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A Passive and Wireless Sensor Based on RFID Antenna for Detecting Mechanical Deformation

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ABSTRACT Sensors are key components in structural health monitoring. Although significant improvements have been made on monitoring technologies by using many advanced smart sensors, the need of cables and power supplies still causes much inconvenience in the practical implementation of these technologies. In this paper, we propose a novel rectangular patch antenna to monitor the structural health in a wireless and passive manner so that the drawback of traditional monitoring methods can be fully overcome. The antenna is used as a sensor and its resonant frequency will change linearly in terms of its size changes in both horizontal and vertical directions. The antenna will transmit an electromagnetic wave with the resonant frequency information to a reader by a long distance and activate the chip in the reader. According to the received information about the resonant frequency, the change of the targeted structure's strain can be measured in real time and its health state can then be evaluated. Simulations and experiments show that the designed antenna is an excellent strain sensor and can be applied to the health detection for many types of structure.

INDEX TERMS Sensor, RFID, antenna, mechanical deformation, structural health monitoring.

I. INTRODUCTION

THE HEALTH of structures is a major concern in civil engineering because it could cause a serious casualty or property loss if the structures are damaged or cause a collapse. To know the health state of structures in a dynamic and real-time manner, we need to develop advanced detection and monitoring methods which have been widely studied and rapidly updated with the development of information technology in recent years [1]. Structural health monitoring (SHM) refers to a system that can provide the relevant information about the health status of structures dynamically and in real time and give an immediate warning when there was a significant change in the state of structures [2]. The SHM technology originated from the field of aerospace and its initial purpose was to carry out a structural load monitoring. With the increase of scale, complexity, and intelligence in structural design, the content of SHM is gradually enriched and it is no longer a simple load monitoring, but becomes a comprehensive detection and monitoring for the structural health, including the occurrence of damage, localization and scope of damage, and life prediction, etc. In civil engineering, the SHM was proposed in 1980's and was initially developed primarily for the health monitoring of bridges. Since the middle 1990's, civil engineers have conducted a great deal of investigation on the SHM technology for building structures.

Structural health monitoring system consists of four functional subsystems that work through the network link. These four subsystems are Sensor System, Information Collection and Processing System (ICPS), Information Communication and Transmission System (ICTS), and Information Analysis and Monitoring System (IAMS), respectively [3]. The sensor system includes accelerometer, wind speed and direction meter, displacement meter, thermometer, strain gauge, signal amplifier processor, and connection interface, which can transform a measured physical quantity into an electrical signal. ICPS includes signal acquisition components and corresponding data storage devices. ICTS transmits the data which have been collected and processed to the monitoring center. IAMS analyzes the received data and makes an evaluation on the health status of the structure.

It is often needed to redesign the entire system in order to accommodate the connection among a large number of sensors. Therefore, one could waste much energy and time on some unnecessary connections. Radio Frequency Identification (RFID) technology opens a good way to solve the problem [4]. By using RFID tags, one can receive the data about the status of structure distantly and wirelessly. Meanwhile, there is no need to worry about the power supply for the sensors. As a passive sensor, the RFID tag is activated by the received electromagnetic (EM) signal from the reader, and then the stored data in the tag is transmitted by the reflected EM wave which will be received and decoded by the reader. Obviously, Such a kind of detection or monitoring method is much more flexible and is also cheaper in costs. Furthermore, it is easy to incorporate with the Internet or Internet of things so that the monitoring can be highly intelligentialized.

In the RFID monitoring, we propose to design an antenna whose specific characteristic can be changed through its certain parameters in terms of the strain of antenna. Particularly, we prefer to use a single size parameter rather than a lot of size parameters to make the specific characteristic changeable. The resonant frequency of an antenna is a common parameter describing the characteristic of the antenna. However, due to the existence of bandwidth, it is not easy to get the accurate value of resonant frequency for a wideband antenna, so we use a narrowband antenna as a sensor. One of choices for such an antenna is the microstrip antenna which was first proposed by Deschamps in 1953 and was greatly developed in 1970's due to the development of microwave integration technology and the emergence of various low-loss dielectric materials [5]. Later on, with the development of space technology and the urgent need for low profile antenna, the microstrip antenna further attracted a great deal of attention and various new forms of the antenna with new performances continuously emerged.

