Passive RFID Antenna Sensor Technology for Structural Behavior Monitoring

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Abstract— **This study introduces a novel approach for strain measurement by employing antenna sensors and Radio Frequency IDentification (RFID) readers. The functionality of passive antenna sensors is based on the alteration of resonant frequency due to structural deformation. Custom software was developed to manage RFID readers and collect data on the relationship between signal strength and frequency. The system was validated through experiments tensile strain of aluminum plates with antenna sensors and strain gauges. The antenna sensors showed an error of 5% compared to strain gauge measurements, which confirms the feasibility of using antenna sensors. Antenna sensor technology is anticipated to be utilized in various fields in the near future.**

Keywords-Antenna sensor; RFID; Resonant frequency; Strain Monitoring; Structural behavior.

I. INTRODUCTION

The construction industry is rapidly developing, and structural safety is a significant challenge in this field. Conventional wired measurement methods have limitations in sensor durability and require substantial installation and maintenance labor costs, making long-term and reliable monitoring difficult. This paper presents the result of our research on improving deformation measurement technology using passive Radio Frequency Identification (RFID) antenna sensors.

Recent advancements in Structural Health Monitoring (SHM) have led to the exploration of innovative sensing technologies, particularly passive RFID antenna sensors. These sensors offer real-time, wireless monitoring of structural behavior, providing engineers with valuable insights into infrastructure integrity. Wired methods for SHM are often hindered by sensor durability, complex installation, and high maintenance costs. Integrating the passive RFID antenna sensors into SHM systems represents a significant shift, overcoming many challenges of traditional sensor technologies. These sensors detect structural deformations via changes in resonant frequency, offering accurate measurements without direct physical contact. Additive manufacturing has improved sensor versatility by allowing for customizable shapes and materials to be used in various monitoring scenarios.

These systems offer the potential for real-time, wireless tracking and monitoring of physical, chemical, and mechanical properties, as well as environmental conditions [1]. Moreover, the advent of wireless and passive RFID technologies has ushered in a new era of intelligent strain monitoring systems for large-scale engineering structures [2].

However, despite the significant progress in this field, accurately detecting and characterizing defects based on passive antenna sensors in a remote distance poses special challenges due to the limited transmitting power and fading effect of Radio Frequency (RF) signals. Therefore, it is necessary to systematically study these challenges.

Passive RFID antenna sensors measure the deformation of structures by detecting the change of resonant frequency occurred by deformation [3][4]. Traditional antenna sensors are manufactured through chemical etching, which is time and cost ineffective. Therefore, we applied an additive manufacturing method through 3D printing and evaluated the performance by applying various materials to the elements of the antenna sensor [5]. Previous research on the measurement of structural deformation using passive RFID antenna sensors was addressed and validated at the laboratory scale. Therefore, there are still challenges to be overcome to commercialize the technology. In general, high-precision RFID testers have higher scanning resolution than commercial RFID readers. However, scanning with high-precision testers is time-consuming. In order to commercialize antenna sensor technology, measurement time must be reduced while measurement accuracy is increased.

The primary objective of our research is to commercialize strain measurement technology by using passive RFID sensors. In this paper, we introduce a developed methodology and software that derive accurate resonant frequencies from a smaller data set (signal strength versus frequency data) to achieve our main goal. Passive RFID antenna sensors were utilized in this research, which currently have maximum scanning distance of 2 meters and minimum measurement cycle time of 20 seconds.

Tensile testing of aluminum plates with antenna sensors and strain gauges attached was conducted, and the performance of the developed software and passive RFID antenna sensors was verified to determine accurate resonant frequencies. Further study is still required for improvement of passive RFID antenna sensor technology.

The paper is organized as follows. Section II provides a brief introduction to the components and operation of the passive RFID antenna sensor. Section III describes the

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additive manufacturing process for antenna sensors using 3D printers and various materials. Section IV explains the proper scan resolution to increase efficiency when measuring resonant frequencies using commercial RFID readers. Finally, Section V concludes our paper and proposes area of future work.

