

## Passive Telemetry Capacitive Humidity Sensor System using RLSE Algorithm

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### Abstract

In this paper, passive telemetry capacitive humidity sensor system using a RLSE(Recursive Least Square Estimation) technique is proposed. To overcome the problem like power limits and complications that general passive telemetry sensor system including IC chip has, the principle of inductive coupling is applied to model the sensor system. Specially, by applying the forgetting factor, we show that the accuracy of its estimation can be improved even in the case of time varying parameter and also the convergence time can be reduced.

**Keywords :** Passive Telemetry RF Capacitive Sensor System, inductive coupling, RLSE, capacitive humidity sensor

### 1. INTRODUCTION

A sensor can be regarded as a device that transforms a physical quantity to be measured into information that can be further processed. Traditionally, a sensor should be powered by an external supply or a battery. But, passive sensors have no extra power source or battery, but also use back scattering for RF communication [1,4].

Therefore, principal concept of RF identification system allows the sensor to be operated without external power supply. Wireless RF sensors are also divided according to the type of electromagnetic coupling; those are, *Inductive type* is used in magnetic field, *Capacitive type* is used in electric field and *Radiating type* is used in radiating field [2].

In this paper, we want to focus on the fact that low-frequency inductively coupled systems are in widespread use in RF identification. The passive sensors require in practice a very short distance, near contact, in fact, between the sensor and the reader head, and have therefore given way to inductive and radiating systems [4]. When properly designed, the production costs of these sensors might be very low. Sensors using Bluetooth or GSM technology can be called, according to these definitions, radiating active sensors.

In this article we focus mainly on radiating passive sensors. The simplest and cheapest wireless sensor is based on an inductor-capacitor resonator. The functionality of this sensor is, however, limited. Data can only be coded into the resonant frequency or the Q-value of the resonance. If an integrated circuit (IC) chip is connected to an antenna, the wireless sensor can have much more complicated functions, because the IC is like a small micro-controller that communicates in both directions wirelessly. If this kind of system tries to be implanted in human body for the purpose of medical care, the power must be limited to  $10[mW/cm^2]$  and the size has to be as small as possible [1].

So, in order to solve this problem of the traditional passive telemetry sensor system, this paper proposes the passive telemetry capacitive humidity sensor system to measure the capacitance of implanted capacitive humidity sensor using RLSE algorithm with forgetting factor. This technique will make it possible to realize new measurements and to reduce the installation costs of the sensors.

### 2. CAPACITIVE HUMIDITY SENSOR

In general, the material of humidity sensor is ceramic, polyamide and so on. Especially, the polyamide is a dielectric material, changing its permittivity with respect to humidity. As humidity increases, the permittivity increases. This characteristic results in the development of a capacitive-type humidity sensor [5]. And capacitive humidity sensor made of polyamide has proper linearity and hysteresis to be used as a sensor. Hence, in this paper, in order to implement the passive telemetry capacitive humidity sensor system, capacitive humidity sensor is selected as time varying capacitance used in sensor part. According to the characteristic of humidity sensor shown in Eq. (1) and Fig. 1, the relation between capacitance  $C_2$  and relative humidity RH can be obtained [5].

$$C_2 = 0.0000225RH^3 - 0.002448RH^2 + 0.3942RH + 162[pF] \quad (1)$$

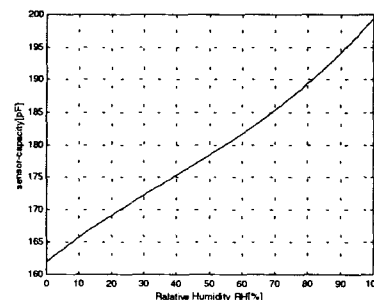


Fig.1 Characteristics of Humidity Sensor

### 3. PASSIVE TELEMETRY CAPACITIVE HUMIDITY SENSOR SYSTEM

General passive telemetry sensor system including IC chip operates as following block diagram.