There have been many studies on the SHM based on wireless sensors or RFID technology [6]–[11]. In [6], A sensor that employs a planar inductor connected with an interdigital capacitor to remove the wire connection of power supply and data transmission was proposed. In [7], the authors focused on the enhancement of sensitivity for the wireless passive RF strain transducer by using a cantilever at the gap of the open loop. In [8], the authors developed an energy harvester to replace the battery of wireless sensors based on piezoelectric material for monitoring the pressure of vehicles' tires. In [9], a fully passive RFID sensor for strain monitoring was designed, but it was based on a meander-line dipole antenna. Also, the authors in [10] presented a very simple patch antenna used as a sensor for strain measurement and the authors in [11] showed a remote inspection method for the defects of materials in engineering structures by using a set of passive modulated-scattering-technique (MST) probes. We also proposed a dual band microstrip antenna for RFID tag which was used as a strain sensor in [12], but it is only in the simulation stage without a practical implementation. In this work, we develop a different antenna structure used as the sensor of detecting the deformation of structures by the strain change and it has been implemented in real-world applications. We use a row of short-circuit holes to reduce the size of antenna and also enhance the sensitivity and linearity of structural deformation corresponding to the frequency shift [13]. It is the first time for such kind of antenna to be used as a sensor whose shape will be deformed by applied external force. Experiments show that the antenna sensor has a good performance even used in a severe environment. Note that the relationship between the resonant frequency of an antenna and the applied strain to it is of multiphysics because the applied strain not only changes the geometric dimensions but also alters the electrical property of materials. For the dielectric material in the antenna, the permittivity will be changed due to the change of gap between molecules when the antenna is strained. The experimental results show that when the antenna is strained, the permittivity will be reduced accordingly since the increased gap of molecules will be filled with more air. However, the reduction is very small and within the order of ten thousandths for regular dielectric materials [14]. Therefore, one usually neglects the change of permittivity and only considers the change of major geometric dimension in the cavity model of patch antenna. To more accurately analyze the behavior of patch antenna under the action of a strain, the theoretical analysis of multiphysics based on elastodynamics and electromagnetics is given in detail.

This paper is organized as follows. Section II describes a model analysis for the proposed microstrip antenna; Section III presents the multiphysics analysis and the RFID antenna design for the SHM application; Section IV introduces the composition and verification of the whole system; Section V gives an analysis for experimental results by comparing to simulation results; and Section VI gives a conclusion for the work and discusses possible improvements in the future.

II. MODELING OF MICROSTRIP ANTENNA

For a typical microstrip antenna, we can use a transmission line model to approximately to analyze it [15]. Most of microstrip antennas are of low profile or $h << \lambda$, where λ is the wavelength, and the EM wave is concentrated in the form of standing waves inside the medium between the patch and ground. Therefore, a rectangular microstrip patch antenna can be equivalent to a medium-filling cavity whose upper and lower walls are conducting while surrounding wall is dielectric [16], as shown in Fig. 1.

Regardless of the edge effect (portrait and landscape) of the microstrip antenna, the field around the patch will be

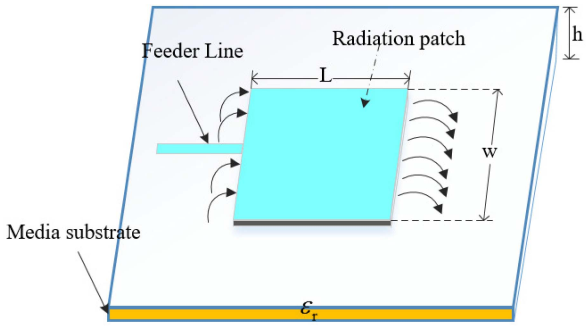

FIGURE 1. Structure of a rectangular microstrip antenna.

perpendicular to the surface of the patch. Therefore, we can only consider the TMx mode field in the cavity [17]. Assume that the relative permittivity of the medium filled in the cavity is ϵ_r and the all-around of the patch limits the area of medium. Depending on the values of L, W, and h, there will be different dominant modes inside the cavity, and the dominant mode is TM_{010} if $L > W > h$ which is the case of our design. The resonant frequency of this mode is [18]

$$(f_r)_{010} = \frac{1}{2L\sqrt{\mu\epsilon}}. \tag{1}$$

III. DESIGN OF RFID ANTENNA FOR STRAIN MEASUREMENT

A rectangular RFID tag antenna with a chip is proposed and designed for the SHM application. It has such a characteristic that can change its resonant frequency by changing the strain of the antenna. We can observe the shift of its resonant frequency when a strain is applied to it horizontally and vertically, respectively. The antenna consists of two parts, i.e., a rectangular microstrip patch section and an impedance matching section. The RFID antenna works in the ultra-high frequency (UHF) band, thus it will be too large in dimensions if we use a routine method to design it. We propose to design a quarter-wavelength RFID antenna with a chip by making a row of holes in the edge of the main body of the rectangular microstrip patch. In theory, the resonant frequency of a standard quarter-wavelength rectangular microstrip antenna can be calculated by [19]

