13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-107

A Wireless Passive RFID Patch Antenna Strain Sensor

Chengkai Wei[1], Jingkang Shi[1], Zhenchang Guan[1]
[1]Department of Intelligent Construction, College of Civil Engineering, Fuzhou University,
Fuzhou City, Fujian Province, China
email: Chengkai Wei,240527093@fzu.edu.cn,
Jingkang Shi,jkshi@fzu.edu.cn,
Zhenchang Guan,zcguan@fzu.edu.cn

ABSTRACT: With the aging of civil infrastructures, strain monitoring is essential for predictive maintenance. However, current sensing technologies mainly rely on active battery powered sensors, leading to substantial expenses and low placement granularity. This paper proposes a wireless, passive RFID patch antenna strain sensor, characterized by a favorable linear relationship between its resonant frequency and the applied strain. In this paper, simulation is carried out by using the COMSOL multi-physics coupling software. The solid mechanics field is coupled with the electromagnetic field, and the frequency-domain scanning is conducted after the model generates strain. The simulation results are compared with the experimental results in the literature to determine their correctness. According to the simulation results of the scattering parameter S11, a patch antenna sensor is designed and fabricated, and corresponding experiments are conducted to detect the variations of the spectral curve before and after the sensor is embedded in concrete, thereby verifying its validity. Finally, the sensor is optimized based on the experimental results.

KEY WORDS: Wireless; Passive; Strain Sensor; RIFD; Patch Antenna.

1 INTRODUCTION

In the field of structural health monitoring (SHM), acquiring accurate, long-term, and stable monitoring data remains a core concern. Structural strain, a critical indicator reflecting the health status of structures, effectively characterizes local deformation and precisely reveals internal stress distributions and health conditions [1]. Traditional strain sensors typically employ wired connections using conductors or optical fibers as media. In large-scale structures, extensive cabling works are cumbersome, costly, and further exacerbated by the complexity of wiring and the need for relay devices, increasing economic burdens. Moreover, excessive cabling significantly amplifies resistance and introduces noise interference, severely degrading strain measurement accuracy and failing to meet high-precision monitoring requirements.

Digital image-based methods [2] leverage precision optical instruments and advanced image processing algorithms to obtain high-accuracy strain data. However, these methods have notable limitations: they impose stringent requirements on light source conditions, limiting adaptability in low-light environments such as tunnels; they also demand extreme equipment stability, making sustained and accurate measurements challenging in complex outdoor settings. The complexity of algorithms and harsh measurement conditions restrict their long-term monitoring applications.

Radio Frequency Identification (RFID) technology, a mature wireless information transmission method [3], has garnered substantial attention from scholars due to its compact size and low cost. Peng Guofeng et al. [4]proposed a wireless passive RFID humidity sensor based on U-shaped resonant units, achieving environmental humidity detection and encoding capabilities through grouped U-shaped resonators. Wang Xian et al.[5] designed a miniaturized wireless passive strain sensor array using split-ring resonators to detect strain magnitude and direction on metal surfaces. Wang Bo et al.[6] developed a wireless passive metal crack sensor using RFID technology, detecting surface cracks by measuring radar cross-section (RCS) values.

Integrating RFID technology with sensors introduces a novel approach for structural strain measurement. This paper presents a rectangular patch antenna-based wireless passive strain sensor using RFID technology, simulated in COMSOL Multiphysics finite element analysis software. This sensor offers low cost, non-contact measurement, and passive operation, effectively addressing challenges such as cumbersome cabling, noise interference, and real-time power supply limitations in wired systems. Compared to other strain sensors, it features a simple structure and high sensitivity (4.45 kHz/με), demonstrating significant advantages and promising applications in SHM[7].

2 THE PRINCIPLE OF ANTENNA STRAIN SENSOR

2.1 Relationship Between Strain and Resonant Frequency

The patch antenna strain sensor achieves precise strain measurement by detecting shifts in the antenna's resonant frequency. The resonant frequency, as the optimal operating frequency of the antenna, exhibits distinct electrical characteristics: when the antenna operates at its resonant frequency, the backscattered energy reaches its minimum while the received energy attains its maximum. The resonant frequency shift of the patch antenna is closely linked to changes in antenna dimensions. Specifically, alterations in antenna geometry inherently modify the electrical length. An increase in electrical length leads to a decrease in resonant frequency, whereas a reduction in electrical length results in an increase in resonant frequency.