This system also contains a circuit, like a voltage rectifier, that derives power for the sensor from the field of the transceiver. Fig. 2 shows the concept of a traditional passive wireless RF sensor system. The antenna of a wireless sensor which transmits and receives RF signals is fabricated on a

laminate or a printed circuit board. Because the power available from this supply gets less when the distance between the base station and sensor increases, the power consumption must be very little if long operation distances are required

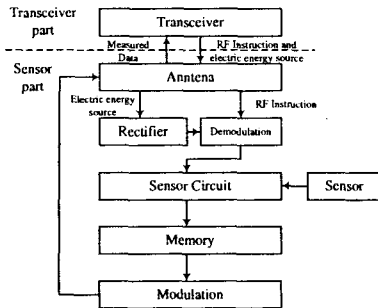


Fig. 2 Block Diagram of the Traditional Passive Telemetry Sensor System

A transceiver sends out a RF instruction signal for measurement, and supplies electric energy sources by giving a regular RF signal. The measured value is transformed into the digital signal, and stored in the RAM. After then, this transformed signal is instantly re-transmitted through an antenna. However, typical passive telemetry sensor system encounters the limits in complication, power consumption, and size in application field. Hence, the system to overcome the limits is need and this paper proposes the passive telemetry humidity sensor system.

### 4. MODELING OF PASSIVE TELEMETRY CAPACITIVE HUMIDITY SENSOR SYSTEM

#### 4.1. Equivalent Circuit of Passive Telemetry Capacitive Humidity Sensor System

The proposed passive telemetry capacitive humidity sensor system is divided into two parts; transceiver and sensor part as Fig. 3. First, the sensor part, comparing to typical passive telemetry sensor system, doesn't have any active components like logic circuit for modulation and demodulation nor memory in order to store the measured data (ie. humidity, pressure, temperature, etc.) inside. Also, it consists of only R, L and C components. So, sensor part to be implanted is very simple. And the transceiver part of the proposed passive telemetry capacitive humidity sensor system plays a role, like AD converting and so on, of the sensor circuit of typical passive telemetry sensor system

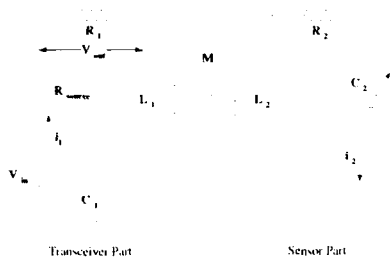


Fig.3 Principle of Passive Telemetry Capacitive Humidity Sensor System

So, the sensor part of the proposed passive telemetry capacitive humidity sensor system can be smaller than typical one [1]. Because the capacitance  $C_2$  shown in Fig. 3 is estimated by applying the principle of inductive coupling, this proposed system can be implemented very simply. Because of the RF source signal  $V_{in}$ , the alternating current  $i_1$  is flowing through the primary source resistance  $R_{source}$ , the line resistance  $R_1$ , the line capacitance  $C_1$  and the inductance  $L_1$  in transceiver side for the purpose of inductive coupling. Hence the secondary electric motive force is induced across the coil inductance  $L_2$  of sensor side by the linkage flux  $Mi_1$ . In this case, because we cannot observe the secondary electric motive force, we must measure the voltage  $V_{out}$  across  $R_1$ . But, the capacitance of passive telemetry sensor gets continuously changed, the impedance of sensor part also various. This means that the reflected impedance equivalent with the impedance of sensor part various too. But the capacitance of sensor can be estimated by monitoring the continuous variation of impedance. Fig. 4 is the transferred equivalent circuit of Fig. 3.