$$f_{re} = \frac{c}{4\sqrt{\epsilon_{re}}} \frac{1}{L + 2\Delta L_{com}} \tag{2}$$

where c is the speed of light, L is the length of the conducting patch, ϵ_{re} indicates the effective dielectric constant of the substrate, and ΔL_{com} is the length of compensation which is related to the width of the conducting patch W, the effective dielectric constant of the substrate ϵ_{re}, and the ratio of the width of the conducting patch to the thickness of the dielectric substrate W/h. If the longitudinal strain of the patch antenna increases, the resonant frequency of the antenna will shift. In engineering, the longitudinal strain ξ_L is usually defined as the relative change in the length of an object [20], i.e.,

$$\xi_L = \frac{L_s - L_o}{L_o} \tag{3}$$

where L_0 is the original length and L_s is the stretched length of the object, respectively. At the same time, we should note that the thickness of the substrate and the width of the radiating patch will change as well when the longitudinal strain increases according to the Poisson effect theorem of elastic mechanics [21], i.e.,

$$W = (1 - \nu_1\xi_L)W_o \tag{4}$$

$$h = (1 - \nu_2\xi_L)h_o \tag{5}$$

where W_0 is the original width and W is the changed width of the patch while h_0 is the original thickness and h is the changed thickness of the substrate, respectively. Also, ν indicates the Poisson's ratio, ν_1 represents the Poisson's ratio of the conducting patch's length to its width, and ν_2 denotes the Poisson's ratio of the conducting patch's length to the substrate's thickness. Therefore, the resonant frequency can be expressed as [22]

$$f_{re} = \frac{c}{2\sqrt{\epsilon_{re}}} \frac{1}{L + 2\Delta L_{com}} = \frac{C_1}{L + C_2 h} \tag{6}$$

where

$$C_1 = \frac{c}{2\sqrt{\epsilon_{re}}} \tag{7}$$

$$C_2 = 0.824\frac{(\epsilon_{re} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{re} - 0.258)\left(\frac{W}{h} + 0.813\right)}. \tag{8}$$

Suppose the longitudinal strain is ξ_L, then the change of resonant frequency can be estimated by [23]

$$f_{re}(\xi_L) = \frac{C_1}{L(1 + \xi_L) + C_2 h(1 - \nu\xi_L)}. \tag{9}$$

According to Eqs. (6) and (9), we can obtain

$$\xi_L = -\frac{L + C_2 h}{L - \nu C_2 h} \frac{f_{re}(\xi_L) - f_{re}}{f_{re}} = -\frac{L + C_2 h}{L - \nu C_2 h}\Delta f_L \tag{10}$$

where

$$\Delta f_L = -\frac{L - \nu C_2 h}{L + C_2 h}\xi_L = K_a\xi_L. \tag{11}$$

Hence, we have

$$f_{re}(\xi_L) = -\frac{L - \nu C_2 h}{L + C_2 h} f_{re}(\xi_L) + f_{re} = K_a\xi_L + f_{re}. \tag{12}$$

From the above equation, we can see that the resonant frequency will have a linear relationship with L if the thickness of antenna is significantly smaller than L. The shift of resonant frequency is not only related to the Poisson's ratio of the antenna, but also its physical shape K_a which is a dimensionless parameter [24]. Also, the linear coefficient is approximately equal to the negative value of the initial resonant frequency without a strain [25].

The substrate of the antenna is made of the material "RT5880" and Fig. 2 shows the specific structure of the