The RFID-based rectangular patch antenna wireless passive strain sensing structure is illustrated in Figure 1. The sensor consists of an upper radiating patch, a feed line, a dielectric

DOI: 10.3217/978-3-99161-057-1-107

substrate, and a lower radiating patch. The upper radiating patch detects strain and facilitates signal transmission/reception, while the lower radiating patch grounds the sensor. The feed line serves dual purposes: providing electrical feed and impedance matching. Both radiating patches and the feed line are fabricated from copper. The dielectric substrate, positioned between the upper and lower radiating patches, is constructed from RO4003C material with a dielectric constant of 3.55.

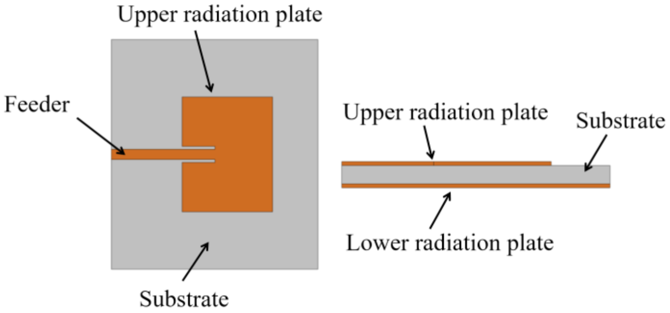

Figure 1. Sensor schematic diagram.

According to classical theory, the initial resonant frequency of a rectangular patch antenna can be expressed as:

$$f_{RO} = \frac{c}{4\sqrt{\varepsilon_e}} \frac{1}{L_1 + 2\Delta L_1} \quad (1)$$

Where f_{RO} is the resonant frequency of the antenna under the initial condition; c is the speed of light in a vacuum; ε_e is the equivalent dielectric constant of the dielectric plate;; L_1 is the length of the upper radiation patch; ; ΔL_1 is the additional length of the antenna, which is related to the antenna width, thickness and material.

When the antenna experiences strain ε in the length direction, the resonant frequency f_R changes accordingly. For: $\Delta L_1 \leq L_1$, f_R exhibits an approximately linear relationship with strain, expressed as:

$$f_R \approx \frac{c}{4\sqrt{\varepsilon_e}} \frac{1}{L_1(1+\varepsilon)} = \frac{f_{RO}}{(1+\varepsilon)} \approx f_{RO} \ (1-\varepsilon) \quad (2)$$

From equation (2), it can be seen that f_R is mainly affected by strain in the direction of antenna length, and f_R has A linear relationship with ε, the slope is about equal to f_{R0}, that is, every 1με strain occurs, the resonant frequency of the antenna will decrease $f_{RO} \times 10^{-6}$.

Since the substrate thickness is much smaller than the length-width size, the dielectric constant of the antenna substrate is approximately the same as the relative dielectric constant:

$$\beta_r = \frac{\beta_{r0}+1}{2} + \frac{\beta_{r0}-1}{2}[1 + 12\frac{h}{w}]^{-1/2} \cong \beta_{r0} \quad (3)$$

Where:$\beta_r$is the effective dielectric constant of the antenna substrate; h is the thickness of the substrate; $w$is the width of the substrate;β_{r0}indicates the relative dielectric constant of the substrate at room temperature.

2.2 *Resonant Frequency and Echo Reflection Coefficient*

With full The antenna's echo reflection coefficient (S_{11}) is a metric that quantifies the ratio of reflected signal power to incident signal power at the antenna port, reflecting the degree of signal matching. A signal transceiver emits an electromagnetic wave with frequency f and power P_{in}. The wave is reflected by the antenna and received by the transceiver with power P_{ref}. The echo reflection coefficient S_{11} at this frequency is calculated using Equation (4):

$$S_{11} = 10\lg\left[\frac{P_{in}}{P_{ref}}\right] \quad (4)$$

By transmitting an electromagnetic wave spectrum to the antenna and using a signal transceiver to record the echo reflection coefficient S_{11} at each frequency, the echo reflection curve (i.e., the S_{11} curve) across the frequency band is obtained. The minimum point of the S_{11}curve corresponds to the antenna's resonant frequency under the given conditions. As theoretically derived in the previous section, the minimum point of the S_{11} curve shifts when strain is applied, indicating a change in the resonant frequency, as illustrated in Figure X. Here, f_{R0} denotes the initial resonant frequency, and f_R represents the resonant frequency after strain application.

