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Research Article

A Distance Compensated Approach Used in Wireless Passive Pressure Sensor Readout System for High Temperature Application

Yingping Hong,[1,2] Ting Liang,[1,2] Tingli Zheng,[1,2] Qun Cao,[1,2] Wendong Zhang,[1,2] Wenyi Liu,[1,2] Huixin Zhang,[1,2] and Jijun Xiong[1,2]

[1] *Key Laboratory of Instrumentation Science & Dynamic Measurement, Ministry of Education, North University of China, Taiyuan 030051, China*
[2] *Science and Technology on Electronic Test & Measurement Laboratory, North University of China, Taiyuan 030051, China*

Correspondence should be addressed to Jijun Xiong; xiongjijunnuc@126.com

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This paper proposed a distance compensated measurement system for a wireless passive sensor based on the high temperature cofired ceramics (HTCC) applied to high temperature environment. The sensor model is provided and fabricated. Also, a telemetric measurement system consists of a readout instrumentation and a heat insulation unit is described due to the thickness of heat insulation material between the sensor and readout unit's inductance coils in high temperature testing environment. Consideration of the leakage inductance and parasitic parameters which depend on the coupling distance is equivalent to the thickness of heat insulation material, and a distance compensated method is presented. The compensation is based on the mathematical feature of the testing results from readout unit which show us information about the relation between the extracted resonant frequencies. This method can be used simply and reliably in the other telemetric mutual inductance coupling readout system as a viable solution to compensate the coupling distance related error when inductive coupling is varied. It has been experimentally tested, and the results are in good agreement with those measured by a reference impedance analysis instrument. Theoretical explanations, experimental results, and discussion are reported.

1. Introduction

Many harsh environment applications such as aerospace [1], automotive [2], and biomedical [3] industries, or measurement in hermetic boxes do not allow connecting the sensitive element to the measurement circuit or conditioning electronics by the standard cables. Therefore, a completely wireless and passive sensor which is based on an LC resonant circuit is proposed.The parameters in environment to be measured depends on the capacitance. A lot of quantities, for example, temperature, pressure [4–6], and humidity [5], can be measured by the passive wireless sensor in the harsh environment or hermetic space which are incompatible with electronics and it is not accessible. For these cases, the measurements of the quantities are necessary using the sensor by communicating the variables by a telemetric system, due to the fact that it does not require a wiring linking and power supply.

Many previous literatures focus on the optimization design of the wireless passive sensor with its structure and performance [7], and less effort has been made to develop an accurate and reliable readout measurement system for these kinds of wireless passive sensors.

In this paper, a telemetric system was proposed using the passive sensitive element for two main parts. One is the readout circuit which can provide the energy for the sensor and obtained information from the external environment. The other is the sensing element, just a capacitance transducer which is designed and fabricated on the high temperature

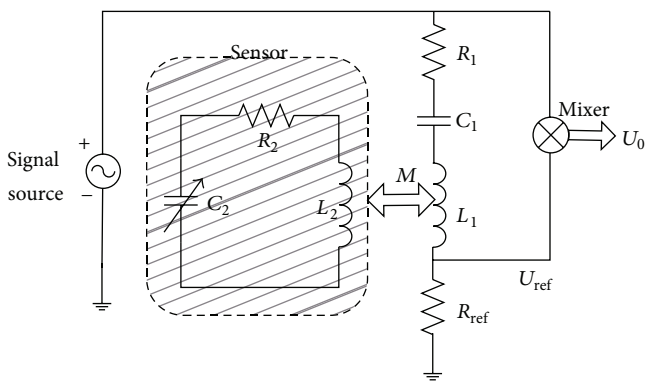


Figure 1: Equivalent circuit diagram of readout system.

cofired ceramics (HTCC) whose performance can withstand the harsh environment [8]. The two parts are connected with each other by the energy of magnetic field. In most cases, we regarded the coupling inductance system model as an ideal transformer, but, because of the leakage fluxes and parasitic parameters related to the coupling distance [9], a compensated measuring method with readout circuit is provided.