II. Passive RFID Antenna Sensors

A. *Methodology*

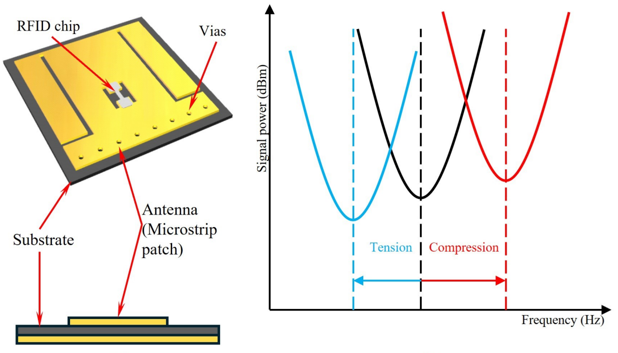
Passive RFID antenna sensors are organized with metallic ground plane (bottom), dielectric substrate (middle), microstrip patch antenna (top) and RFID chip. The antenna on the top surface is connected to the ground plane on the bottom surface through vias. The sensors are designed to operate using RFID in the Ultra High Frequency (UHF) range, specifically 868 ~ 956 MHz. The passive RFID antenna sensors are affixed to the structure (Figure 1(a)). As the structure deforms, the sensor deforms with it, causing a change in the sensor's resonant frequency that follows a negative linear relationship between strains and resonant frequencies. The relationship equation, (1), is obtained through linear regression. The first term coefficient, slope, represents the resonant frequency change characteristic of the sensor in response to deformation and is called the Sensor Factor (SF).

$$\varepsilon = \mathrm{SF} \cdot (f_r - f_{r,0}) \tag{1}$$

It is possible to calculate the strain, ε, of the structure at each stage of deformation by using the measured resonant frequency, f_r, at each stage, a known sensor factor and initial resonant frequency, $f_{r,0}$ (Figure 1(b)).

B. *Materials and Manufacturing*

Antenna sensors are typically produced using chemical etching. However, this method is inefficient to manufacture small quantities when developing sensors and testing different shapes. To overcome these limitations, we attempted additive manufacturing with 3D printers. The main components, including the antenna and dielectric, were manufactured using the following materials.



(a) (b)

Figure 1. Antenna sensor sensing: (a) Components of sensor; (b) Sensing mechanism.

1) *Materials for Components*

- Ground plane – aluminum foil, copper foil
- Substrate – PolyLactic Acid (PLA), Poly Carbonate (PC), PolyTetraFluoroEthylene (PTFE, Teflon)
- Antenna – silver nano ink, aluminum foil, copper foil, copper etching

2) *Manufacturing*

a) *3D printed substrates*

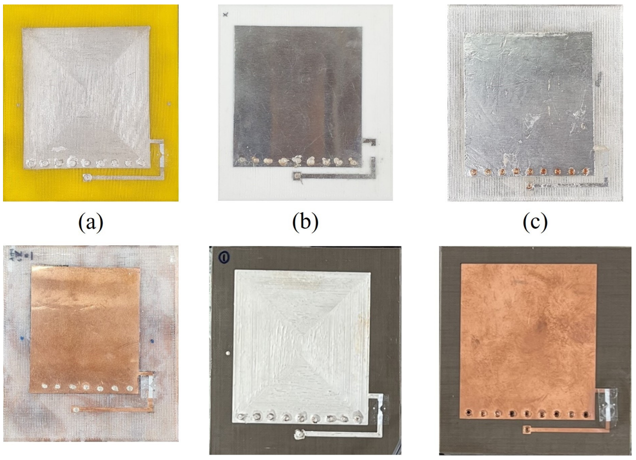
- Ground plane – glueing metallic (silver/copper) foil
- Substrate – 3D printing with PLA, PC
- Antenna – additive printing with silver nano ink or glueing metallic foils

b) *Nonprinted substrates*

- Ground plane – metallic (copper) coating
- Substrate –Teflon
- Antenna – additive printing with silver nano ink or copper etching