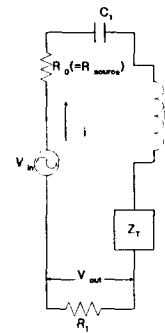


Fig.4 Equivalent Circuit Model of the Proposed Passive Telemetry Capacitive Humidity Sensor System

#### 4.2. Mathematical Modeling of the Proposed Passive Telemetry Capacitive Humidity Sensor System

In Fig. 4, transceiver part and sensor part are coupled inductively with mutual inductance M and impedance of sensor part

$Z_{sensor}$  is included in reflected impedance  $Z_T$ .

$$Z_T = \frac{(\omega M)^2}{Z_{sensor}} = \frac{\omega^2 M^2}{(j\omega L_2 + R_2 + 1/j\omega C_2)} \tag{2}$$

where,  $\omega$  means an angular velocity[rad/sec]. The transfer ratio between the RF input voltage  $V_{in}$  and the measured voltage  $V_{out}$  across  $R_1$  is equal to Eq. (3). Where, M and  $C_2$  are unknown. RLSE is introduced to estimate the variables M and  $C_2$ . In order to simplify this model, Eq. (4) can be rearranged as Eq. (5) and (6).

$$G(j\omega) = \frac{V_{out}}{V_{in}} \tag{3}$$

$$= \frac{R_1}{(R_1 + R_s) + j(\omega L_1 - 1/\omega C_1) - (\omega^2 M^2)/(R_2 + j(\omega L_2 - 1/\omega C_2))} \tag{4}$$

$$\frac{1}{G(j\omega)} = y_1 + jy_2 \tag{4}$$

$$y_1 = \frac{(R_1 + R_0)}{R_1} - \frac{\omega^2 R_2 x_2 / R_1}{R_2^2 + (\omega L_2)^2 - 2L_2 x_1 + x_1^2 / \omega^2} \quad (5)$$

$$y_2 = \frac{\omega L_1 - 1/\omega C_1}{R_1} + \frac{(\omega^2 / R_1) x_2 (\omega L_2 - x_1 / \omega)}{R_2^2 + (\omega L_2)^2 - 2L_2 x_1 + (x_1 / \omega)^2} \quad (6)$$

where,  $x_1 \triangleq \frac{1}{C_2}$ ,  $x_2 \triangleq M^2$

where,  $y_1$  and  $y_2$  can be obtained through the magnitude and the phase of  $G(j\omega)$ .

$$y_1 + jy_2 = \frac{1}{|G(j\omega)|} (\cos\theta + j\sin\theta) \quad (7)$$

where,  $\theta$  is equal to  $-\angle G(j\omega)$ . For the vector type presentation of Eq. (5) and (6), parameters are set as  $x_3 = x_1^2$  and  $x_4 = x_1 x_2$ .

$$\phi_1 x_1 + \phi_2 x_2 + \phi_3 x_3 + \phi_4 x_4 = z_1 \quad (8)$$

$$\phi_5 x_1 + \phi_6 x_2 + \phi_7 x_3 + \phi_8 x_4 = z_2 \quad (9)$$

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} \phi_1 & \phi_2 & \phi_3 & \phi_4 \\ \phi_5 & \phi_6 & \phi_7 & \phi_8 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \quad \text{or}$$

$$\mathbf{Z} = \Phi \mathbf{X} \quad (10)$$

where,  $\mathbf{Z}$  and  $\Phi$  means the outputs of this model and regression variables respectively and will be defined in following chapter 5 in detail.

### 5. ESTIMATION OF VARIABLES AND OUTPUTS BY RLSE

These recursive variables  $\phi_1 \sim \phi_8$  are varied with the applied input frequency  $\omega$ . See Table 1. And four variables  $x_1 \sim x_4$  are estimated by RLSE with forgetting factor  $\lambda$ . The data pairs for the estimation of variables are obtained from gain  $|G(j\omega)|$  and the phase argument  $\angle G(j\omega)$ .