In this paper, we proposed a new distance compensated method with a readout circuit which is theoretically analyzed and experimentally tested. In the following, an analog sensor based on the PCB and a wireless passive sensor based on the HTCC are, respectively, designed and fabricated, and the compensated readout circuit is prepared for the experiments. After the compensation, the resonant frequency of the sensor is almost invariant when the coupling distance varies. This compensated system realizes that the test of the resonant frequency of the sensor is not dependent on the distance and the experimental results are in good agreement with the theoretical analysis.

2. Electronic Model and Compensated Method

2.1. Distance Compensated Method. In this paper, the inductive measurement system of the pressure sensor signal proposed consists of a reader antenna, a readout circuit, and a signal processing unit. Figure 1 illustrates the electrical equivalent circuit: the *LC* resonant sensor circuit is modeled with a planar spiral inductor (L_2), a variable capacitor (C_2), and a parasitic series resistance (R_2). An inductor (L_1), a parasitic series resistance (R_1), and a fixed capacitor (C_2) represent the readout circuit. The mutual inductance (M) between the two coupled inductor coils was generated with the signal source.

The relationship of mutual inductance M and vertical coupling distance d between the two identical inductance coils, in the case of the identical dimension of inductance between the two coupled coils, can be given by [10]

$$M = \sum_{i=1}^{Na}\sum_{j=1}^{Nb} M_1\left(a_i, b_j, d\right) + \sum_{i=1}^{Na}\sum_{j=1}^{Nb} M_2\left(a_i, b_j, d\right). \quad (1)$$

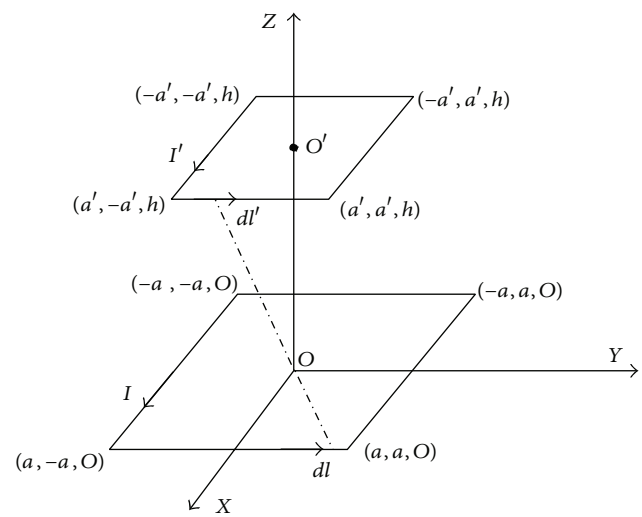
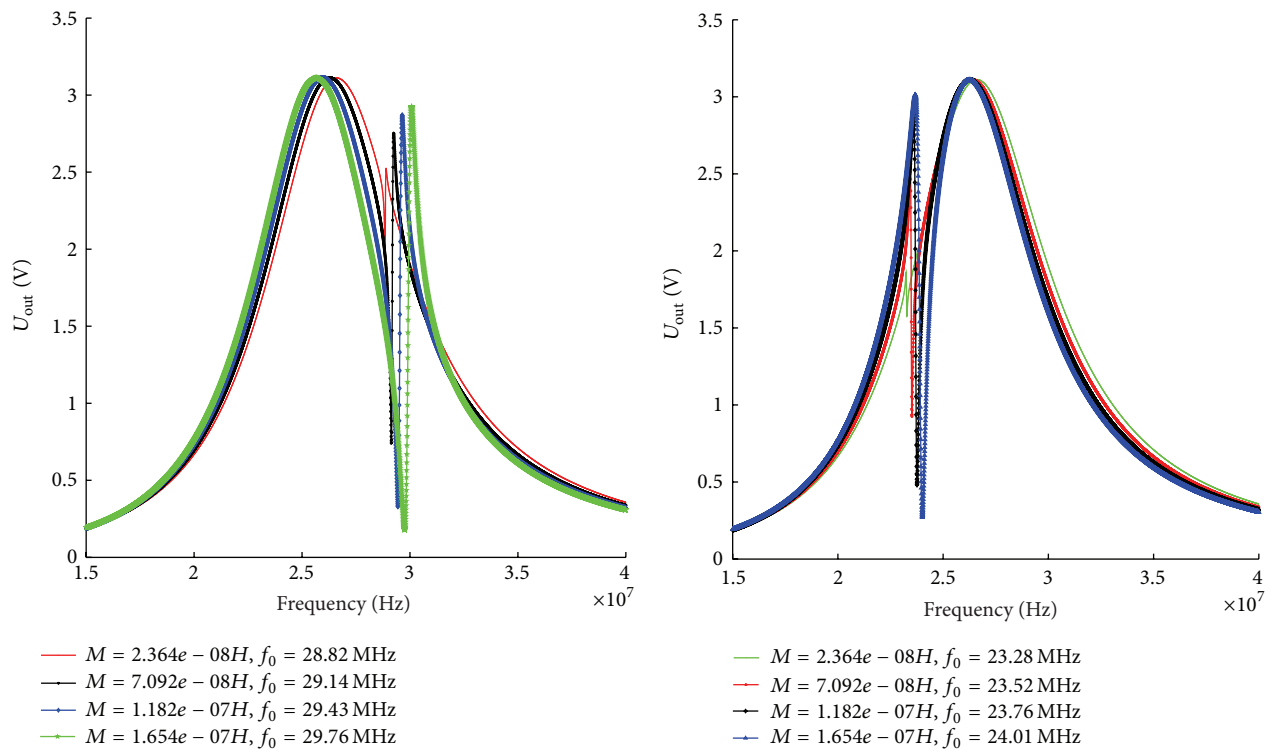