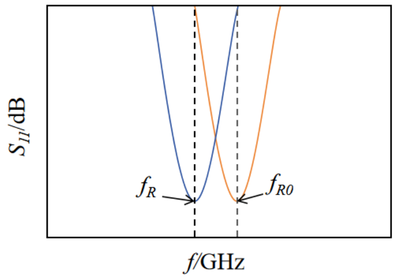

Figure 2. The shift of resonant frequency.

3 SIMULATION AND PARAMETER OPTIMIZATION

3.1 *Finite element modeling of the antenna*

The finite element analysis software used in this simulation is COMSOL. COMSOL's multiphysics coupling can accurately describe the interactions between different physical phenomena and achieve multi - field collaborative simulation by establishing and solving the coupled partial differential equations of each physical field.

Following optimization, the Geometric Dimensions of the Sensor in [Table 1] below:

Table 1. Geometric dimensions of the sensor.

Thickness of substrate/ t_1	0.8mm
Thickness of metal/t_2	35μm
Width of patch/W_1	20mm
Length of patch /L_1	16mm
Width of substrate/W_2	40mm
Substrate length/L_2	36mm
Width of feed line/W_3	1.8mm
Length of feed line/L_3	18mm

In addition, the dielectric constant of the dielectric substrate is 3.55.

DOI: 10.3217/978-3-99161-057-1-107

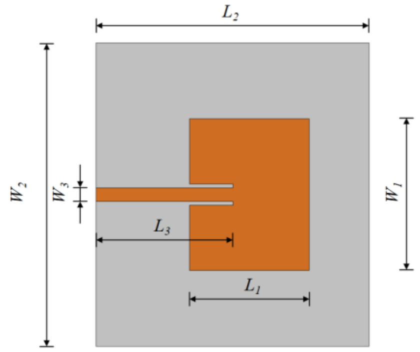

Figure 3.Dimensional schematic diagram of the sensor.

The simulation of the patch antenna strain sensor in this paper adopts the dual-physics-field coupling of the electromagnetic field and the solid mechanics field, enabling the calculation of the change in the resonant frequency of the antenna after strain occurs within a single model. The 3D model of this antenna is shown in the following figure. The outer shell-shaped structureis a perfectly matched layer (partially hidden) , which serves to absorb the electromagnetic waves propagating outward, thereby simulating the open boundary conditions without reflection.

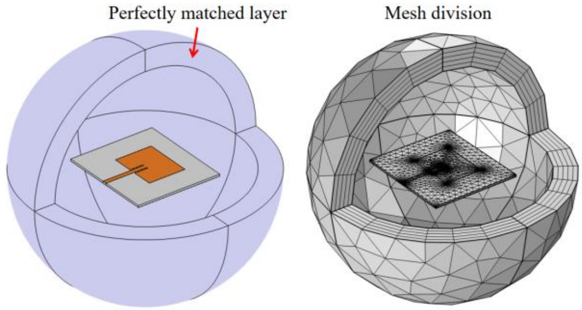

Figure 4. Sensor's finite element model.

First, an adaptive frequency sweep is performed on the antenna under strain-free conditions, and the curve is plotted to obtain its initial resonant frequency, as shown in the following figure.

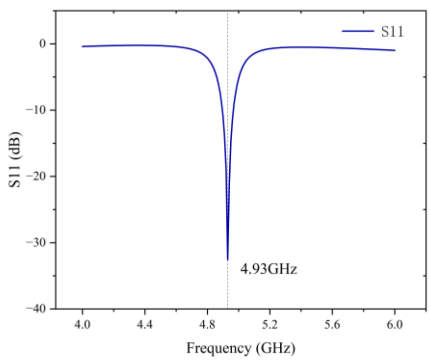

Figure 5. Initial resonant frequency.

Apply a specified displacement to the antenna in the length direction of the antenna through the solid mechanics field to simulate the generation of strain in the length direction of the patch antenna. The total strain is set to 4000 $\mu\varepsilon$, and the step size of strain increase each time is 400 $\mu\varepsilon$. Obtain the curves under different strain values, and according to the obtained results, plot the linear regression curve of the relationship between the strain and the resonant frequency.