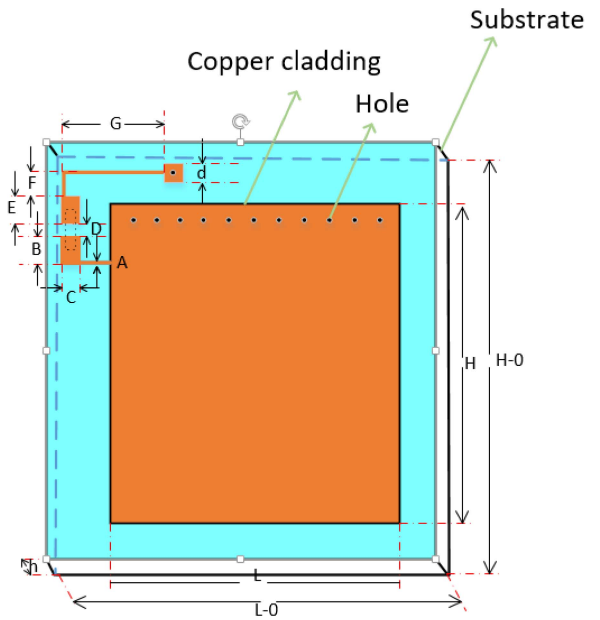

FIGURE 2. Structure of the proposed microstrip antenna.

TABLE 1. Parameters of the antenna.

Parameter	H-0	L-0	H	L	A	B
Scale (mm)	69.1	60.9	55.01	49.97	0.25	4.93
Parameter	C	D	E	F	G	d
Scale (mm)	3.96	1.02	41.92	3	18	2.5

antenna where there is a layer of copper in the back. Table 1 lists the specific values of the designed parameters.

The chip of RFID antenna is "ALIEN H3", which is a highly integrated single chip used for UHF RFID Tag. Its equivalent input resistance and capacitance is 1500 Ω and 0.85 pF, respectively. The impedance of the chip that we can get is $(27 - j200)$ Ω, so the impedance of the RFID antenna is $Z_{RFID} = (27+j200)$ Ω, and the threshold power is −18 dBm. As shown in Fig. 3, the initial resonant frequency of the antenna is about 919.9 MHz, and the reflection loss at the resonant point is close to −21 dB. This figure shows that the antenna has a favorable performance. When it is fabricated physically, its resonant frequency can be more easily detected and this is one of several prerequisites as a strain sensor [26].

We then simulate the antenna with an applied strain in both vertical and horizontal directions. As seen in Fig. 4, the length of RFID antenna is increased by applying ten steps of strain and each step is 410 micro-strains. At the same time, we should also decrease L by 410×0.33 micro-strains because of Poisson's effect. The simulation results show that there is a good linear relationship between the frequency offset and the strain change, and the slope of the linearly-fitting line is 0.9280. Compared with the initial resonant frequency 919.9 MHz, the relative error is about 0.8%, which is very close to the theoretically-derived value. Similarly, we increase the width of RFID antenna by ten grades of strain and each grade is 720 micro-strains. The simulation results are shown in Fig. 5 and the slope of the linearly-fitting line is about 0.2999. Theoretically, the slope of horizontal strain should be close to the slope of longitudinal strain multiplied by the Poisson's ratio [27].

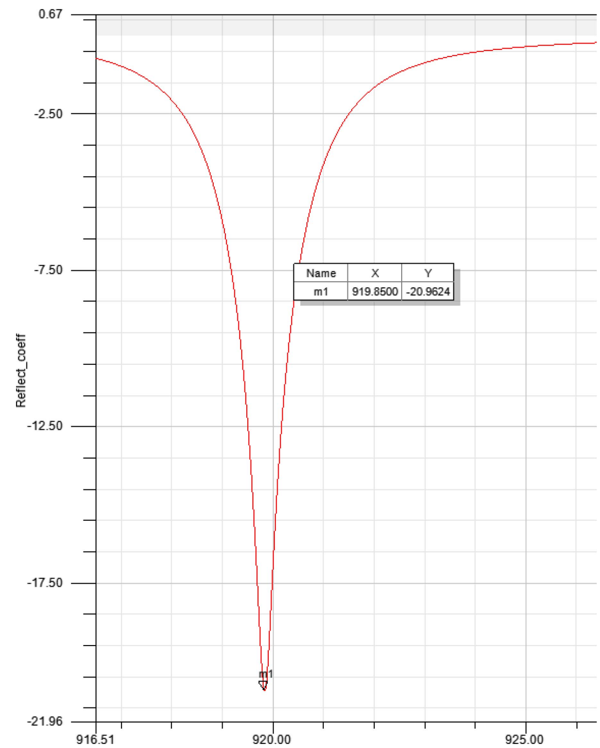

FIGURE 3. Simulation result for S_{11}.

TABLE 2. Simulation results.