Figure 2: The geometrical relationship of square planar spiral inductors.

Figure 2 is the geometry diagram of two parallel coaxial rectangular planar spiral inductors with loading current, the plane of coil is perpendicular to the axis OO', the bottom coil's side length, number of turns, and loading flow are, respectively, $L(2a)$, N_1, and I_1, and the upper coil is represented as $L'(2a')$, N_2, and I_2, the distance between two planer coils $OO' = h = D$, and D is the coupling distance studied in this work. Because the current I_1 and I_2 have the same flow direction, we can get

$$\begin{aligned} M = \frac{\mu_0}{\pi}\Bigg[&\left(a - a'\right) \\ &\cdot \ln\Bigg(\Bigg(\left(a + a' + \sqrt{2\left(a^2 + a'^2\right) + D^2}\right) \\ &\quad \cdot \left(-a + a' + \sqrt{2\left(a - a'\right)^2 + D^2}\right)\Bigg) \\ &\quad \cdot \Bigg(\left(-a + a' + \sqrt{2\left(a^2 + a'^2\right) + D^2}\right) \\ &\qquad \cdot \left(a - a' + \sqrt{2\left(a - a'\right)^2 + D^2}\right)\Bigg)^{-1}\Bigg) \\ &+ \left(a + a'\right) \\ &\cdot \ln\Bigg(\Bigg(\left(a + a' + \sqrt{2\left(a^2 + a'^2\right) + D^2}\right) \\ &\quad \cdot \left(-a - a' + \sqrt{2\left(a + a'\right)^2 + D^2}\right)\Bigg) \\ &\quad \cdot \Bigg(\left(-a - a' + \sqrt{2\left(a^2 + a'^2\right) + D^2}\right) \\ &\qquad \cdot \left(a + a' + \sqrt{2\left(a + a'\right)^2 + D^2}\right)\Bigg)^{-1}\Bigg) \end{aligned}$$



(a) Frequency to output voltage with $f_0 > f_1$

(b) Frequency to output voltage with $f_0 < f_1$

Figure 3: Simulation of output voltage U_{out} versus frequency f with $f_1 = 26$ MHz at various coupling distances between the reader and sensor coil.

$$+ 2\sqrt{2(a-a')^2 + D^2} - 4\sqrt{2(a^2 + a'^2) + D^2} + 2\sqrt{2(a+a')^2 + D^2}\Bigg]. \tag{2}$$

As can be seen from the formula, mutual inductance varies with the changes of the distance, then there are changes at resonance frequency as a result.