Figure 2 displays antenna sensors with substrates made of various materials and antennas created for performance testing. The various types of antenna sensors ware tested with the modified RFID reader for scanning antenna sensors based on commercial RFID reader (α213 from Apulsetech Inc.) using Impinj RFID chip, R2000, at a distance of 1 meter. The sensors with the 3D printed PLA substrate (Figure 2(a)-(d)) required high transmit power to respond to the RFID reader at a distance of 1 meter, making it difficult to determine their resonant frequency. This is likely due to the low melting point of the PLA substrate, which makes it challenging to solder the RFID chip during installation, resulting in incomplete adhesion between the RFID chip and antenna. However, sensors that used Teflon substrates showed satisfying performance and were compared to sensors with antennas made by silver nano ink and etching.

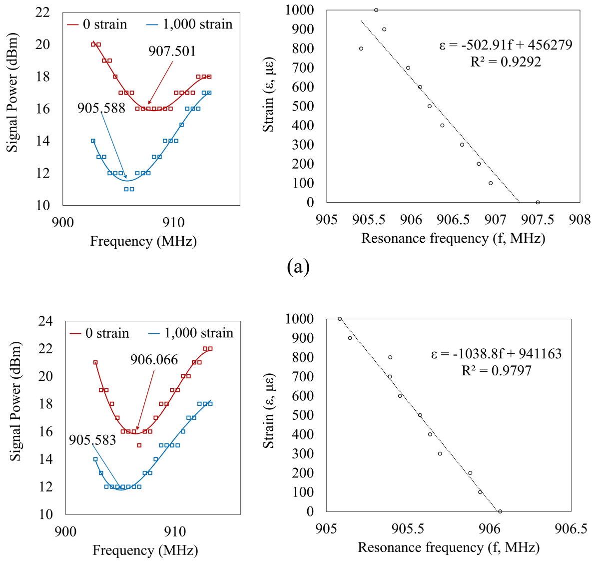
Figure 3 presents the test results of two antenna sensors Figure 2(e), (f). Those two sensors have a Teflon substrate and copper ground plane. However, the sensor in Figure 2(e)



(a) (b) (c)

(d) (e) (f)

Figure 2. Different types of antenna sensors: (a) PLA+silver nano ink; (b) PLA+aluminum foil; (c) PC+aluminum foil; (d) PC+copper foil; (e) Teflon + silver nano ink; (f) Teflon +copper etching.



(a)

(b)

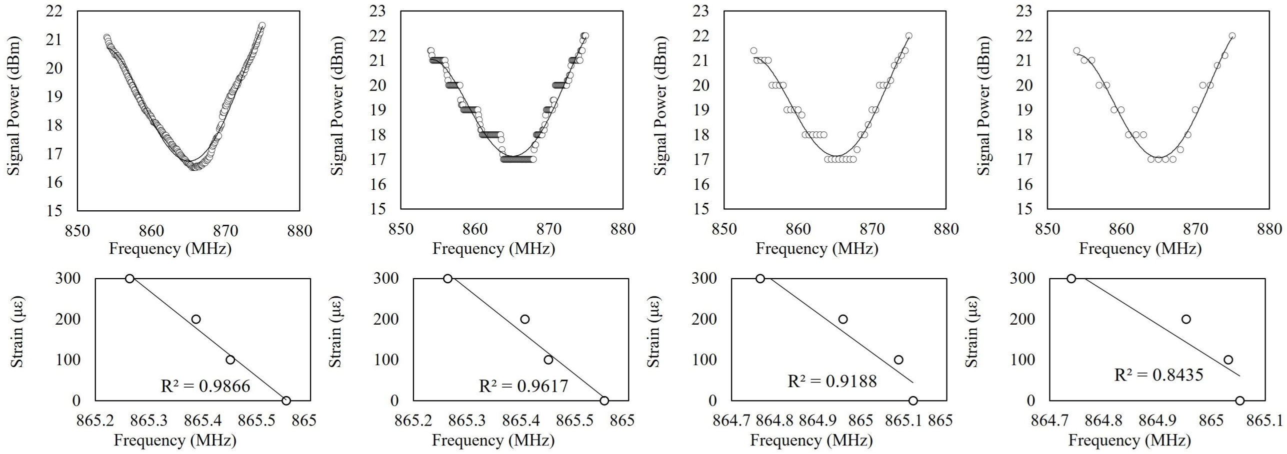
Figure 3. Antenna sensor : (a) Teflon+silver nano ink (printed); (b) Teflon+copper (etching).