	Vertical strain	Horizontal strain
Initial frequency	919.9 MHz	919.9 MHz
Strain step	410 $\mu\xi$	720 $\mu\xi$
Linear slope	-0.9280 GHz/$\mu\xi$	0.2999 GHz/$\mu\xi$
Relative error	0.8%	1.5%

IV. CONSTRUCTION OF SYSTEM

RFID technology is a kind of noncontact automatic identification technology that can automatically identify an object through EM signals and can quickly track items and exchange data. As shown in Fig. 6, there is no human intervention in the recognition and it can work in a variety of harsh environments. Also, the technology can identify quickly-moving objects and can simultaneously identify multiple labels which are also known as "electronic tags" or "radio-frequency tags" [28].

In order to test our RFID strain sensor, we stick the RFID tag antenna on a metal plate made of aluminum. The aluminum plate is then fixed on the stretcher, and we can regularly and slowly increase the tension through a stretching machine. In the real-world application as shown in Fig. 7, after each stretch, the antenna's signal is received through

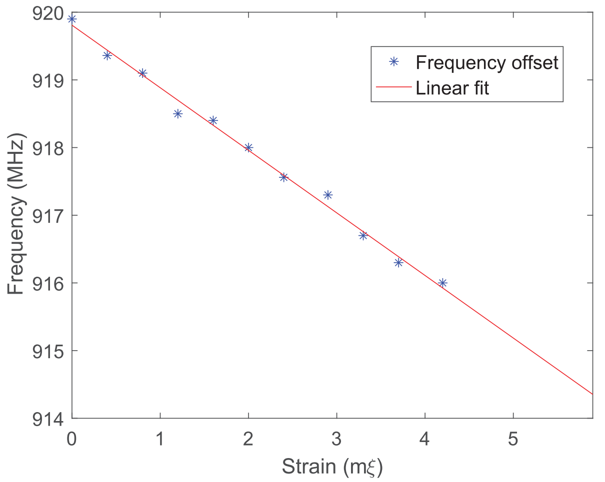

FIGURE 4. Simulation result of the relationship between the resonant frequency and the strain based on a vertical stretch.

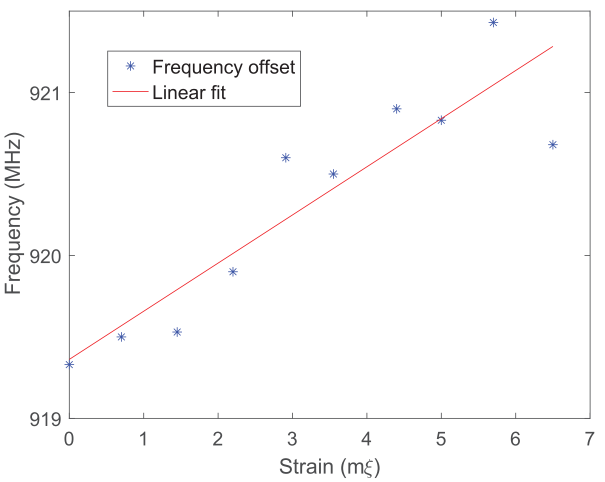

FIGURE 5. Simulation result of the relationship between the resonant frequency and the strain based on a horizontal stretch.

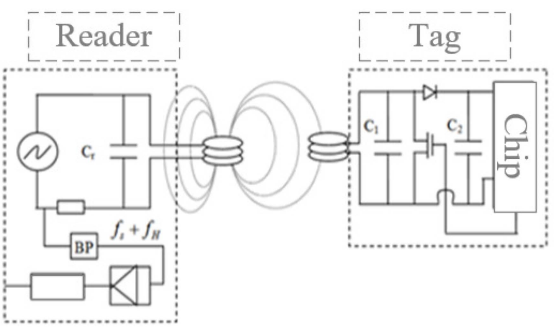

FIGURE 6. Basic principle of RFID technology.

the reader over a long distance, and thus the change of the resonant frequency of the antenna attached to the aluminum plate can be collected. Fig. 8 shows the size of the aluminum plate and we plot the simulated stress distribution of the plate in Fig. 9. The stress distribution is concentrated and uniform in the blue area, so we will attach the antenna to this area on the aluminum plate.

FIGURE 7. A typical application scenario. The RFID tag is attached to a steel structure for detecting its deformation.

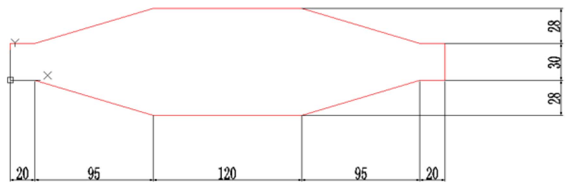

FIGURE 8. Geometry of the aluminum plate. The unit is millimeter (mm).