While in terms of the Kirchhoff's law [11], the mixer's output signal voltage U_0 from the terminal of the readout circuit can be defined by the following equation

$$U_0 = \frac{R_{ref}}{Z_1 + (2\pi f M)^2 Y_2} U_1 * U_1 \tag{3}$$

with

$$Z_1 = R_1 + R_{ref} + j2\pi f L_1 + \frac{1}{j2\pi f C_1},$$
$$Z_2 = R_2 + j2\pi f L_2 + \frac{1}{j2\pi f C_2}. \tag{4}$$

Here, f is the frequency of the signal source. Equations (1)–(4) show that output voltage change is caused by the coupling distance, and the output voltage versus frequency is plotted in Figure 3 if the sensor's resonance frequency (f_0) is higher or lower than the resonance frequency of the antenna (f_1). In fact, according to the increased distance, the mutual inductance decreases. Therefore, the simulation has well performed the relationship between the resonant frequency of sensor and coupling distance. As shown in Figure 1, due to the coupling effect, a sudden change in the shape of the output voltage response curve occurs, and the corresponding frequency of the mutation point on the curve is the sensor's resonant frequency.

In the previous papers, due to the distance between the sensitive and the readout components changes, we can see that the parasitic capacitance and the leakage flux between the two circuits cannot be ignored [12], the frequency of the pressure sensor attained from the output voltage of readout circuit depends on the distance.

We define a function "F," which depends only on coupled and leakage fluxes and has sensibility to coupling distance, called compensated frequency. The parameter F can be calculated by the measurement of self-frequency f_0, measured frequency of the sensor obtained from the readout circuit and the varied distance. In fact, the F is a fitting function by the D-value between the measured frequency and the self-frequency of the sensor to obtain an approximate function; the expression is

$$F = |f(d) - f_0|. \tag{5}$$

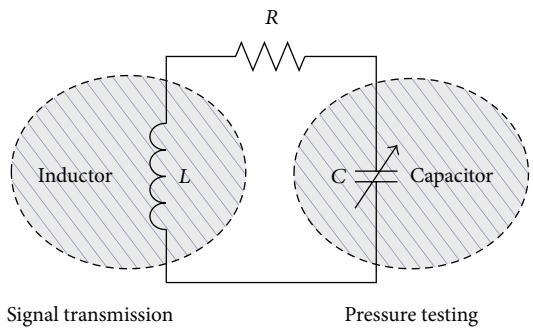


Figure 4: Sensor model.

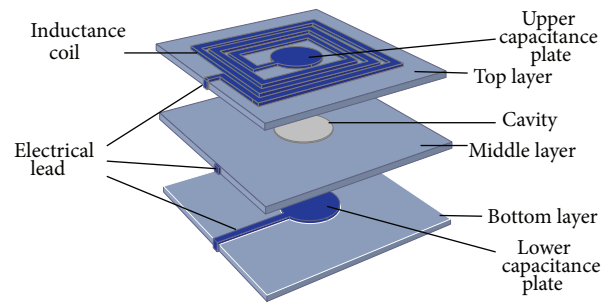


Figure 5: Stereogram of the sensor.

Table 1: Geometrical parameters of the capacitor.

Parameter	Characteristic	Value
Radius of the round electrode plate	r	4 mm
Cavity thickness	t_g	100 μm
Thickness of the sensitive membrane	t_m	100 μm

Table 2: Geometrical parameters of the inductor.

Parameter	Characteristic	Value
Inner diameter	d_{in}	12 mm
Outer diameter	d_{out}	36 mm
Number of turns	n	15
Line width	L_w	0.6 mm

3. Experimental Apparatus Based on Telemetric System

3.1. Sensor Design. The sensor reported in this paper is modeled as a LC series circuit, with a series resistance R and an inductor L in parallel with a variable capacitor C. The sensor model is shown in Figure 4. And the resonant frequency f_0 is given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}}. \tag{6}$$

In this work, we used a general pressure sensor fabricated based on the high temperature cofired ceramics (HTCC); the sensor stereogram is reported in Figure 5. In this three-layer structure, the top and bottom capacitance plates and cavity gap of middle layer forming a capacitor, connected with a planar spiral inductor on the top layer to model the sensor. The geometrical parameters of capacitor and inductor are, respectively, demonstrated in Tables 1 and 2.

The sensor is designed and fabricated in traditional HTCC technology. We use the HTCC green tapes to shape sensor structure and screen printing with Ag paste to form circuit pattern, then stacking, laminating, and cofiring. Figure 6 is the finished sensor sample.