Table 1 Regression Variables  $\Phi$  and Outputs  $\mathbf{Z}$

$\phi_1$	$\left(y_1 - \frac{R_0 + R_1}{R_1}\right) 2L_1$	$\phi_2$	$-\omega^2 R_2 / R_1$
$\phi_3$	$\left(y_1 - \frac{R_0 + R_1}{R_1}\right) \frac{1}{\omega^2}$	$\phi_4$	0
$\phi_5$	$\left(y_2 - \frac{(\omega L_1 - 1/\omega C_1)}{R_1}\right) 2L_2$	$\phi_6$	$\omega^3 L_2 / R_1$
$\phi_7$	$\left(y_2 - \frac{(\omega L_1 - 1/\omega C_1)}{R_1}\right) \frac{1}{\omega^2}$	$\phi_8$	$-\omega / R_1$
	$\left(y_1 - \frac{R_0 + R_1}{R_1}\right) (R_2^2 + (\omega L_2)^2)$		
	$\left(y_2 - \frac{(\omega L_1 - 1/\omega C_1)}{R_1}\right) (R_2^2 + (\omega L_2)^2)$		

The estimation vector  $\hat{\mathbf{X}}(k) = [\hat{x}_1 \hat{x}_2 \hat{x}_3 \hat{x}_4]^T$  is updated with the correction factor  $\mathbf{K}(k)$ . The estimated output  $\hat{\mathbf{Z}}(k) = [\hat{z}_1 \hat{z}_2]^T$  approaches to the measured output  $\mathbf{Z}(k) = [z_1 z_2]^T$  with little deviation. Because this calculation procedure is recursively achieved, this estimation technique can be applied to the online modes [3,6].

$$\hat{\mathbf{X}}(k) = \hat{\mathbf{X}}(k-1) + \mathbf{K}(k)(\mathbf{Z}(k) - \Phi(k)\hat{\mathbf{X}}(k-1)) \quad (11)$$

$$\mathbf{K}(k) = \mathbf{P}(k-1)\Phi^T(k)(\lambda\mathbf{I} + \Phi(k)\mathbf{P}(k-1)\Phi^T(k))^{-1} \quad (12)$$

$$\mathbf{P}(k) = (\mathbf{I} - \mathbf{K}(k)\Phi(k))\mathbf{P}(k-1)/\lambda \quad (13)$$

where, the forgetting factor  $\lambda$  is used in estimating time variant variables  $\hat{\mathbf{X}}(k)$ . By considering the above equations, the estimation model can be depicted as Fig. 5.

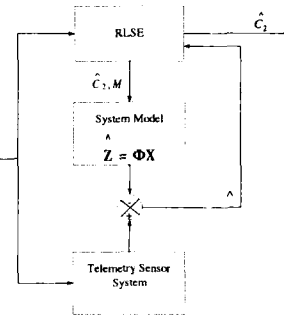


Fig. 5 Block Diagram of RLSE System

Where,  $\omega_{span}[\text{rad/sec}]$  means the angular frequency area between the starting frequency  $\omega_{start}[\text{rad/sec}]$  and the stopping frequency  $\omega_{stop}[\text{rad/sec}]$ . And  $\hat{C}_2$  is the estimated value of  $C_2$  which is obtained in resonant frequency  $\omega_0 = 2\pi f_0[\text{rad/sec}]$ .

### 6. SIMULATION RESULTS

In this section, the simulations for the proposed system are performed to prove the availability of proposed passive telemetry capacitive humidity sensor system.

Table 2 Passive Telemetry Capacitive Humidity Sensor System Parameters

Parameter	Value	Parameter	Value
$L_1$	700[ $\mu H$ ]	Initial $C_2$	4000[pF]
$C_1$	80[pF]	$M$	8.2[ $\mu H$ ]
$L_2$	50[ $\mu H$ ]	$R_{source}$	30[ $\Omega$ ]
$C_2$	160,180,200 [pF]	$R_2$	10[ $\Omega$ ]
$R_1$	5[ $\Omega$ ]	$\omega_{span}$	1[kHz] - 2[MHz]
$\lambda$	1	Distance between coils	2.5[cm]

Table 2 shows each component value used in simulating the proposed telemetry humidity sensor system like Fig. 3. These parameters are setup according to the resonance frequency of this proposed system and implementation. Because it is assumed that the capacitance of humidity sensor is time-invariant, the forgetting factor is defined as  $\lambda = 1$ .