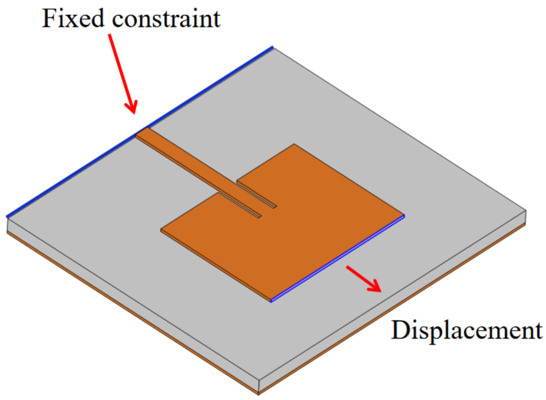

Figure 6. Schematic diagram of Strain.

3.2 *Modeling Results*

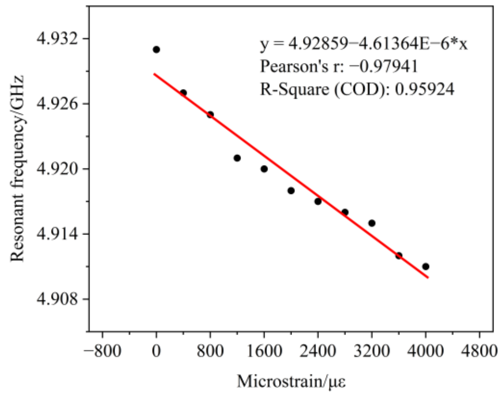

Figure 7. The relationship between resonant frequency and microstrain.

As shown in the figure, the regression coefficient is 0.979, indicating that there is a good linear relationship between the resonant frequency of the antenna and the strain in the length direction. The sensitivity of the antenna as a strain sensor is 4.6136 kHz/με. The relative error between the simulation result and the theoretical calculation value of 4.45 kHz/με is 3.68%.

4 CONCLUSION

In response to the imperative for wireless strain detection of building structures within the domain of structural health monitoring, leveraging the pronounced radiation efficiency, minimal power dissipation, and elevated quality factor characteristic of rectangular patch antennas, a wireless passive rectangular patch antenna strain sensor was meticulously devised. This design is firmly grounded in Radio - Frequency Identification (RFID) technology. Concurrently, a comprehensive finite - element analysis (FEA) simulation of the sensor was successfully executed.

The simulation outcomes unambiguously demonstrate that the sensor exhibits a sensitivity of 4.6136 kHz/με along the lengthwise dimension of the patch, with a linearity regression

DOI: 10.3217/978-3-99161-057-1-107

coefficient of 0.959. These strain - related simulation results incontrovertibly validate the viability of deploying an RFID - enabled rectangular patch antenna as a wireless passive strain sensor.

Looking ahead, the fabrication of the sensor will be expeditiously completed, and a series of well - designed tensile experiments will be carried out. These experiments are intended to rigorously verify the sensor's detection performance under diverse real - world working conditions. Post - experimentation, a secondary optimization of the sensor's structure will be implemented, with the explicit aim of further enhancing its sensitivity and thereby attaining a more superior strain - detection outcome.

REFERENCES

[1] Zhou Zhi, Ou Jinping. Intelligent Health Monitoring and Diagnosis System for Civil Engineering [J]. Journal of Transducer Technology, 2001(11): 1 - 4.
[2] Li Xianbao. Measurement of Material Tensile Strain Based on Machine Vision [D]. Jilin University, 2020.
[3] JIA X, FENG Q, FAN T, et al. RFID technology and its applications in internet of things (IoT)[C] The 2nd international conference on consumer electronics, communications and networks (CECNet), IEEE, 2012: 1282-1285.
[4] Peng Guofeng, He Xingli, Li Peng, et al. Wireless Passive RFID Humidity Sensor Based on U-shaped Resonant Unit [J/OL]. Chinese Journal of Radio Science, 1 - 7 [April 16, 2025].
[5] Wang Xian, Gao Shang, Yang Shangke, et al. Design of Miniaturized Wireless Passive Strain Sensor Array Based on Split Ring Resonators [J/OL]. Journal of Electronic Measurement and Instrumentation, 1 - 11 [April 16, 2025].
[6] Wang Bo, Hou Rongrong, Wang Ke, et al. A Metal Crack Sensor Based on Wireless Passive RFID Technology [J]. Journal of Huazhong University of Science and Technology (Natural Science Edition), 2025.
[7] Huang Cheng. Research on the Development of Passive Strain Sensors Based on RFID System [D]. Zhejiang University, 2020.