The design parameters of the inductor are shown in Table 1, and the inductance can be derived as

$$L = \frac{k_1 \mu_0 n^2 d_{\text{avg}}}{1 + k_2 \rho}, \tag{7}$$

where $k_1 = 2.34$ and $k_2 = 2.75$ are shape coefficients, μ_0 indicates the permeability of vacuum, n is the number of coil turns, d_{avg} is the average diameter, ρ is the fill ratio, and

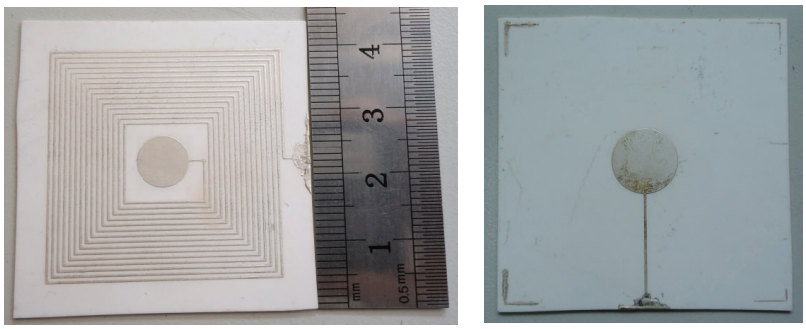
$$d_{\text{avg}} = \frac{d_0 + d_i}{2}, \qquad \rho = \frac{d_0 - d_i}{d_0 + d_i}, \tag{8}$$

where d_i is the inner diameter and d_0 is the outer diameter.

The theoretical inductance geometrical parameters are calculated from (7)-(8), which is conductive to improve the coupling distance and quality factor and the improved designed parameter demonstrated in Tables 1 and 2.

3.2. Readout Instrumentation. In order to measure the sensor's resonance frequency for stability and robustness of automatic resonance detection under a wide frequency range, a readout system combined with PC after processing was adopted. Therefore, the readout circuit generates a swept-frequency signal in a specific frequency range to measure resonance frequency of the sensor. With the PC postprocessing software, we can calculate the resonance frequency from the readout circuit and compensate the error caused by the varying reading distance. In this approach, the readout circuit avoiding the distance limitations will be presented to be suitable for resonance frequency detection under a wide range of measuring distance. When there is a remote wireless passive sensor close to the reading antenna, then the mutual inductance coupling occurs, the DC output voltage changes, and mutation points appear. The sensor's sensitive capacitance makes differences according to the environmental pressure change and the corresponding resonance frequency of LC sensor varies as the mutation point moves on the frequency axis with the change of environmental pressure. Figure 7 shows the flow chart of the measurement system.

3.3. Experimental Apparatus. In order to verify the compensated method proposed, a readout circuit, an analog sensor, and antenna have been made. Table 3 shows the design parameters of the sensor and antenna which are designed based on the printed circuit board (PCB) and the inductors are consistent. The analog sensor and antenna are shown in Figure 8, which have the same geometrical parameters.



Top view Bottom view

Figure 6: Finished sensor sample.

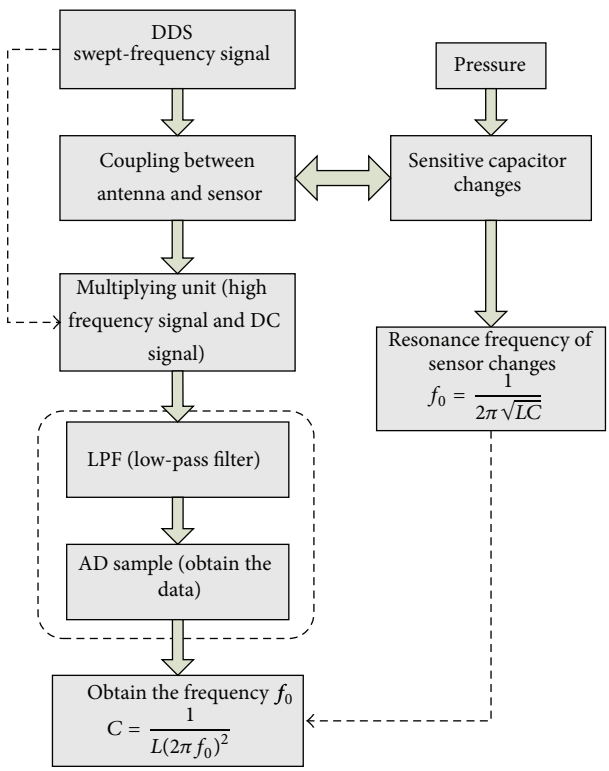


Figure 7: The flow chart of the measurement system.