When the capacitances of humidity sensor in the proposed system are assumed as  $C_2 = 160[pF], 180[pF]$  and  $200[pF]$ , Fig. 6 shows the convergence pattern of estimating the gain and the phase of the system for each  $C_2$  according to the above mentioned block diagram of RLSE system.

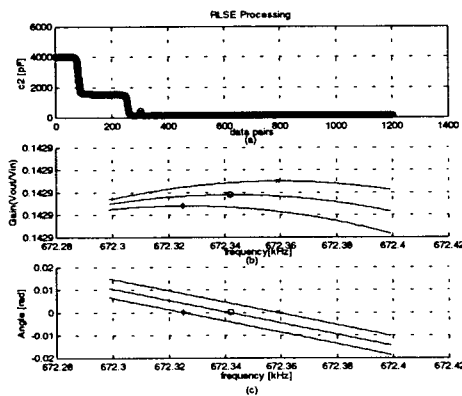


Fig. 6 Convergence Patterns, Gain and Phase Diagrams by RLSE

The capacitance of humidity sensor  $C_2$  estimated using RLSE algorithm is converged to the desired value with a few errors in 1200 data pairs as Fig. 6(a). The notations for '\*', 'o' and 'x' marked in Fig. 6(b) and Fig. 6(c) are denoted as the resonant frequency in  $C_2 = 160[pF], 180[pF]$  and  $200[pF]$  respectively. Fig. 7 shows the relation between the resonant frequency

$$f_0 = \frac{\omega_0}{2\pi} [Hz] \text{ and the calculated capacitance } C_2.$$

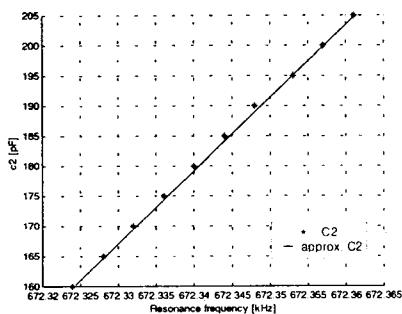


Fig. 7 Resonant Frequency vs  $C_2$

Fig. 8 (a) shows the estimation performances of RLSE algorithm when the capacitance of capacitive humidity sensor  $C_2$  is varying with  $100[Hz]$ . The notation for '-' and 'o' shown in Fig. 8 (a) mean the change of  $C_2$  and its estimated  $C_2$  respectively and the '\*' marked value in Fig. 8 (b) means its estimation errors.

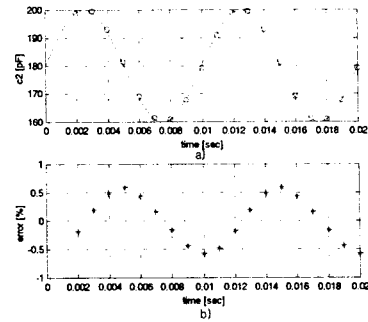


Fig. 8 Simulation for Parameter Estimation for the Time Varying  $C_2$  with  $100 [Hz]$

Where, the forgetting factor was set as  $\lambda = 0.6$ .

### 7. CONCLUSION

Wireless measurements are very important in many application fields where measurements should be made through the impenetrable material. In this paper, the capacitance of passive telemetry capacitive humidity sensor system was successfully estimated with the higher accuracy of mean error  $\pm 0.36[\%]$  using RLSE with forgetting factor. Introduction of a forgetting factor to RLSE algorithm made the estimation time shorten and also achieved higher precise estimation. On the other side, this proposed system has some disadvantages that it cannot be used if it is embedded in a medium material which the RF field can not penetrate such as thick layers of water or some weakly conductive materials. Nonetheless of that defect, the proposed estimation system shall be applicable to the similar implanted sensor system. In the future, the development of the parameter estimation algorithm under the noisy environment is desirable.

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