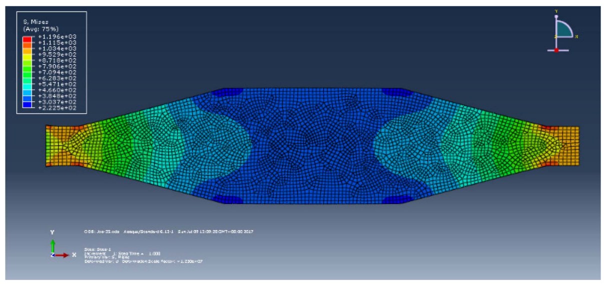

FIGURE 9. Simulated stress distribution of the aluminum plate.

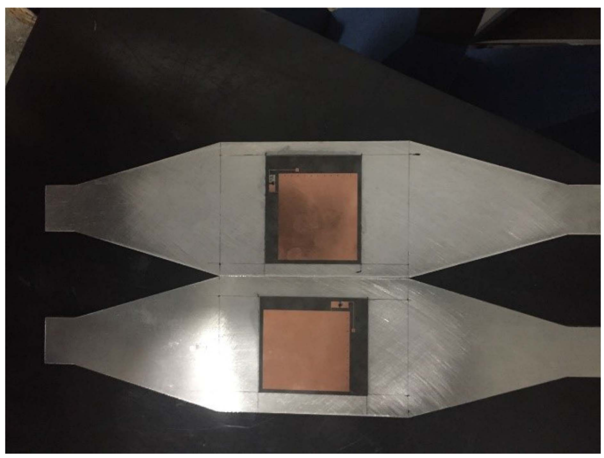

FIGURE 10. A microstrip antenna attached to the aluminum plate.

In the experiment, because the antenna is attached to the aluminum plate as shown in Fig. 10, the strain of the antenna must be less than the strain of the aluminum plate when the

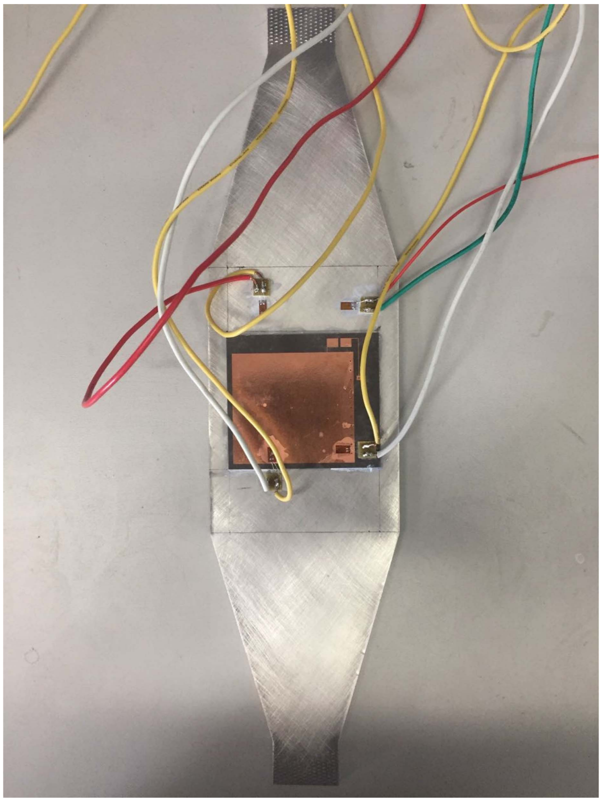

FIGURE 11. Measurement of transmission efficiencies through a strain gauge.