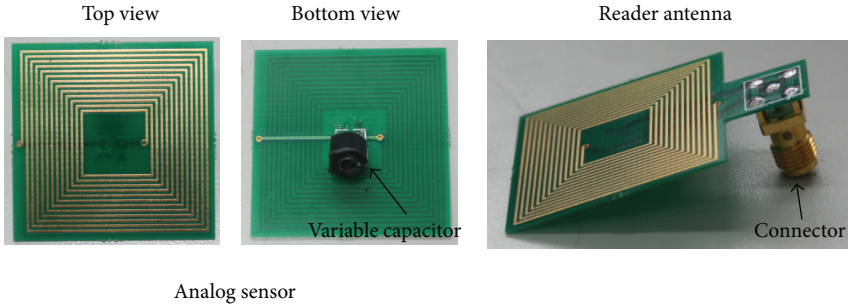


Figure 8: Analog sensor and antenna.

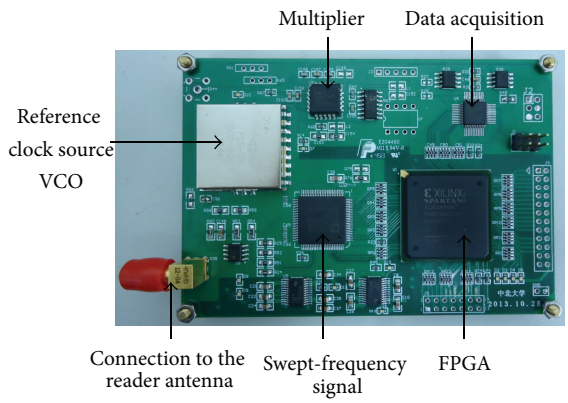


Figure 9: Readout circuit.

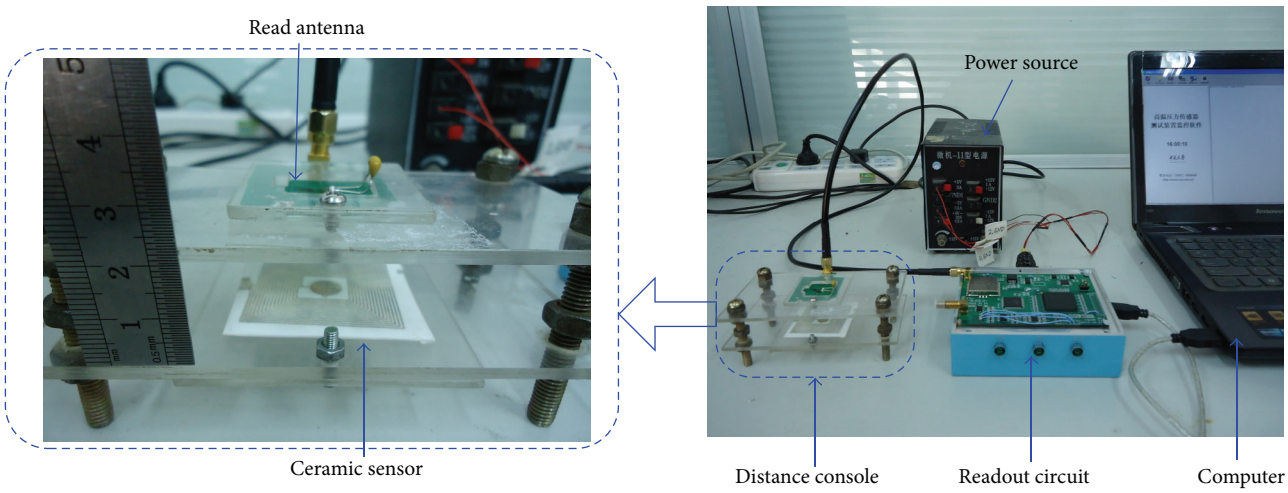


Figure 10: Experimental system with distance compensation.

