component of the data measurement in terms of the corrosion of the medium.
2. Treatment block: The microcontroller is the spirit of the system that is responsible for collecting the data provided by the corrosion sensors, processing this data required to recognize the corrosion rate, and transferring it to the output port to be presented in the final phase.
3. Output block: Output block has two major elements, one for wireless transmission and the other for the final display of the data received. This block consists of linking the two transmitting and receiving parts of our system through a Bluetooth connection established between the HC-05 module and the smartphone, respectively.

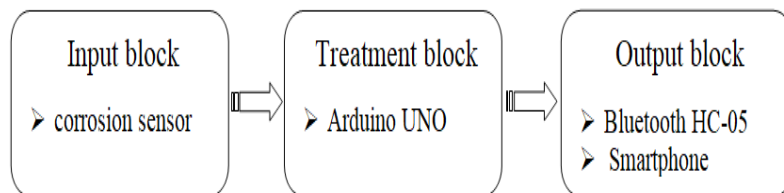


Fig.5. Block diagram of the system hardware environment.

7. REQUIREMENTS SPECIFICATIONS

When establishing the specifications, our system was designed to meet the following requirements:

1. Real-time response: the system will be equipped with a space-saving and sufficiently powerful Arduino UNO to manage the implemented program in real time.
2. Wireless communication : a Bluetooth module will be used to communicate with the smartphone over short distances.
3. Functionality and Ease of use: an Android application will be specially designed for this project and adapted to the needs of the user. It will be easy to use and compatible with the smartphone for display on the screen.

7.1 System Flow Chart

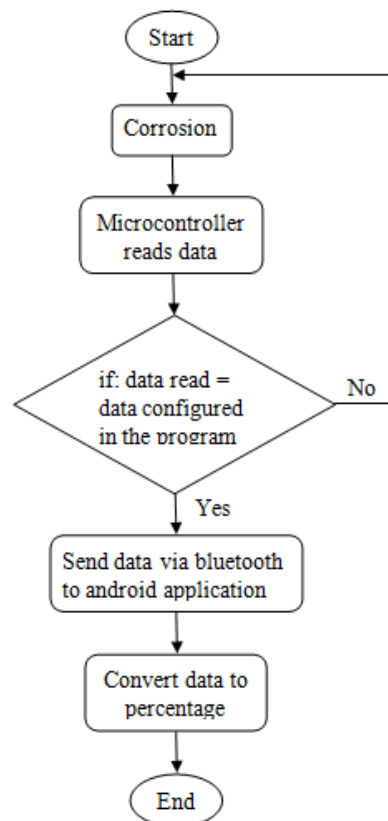


Fig.6. Flow Chart Describing the Study Methodology.

The software part includes the open-source Arduino software (IDE) to program the Arduino UNO and the MIT app Inventor-2 Software tool to develop the Android application, which is downloaded to the smartphone. The program developed under Arduino software is an essential component for the functioning of the corrosion rate recognition system; it is vital for data processing and the effectiveness of the resulting outcomes. As outlined in the flow chart in Fig. 6, the method for recognizing the corrosion rate relies on either matching predefined models or applying learning techniques. The electronic system produced is clearly shown in Fig. 7. We have developed an on-board system to be able to display the corrosion rate

remotely on a smartphone.

7.2 Discussion of The Results Obtained

The whole system is efficient and meets the specifications. The sensor provides good results, and the system accurately detects the corrosion rate from the sensor. The Bluetooth connection between the sensor and the smartphone is synchronized, and the real-time results are highly effective.

A. Corrosion Rate Dynamics

Time and Thickness Effects: Depending on the materials considered, the law giving the corrosion rate as a function of time may be different.

We represented time and the thickness of the corroded metal as t and e , respectively.

$$\frac{de}{dt} = k \quad \text{and} \quad e = k \cdot t \quad (2)$$

Evolution is depicted as a linear progression.