had a printed silver ink antenna, while the sensor in Figure 2(f) had a chemically etched copper antenna. The two sensors were under tensile deformation from 0 to 1000 micro-strain (με), and their resonant frequencies were measured in each state. The left graph in Figure 3 displays the scanned data of frequency versus signal strength at strains of 0 and 1000 με and the resonant frequency. The right graph in Figure 3 shows the resonant frequency data for strains and the linear relationship with the equation. The resonant frequency-strain relationship equations were derived through linear regression of the measured data, resulting in coefficient of determination values, R^2, of 92.92% and 97.97%, respectively. These results indicate that sensors made by printing silver nano ink could be slightly inferior to those made by etching, but the measurement is accurate enough.

III. POWER-FREQUENCY SCANNING RESOLUTION

To enhance the accuracy of antenna sensors, it is crucial to determine the correct resonant frequency. By using a high-precision RFID tester (Tagformance Pro©), scanning could be performed by adjusting the signal strength and frequency to 0.1 dBm and 0.1 MHz, respectively. Based on a large specimen set, the resonant frequency could be predicted accurately. However, high-resolution scanning is unsuitable for field applications as it takes longer measurement time and is designed for laboratory use. A commercial RFID reader is more suitable for field applications, but the signal strength and frequency could not be precisely adjusted, as it is designed to scan the frequency band in use with a fixed (preset) signal strength and to search the corresponding RFID chip and exchange information. A commercial RFID reader has been modified to scan antenna sensors. However, there are limitations to the adjustable resolution of frequency and signal strength. To ensure efficient measurement, a trade-off between the accuracy of the resonant frequency and the resolution of the signal strength/frequency is necessary. We examined the measurement performance as a function of sample size (signal strength and frequency resolution).

Considering the performance of the modified RFID reader, the signal strength could be adjusted in 1.0 dBm increments, and the frequency could be adjusted in 0.1, 0.5, and 1.0 MHz increments. High-precision data of signal strength and frequency (raw data for strain rates 0, 100, 200, and 300) obtained from an RFID precision tester was prepared. The raw data was filtered to limit the number of specimens to simulate the situation of limited scanning resolution using the modified RFID reader (data set1: power step = 1.0 dBm, frequency step = 0.1 MHz; data set2: power step = 1.0 dBm, frequency step = 0.5 MHz; data set3: power step = 1.0 dBm, frequency step = 1.0 MHz). Figure 4 shows the results of deriving the signal strength-frequency curves and resonant frequency versus strain relationships for each data set. The coefficient of determination values, R^2, for the resonant frequency-strain relationship equations were 98.66% for the raw data, 96.17% for data set 1, 92.88% for



(a) (b) (c) (d)

Figure 4. Results based on scanning resolution: (a) raw data; (b) dataset 1; (c) dataset 2; (d) dataset 3.