Table 3: Parameters of analog sensor and antenna.

Parameter	Characteristic	Value
Inductance of sensor and antenna	L_1, L_2	1982 nH
Capacitance of the antenna	C_1	30 pf
Capacitance 1 of the sensor	C_2	25 pf
Capacitance 2 of the sensor	C_2'	36 pf

Table 4: Test values of the sensors with impedance analyzer.

Resonance frequency	Characteristic	Theoretical value (MHz)	Test value (MHz)
Analog sensor 1	f_0	18.84	19.39
Analog sensor 2	f_0'	22.61	23.26
Reader antenna	f_1	20.64	21.24
Ceramic sensor	f_{c0}	17.4	20.11

A readout circuit designed using analog integrated circuits on a PCB is reported in Figure 9. The sinusoidal signal with a sweep frequency and the output voltage signal on both sides of the reference resistance (Rref) are multiplied through the Gilbert cell-based mixer (Multiplier), and a low-pass filter circuit is designed to filter the mixer's output signal in a DC output voltage. While a fast 16-bit ADC (AD7667) is designed to convert the DC output voltage into a digital form.

There are two different resonant frequencies of analog sensors and a ceramic sensor and the self-frequency of them have been measured by the Agilent E4991A impedance analyzer. Their values are shown in Table 4, which will be the reference ones added to the measured values of sensor frequencies tested with the readout circuit. Figure 10 reports a photo of the experimental system. It consists of a readout circuit, a sensor, a coupling distance console, and computer. And it is possible to change the distance between the two coupling coils, which are placed facing one another with their central axes coincident.

4. Experimental Results

A series of experiments on the distance compensated system have been carried out with variational distance between the two coupling inductance coils. The measured resonant frequency of the readout circuit versus the adjustable distance

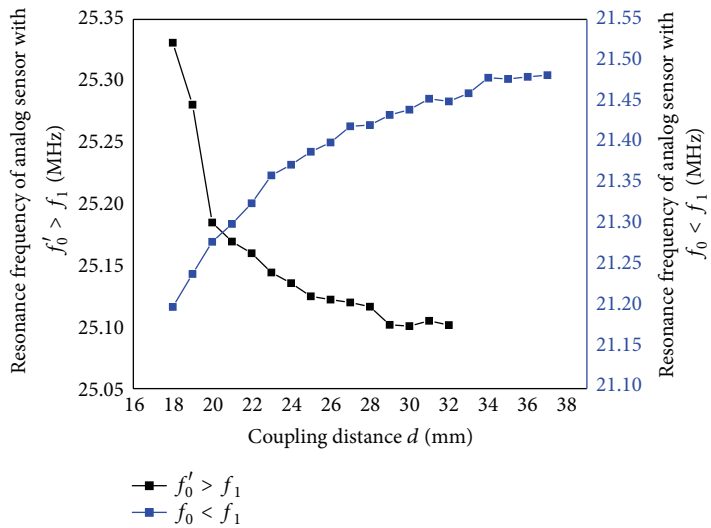


Figure 11: Resonant frequency of analog sensor versus the coupling distance.

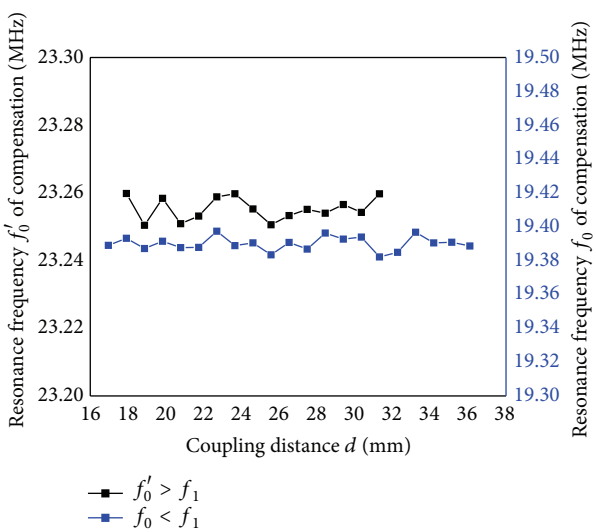


Figure 12: Resonant frequency of analog sensor with distance compensation.