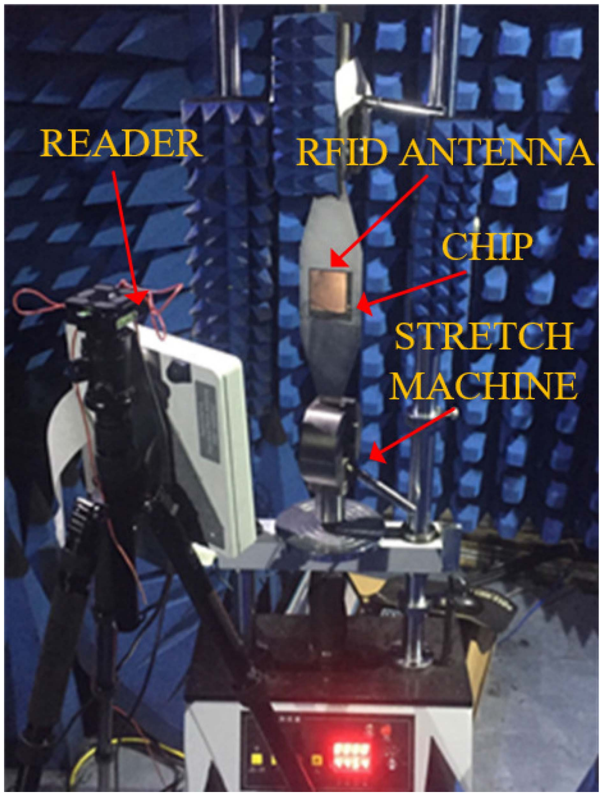

FIGURE 12. Measurement setup in a lab.

TABLE 3. Experiment results of transmission efficiencies.

	1	2	3	Average	Variance
σ (Vertical)	60.62	61.98	62.53	61.71	0.99
σ (Horizontal)	65.73	60.41	62.63	62.92	2.68
ν (Vertical)	0.4022	0.3950	0.4310	0.4094	0.0191
ν (Horizontal)	0.3937	0.3828	0.3916	0.3894	0.0058

aluminum plate is stretched. For the purpose of evaluating the transmission efficiency, we use four strain gauges to measure the vertical and horizontal transmission efficiencies, respectively, as shown in Fig. 11. The reader we use is a Tagformance Pro RFID reader produced by Voyantic company. The reader will automatically adjust the power during the frequency sweep and the power accuracy can reach 0.1 dBm while the frequency accuracy can reach 0.1 MHz.

V. EXPERIMENTAL RESULTS

We fix the aluminum plate with the attached antenna to the stretcher. As Fig. 10 shows, the antenna is positioned horizontally and vertically on the aluminum plate so that the transmission efficiencies in different orientations can be measured. The measurement setup in a lab is shown in Fig. 12.

Table 3 shows the experiment results of transmission efficiencies in which σ represents the modulus of elasticity and ν represents Poisson's ratio, respectively. As shown in the figure, the rate of change of resonant frequency in the horizontal stretch is smaller compared to that in the vertical stretch. We can interpret this phenomenon by the concept of coupling in mathematics. The horizontal stretch and vertical stretch can be viewed as two motions in the two directions. The coupling refers to the phenomenon of two or more systems or two forms of motion that are interacting with each other to bring them together [29]. Conversely, decoupling refers to making a mathematical equation with multiple variables become a system of equations that can be represented by individual variables so that the variables can no longer directly affect the result of an equation together, simplifying the analysis and calculation. Through the selection of appropriate control variables, coordinate transformation, and other means of a multivariable system, a number of independent mathematical models with univariate systems can be formed and the coupling between the various variables can be removed [30].

Assume that the vertical strain calculated on the surface of the aluminum plate is ξ_L when a certain tension is applied. Due to the Poisson's effect, the lateral strain on the surface of the aluminum plate is $-\nu\xi_L$, where ν is the Poisson's ratio of the aluminum. We further assume that the vertical strain transmission efficiency of the radiating patch from the aluminum plate to the patch antenna is n_{22} when the antenna is vertically pasted, and the corresponding horizontal or longitudinal strain transmission efficiency is n_{12}. When the antenna is pasted horizontally, the vertical and horizontal strain transmission efficiencies are n_{21} and n_{11}, respectively.

TABLE 4. Experiment results of transmission efficiencies.

	1	2	3	Average	Variance
n_{22}	71.74	76.19	74.77	74.23	2.27
n_{12}	86.75	91.37	89.30	89.14	2.32
n_{11}	81.84	83.12	83.46	82.81	0.85
n_{21}	88.36	87.98	86.16	87.50	1.17

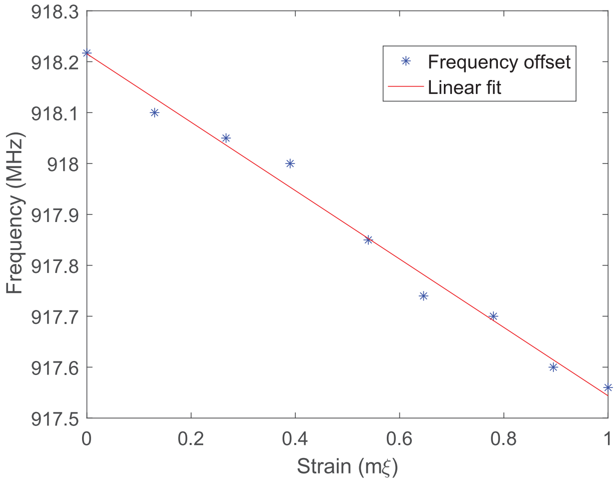

FIGURE 13. Experimental results of the relationship between the resonant frequency and the strain based on a vertical stretch.