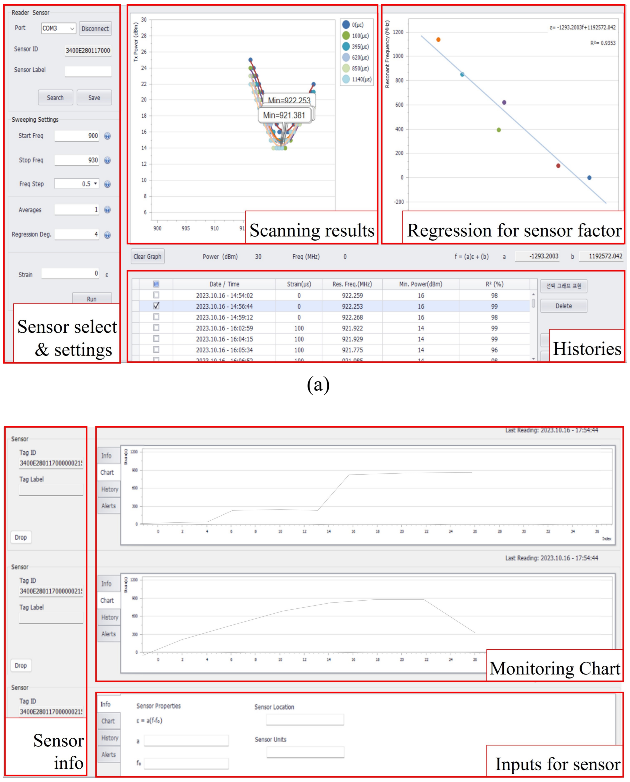
data set 2, and 84.35% for data set 3. It could be concluded that a power step of 1dbm and a frequency resolution of at least 0.5MHz would result in an accuracy of over 90%. Additionally, scanning time can be reduced by decreasing the number of iterations for each scan.

The findings show the importance of balancing accuracy and operational efficiency. This insight is crucial for enhancing structural monitoring capabilities, thereby applying antenna sensors effectively in real structure.

IV. MEASURING AND MONITORING SOFTWARE

A. *Software Development*

To measure strain in a structure using an antenna sensor, these steps were followed: 1) After attaching antenna sensors to the structure, scan and save the initial resonant frequency; 2) When it is necessary to measure the strain of the structure, the antenna sensor is scanned to derive the resonance frequency value; 3) Calculate the structure's strain using the sensor factor and the rate of change of the resonant frequency considering the characteristics of the antenna sensor. The software was developed to measure strain through passive RFID antenna sensor and visualize behavior monitoring. The software has two main functions: 1) determining the sensor factor; and 2) measuring strain and monitoring time history. Figure 5 shows a screen that facilitates the two primary functions, and each function works as follows.



Port: COM3
Sensor ID: 3400E280117000
Sensor Label:
Start Freq: 900
Stop Freq: 930
Freq Step: 0.5
Averages: 1
Regression Deg.: 4
Strain: 0 ε

Power (dBm) 30 Freq (MHz) 0 f = (a)ε + (b) a -1293.2003 b 1192572.042

☐	Date / Time	Strain(με)	Res. Freq.(MHz)	Min. Power(dBm)	R² (%)
☐	2023.10.16 - 14:54:02	0	922.259	16	98
☑	2023.10.16 - 14:56:44	0	922.253	16	99
☐	2023.10.16 - 14:59:12	0	922.268	16	98
☐	2023.10.16 - 16:02:59	100	921.922	14	99
☐	2023.10.16 - 16:04:15	100	921.929	14	99
☐	2023.10.16 - 16:05:34	100	921.775	14	96

(a)

Sensor
Tag ID: 3400E28011700000021
Tag Label:

Sensor Properties
$\varepsilon = a(f-f_0)$
a
f_0
Sensor Location
Sensor Units

(b)

Figure 5. Example screens of measuring and monitoring software: (a) Sensor factor determining, (b) Measuing and monitoring.