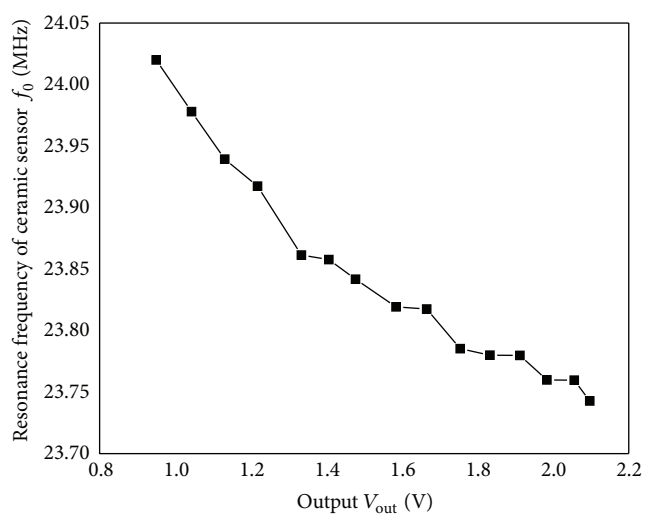


Figure 13: Resonant frequency of ceramic sensor versus the coupling distance.

using the analog sensors inductively coupled to the reader antenna, when there are two different cases: the resonant frequency of the sensor is higher and lower than the antenna, as shown in Figure 11. Analyzing the graphs, these resonant frequencies depend mainly on the distance and are in agreement with the theoretical analysis. However, the fitting function "F" has been used to calculate, according to (5), the resonance frequency of the analog sensors with variational coupling distances. We can add the compensated values to the readout circuit procedure whose test results obtained from the readout circuit are shown in Figure 12, demonstrating that these measured resonant frequencies of the analog sensors are almost insensitive to the distance variation, and the compensation values are, respectively, 19.38 MHz and 23.25 MHz which is approximate to the test values in Table 4.

Figure 13 shows that the resonant frequency of the sensor which is based on the ceramic with uncompensation is in agreement with the analog sensor. However, using the distance compensation method can lead to the results shown in Figure 14, which is insensitive to the coupling distance.

5. Conclusion

A new distance compensated test system for a wireless passive sensor based on the high temperature cofired ceramics (HTCC) has been provided. It is necessary to take the parasitic effects and coupled and leakage fluxes into consideration when coupling distance varies between the inductance coils of the sensor and antenna. Theoretical models of the sensors and distance compensated test system in this paper are provided and analyzed. The simulation analysis of the

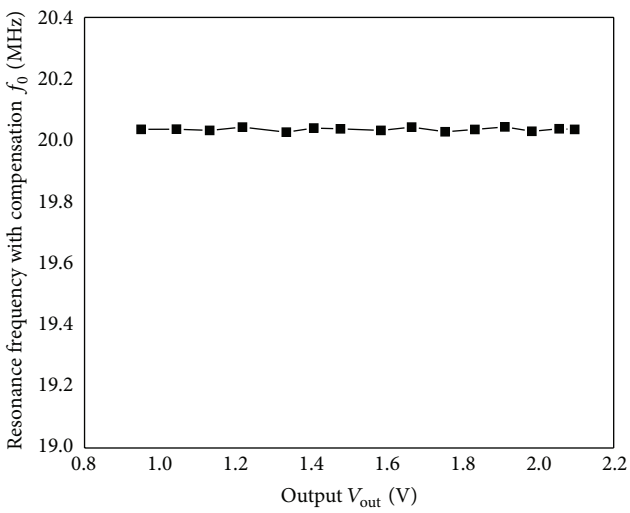


Figure 14: Resonant frequency of ceramic sensor with distance compensation.

coupling system shows that the resonant frequency of the sensor obtained from readout circuit obviously depends on the change of coupling distance. This distance compensation method has been experimentally tested, and the results are in good agreement with the theories. It measures the resonant frequency of the sensor with different distance. While adding the compensated frequency to the test system, we can see that the results are almost not sensitive to the variable distance. In addition, the distance compensated method that we proposed in this paper can be applied to different coupling inductance test systems regardless of the test distance.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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