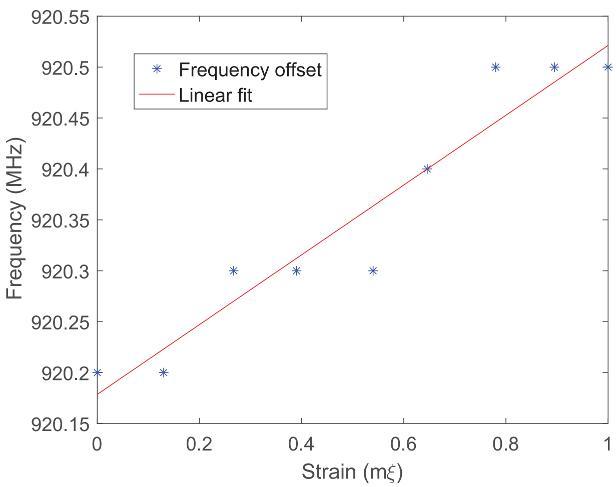

FIGURE 14. Experimental results of the relationship between the resonant frequency and the strain based on a horizontal stretch.

By using the following equations:

$$\xi_L' = \begin{cases} n_{22}\xi_L \\ -\nu n_{11}\xi_L \end{cases} \tag{13}$$

$$\xi_W' = \begin{cases} -\nu n_{12}\xi_L \\ n_{21}\xi_L \end{cases} \tag{14}$$

where ξ_L' and ξ_W' are the strains of the antenna in the horizontal and vertical directions, respectively, we can calculate the transmission efficiencies in both vertical and horizontal directions. The experiment results of transmission efficiencies are shown in Table 4.

TABLE 5. Experiment results of transmission efficiencies.

	Vertical strain	Horizontal strain
Initial frequency	918.2 MHz	920.2 MHz
Strain step	$\approx 130\ \mu\xi$	$\approx 140\ \mu\xi$
Linear slope	-0.671 GHz/$\mu\xi$	0.342 GHz/$\mu\xi$
Relative error	1.4%	5.1%

As shown in Figs. 13 and 14, the expected slope should be $k_{ve} = -f_{initial}\eta_L$ in the vertical stretch and $k_{ho} = f_{initial}\eta_W\nu$ in the horizontal stretch, where $f_{initial}$ is the initial frequency of RFID antenna, η_L is the transmission efficiency of the vertical strain, and η_W is the transmission efficiency of the horizontal strain. The results are shown in Table 5.

From the above figures and tables, we can see that the experimental results are basically consistent with the simulated results and those of theoretical analysis. Because of the existence of transmission efficiencies, the experimental change rate and the change rate of simulations in resonant frequencies will certainly be different. Also, the Poisson's effect should be considered in the horizontal stretch. It can be seen that the resonant frequency of the antenna designed in this paper will change linearly with the strain. Therefore, the change of the strain can be judged by measuring the change of resonant frequency remotely through the reader.

VI. CONCLUSION

This paper is devoted to studying the new strain sensor technology and applying it to the SHM field. For the traditional monitoring methods, there are several disadvantages, including high laying costs, complicated installation, high maintenance costs, the need for manual operation, etc. We propose a RFID patch antenna as a new sensor which can measure the strain of structures by monitoring the antenna's resonant frequency offset and it is absolutely passive and wireless. The sensor provides a new perspective for the development of SHM systems and it possesses obvious advantages compared to the traditional methods. Furthermore, we analyze the linear and multiphysics relationship between the resonant frequency and applied strain by including both the geometrical deformation and change of electrical property in the antenna's substrate.

In the design of RFID antenna, we use a rectangular microstrip antenna with a row of short-circuit holes which can reduce the size of patch antenna and improve the sensitivity to the frequency shift, but actually other types of antennas such as folded dipoles and circular microstrip antennas can also be used as a strain sensor and we will investigate their performance in the future. Also, the relationship between the antenna and strain can be characterized by using other parameters like the reflection coefficient, standing wave ratio, and characteristic impedance, and we shall check whether or not these parameters are better than the resonant frequency as an indicator of structural health change.

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