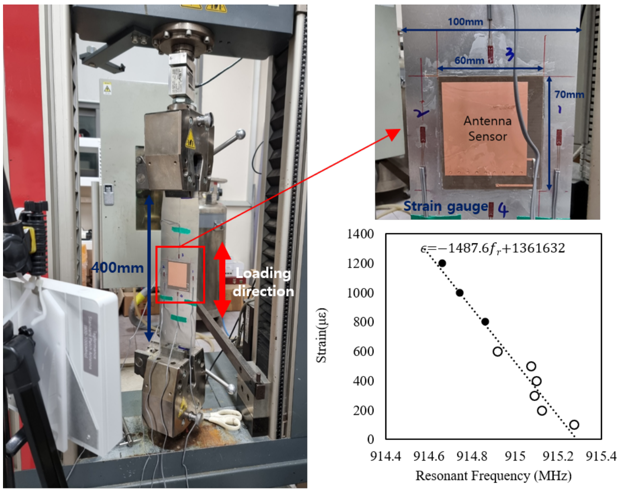


Figure 6. Tensile test setup and results.

1) *Determining Sensor Factor*

a) Install & Setup: Attach the passive RFID antenna sensor to the tensile specimen with a strain gauge.

b) Scan Each Stage: Scanning the sensor for each applied tensile strain to determine the corresponding resonant frequency.

c) Regression for Sensor Factor: Determine the sensor factor by liear regression analysis of the resonant frequency and strain dataset.

2) *Measuring and Monitoring*

a) Install: Attach the passive RFID antenna sensor to the required location of the structure.

b) Setup: Input the sensor factor to the software and scan to determine the initial resonant frequency, $f_{r,0}$.

c) Measure: Scan the sensor periodically or at any time to determine the resonant frequency, and calculate the strain.

d) Monitoring: Visualize historical strain in time series charts and send an alert when the strain exceeds the threshold.

The software enables efficient measurement and monitoring of deformations using the modified RFID readers in less time.

B. *Tensile Tests*

A specimen made of aluminum plate (100mmx400mm) was tested to evaluate the accuracy of passive antenna sensor strain measurement using the developed software.

The specimen attached with a passive RFID antenna sensor (60mmx70mm) and strain gauges was installed on the Universal Testing Machine (UTM) by gripping the top and bottom of the specimen. The antenna of the modified RFID reader is set up to scan the passive RFID antenna sensor at a distance of 1.5 meters. The modified RFID reader was controlled with monitoring software (Figure 6).

The passive RFID antenna sensor was used to scan and calculate the resonant frequency, and strain gauges were

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used to measure the strain in each state of the specimen under displacement-controlled tension.

The test was conducted in two phases. In phase 1, the sensor factor was obtained by measuring the strain from strain gauges and resonant frequency for each state of 0 to 600 με in increments of 100 με. In phase 2, a comparison was made between the strain measured from the antenna sensors and the strain gauge value of 800 με, 1,000 με, and 1,200 με. The results of the test are as follows: 1) The sensor factor is -1487.6, and 2) The average accuracy of strain was 97.85%. The results suggest that antenna sensors can be used for strain measurement, but their accuracy needs improvement before they can be applied in the field.

V. CONCLUSION AND FUTURE WORK

This study investigates the use of passive RFID antenna sensor technology for measuring deformation in structures. Antenna sensors were fabricated using additive manufacturing methods, such as 3D printing, from various materials, and it was concluded that the sensors printed with silver nano ink on the Teflon substrate were more cost-effective and efficient compared to traditional chemical-etched sensors.

Additionally, software was developed to measure strain rapidly using commercially available RFID readers. In tensile tests, comparisons with conventional strain gauges showed an error of less than 5%, validating its feasibility as a sensor. This development is expected to significantly reduce the time and effort required to monitor the health of structures. The study's findings would contribute to structural health monitoring not only in the construction industry but also in various fields.

Future research should focus on improving the measurement accuracy of antenna sensors, increasing the scanning distance, and deriving more effective structural health monitoring methods. This will require optimizing the materials and design of antenna sensors, validating their performance under different environmental conditions, and performing case studies on real structures. This will lay the foundation for the commercialization of the technology, ensuring the safety of structures, reducing maintenance costs, and contributing to a more sustainable development.

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