B. Corrosion rate calculation

The corrosion rate is related to corrosion current (i_{corr}) by the following relationship:

$$\text{corrosion rate} = \frac{0.1296 \cdot i_{\text{corr}} \cdot M_a}{d \cdot A} \quad (3)$$

Where i_{corr} is the current density ($\mu\text{A}/\text{cm}^2$), M_a is the mass of metal in grams, d is the density of the metal in g/cm^3 and A represents the exposed area of the metal in cm^2 .

Corrosion rate is commonly expressed in mm/year (millimetres per year).

As shown by the Stern-Geary equation in [16], [17], the polarization resistance can be determined from the corrosion current i_{corr} .

$$R_p = \frac{\Delta E}{\Delta i} = \frac{B}{i_{\text{corr}}} \quad (4)$$

In (4), ΔE represents the difference between the applied potential and the corrosion potential E_{corr} , while B is a constant specific to the corroding metal.

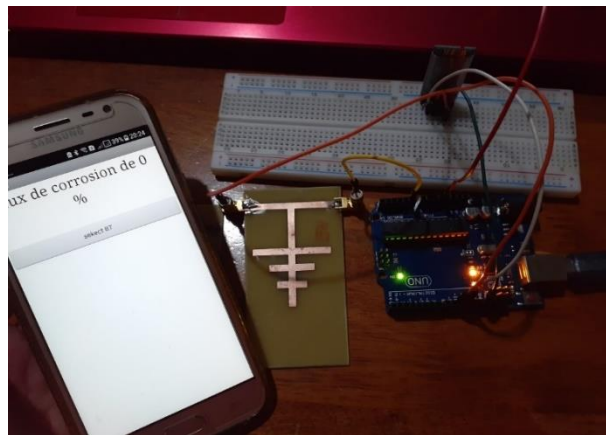


Fig.7. Display of Corrosion Rate for an Uncorroded Sensor on the Smartphone.

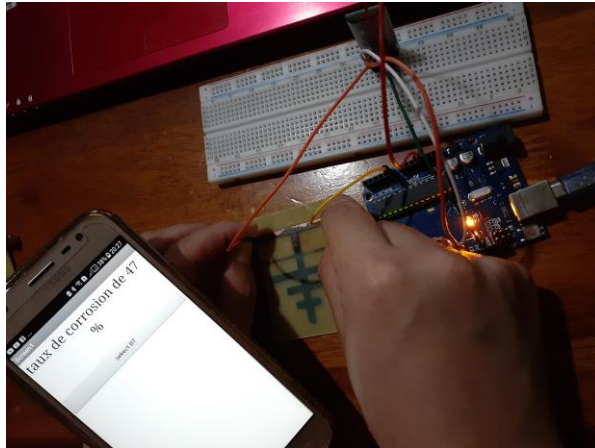


Fig.8. Display of the corrosion rate of a corroded sensor on the smartphone.

Depending on the materials considered, the law giving the corrosion rate as a function of time may be different. Time and the thickness of corroded metal were represented by t and e , respectively.

We have shared the results obtained from the tests conducted on our corrosion sensors. After wiring the system with both the non-corroded and corroded sensors, we observed a corrosion rate display of 0% and 47% on the smartphone, as shown in Fig. 7 and Fig. 8.

The entire system performs quite well, meeting the requirements of the specifications: the sensors provide good results, the system recognizes the corrosion rate of each sensor, the Bluetooth connection between the sensor and the smartphone is synchronized and responds in real-time, and the application displays the received data in percentage (%).

8. CONCLUSION

In this last chapter, we have presented a component sensitive to the evolution of the corrosion potential of metals based on the FR4-differ dielectric substrate, and we have developed a demonstrator that makes it possible to obtain corrosion information remotely via a smartphone.

We cited the material used and presented all the steps we had followed for the validation of the system, and we made frequency measurements to be able to compare the results before and after corrosion. The results demonstrate a strong correlation between the simulation and the measurements.

This work has shown the feasibility and reliability of this on-board system, which controls corrosion using a passive microwave sensor. This technique reads the corrosion rate value and displays it on a smartphone.

9. ACKNOWLEDGEMENTS

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