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Experimental test of patch antenna sensor for simultaneous crack and temperature sensing

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Abstract. This paper presents a patch antenna sensor for simultaneous crack and temperature sensing, and its actual performance is tested. The patch antenna sensor consists of an off-center fed underlying patch and an overlapping sub-patch, which is tightly attached to the underlying patch and allowing the electric current to flow through the integrated patch. The off-center feeding of the patch antenna can activate the resonant modes in both transverse and longitudinal directions. The resonant frequency shift in transverse direction is utilized for temperature sensing, and the crack width can be sensed by the longitudinal resonant frequency shift. Furthermore, this unstressed structure of the patch antenna sensor can avoid the problems of incomplete strain transfer ratio and the insufficient bonding strength. In this paper, the theoretical relationships between the antenna resonant frequencies, the environment temperature, and the crack width were studied. Experimental tests were also conducted, the off-center fed patch antenna sensor was fabricated and several days of continuous monitoring were performed to test the sensing performance of the patch antenna sensor. The experimental results demonstrate the feasibility of the proposed patch antenna sensor for simultaneous crack and temperature sensing.

Introduction

Structural damage such as cracks will inevitably occur during the long-term service of civil engineering structures. Cracks will reduce the bearing capacity and durability of the structure, or even lead to a sudden failure of the structure, resulting in casualties and property losses. Therefore, it is of great significance to monitor the structural cracks in real time [1].

Traditional crack sensing methods such as visual inspections with magnifying lens are time-consuming and usually inaccurate. In recent years, sensors play an important role in structural health monitoring and can provide more accurate sensing of structural cracks. For example, some piezoelectric-based sensor and optical fiber-based sensor have been used for crack sensing [2,3]. These sensors make it easier to monitor structural cracks in real time. However, these crack sensing technologies based on wired sensors usually need numerous wires for power supply and information transmission, which make it difficult to install and maintain the sensors.

In past decades, some antenna-based sensors came into being to avoid the defects of traditional wired sensors [4]. Antenna-based sensors utilize the antenna as the sensor to measure the change in physical parameters, since the change of monitored parameters will lead to the change of electromagnetic parameters of the antenna, and the change of antenna's electromagnetic parameters can be interrogated wirelessly. The antenna-based sensors take advantage of antenna's sensing and signal transmission functions. Furthermore, the electromagnetic waves of the antenna sensor can penetrate some coverings, which make it better suited for structural health monitoring.

A lot of antenna sensors have been developed, such as the deformation sensor, strain sensor, temperature sensor, humidity sensor, bolt loosening sensor, corrosion sensor, and so on [5,6].

Currently, some structural crack sensors based on antennas have been developed and proved to be feasible in laboratory environment. However, these crack sensors usually focus on crack sensing while disregarding the effects of environment temperature [7]. In actual engineering, the environment temperature is not constant; thus, the temperature fluctuation will generate inaccurate measurements. To improve the sensing performance of antenna-based crack sensors under variable temperatures, the temperature effects on antenna should be investigated, and additional temperature sensors are needed to measure the environment temperature for the compensation of the monitored parameters.

Since the additional temperature sensors will bring a lot of trouble in practice, to avoid the additional temperature compensation sensors, some scholars have proposed antenna sensors for simultaneous sensing of temperature and other physical parameters. For example, Tchafa et al. proposed a patch antenna sensor for simultaneous strain and temperature sensing [8]. This multiple physical variable monitoring sensor enabled strain and temperature sensing by a single antenna sensor, additional temperature sensors are no longer needed. However, the proposed sensor based on monolithic patch antenna need to be attached to the surface of the structure and stressed, so there will be some problems such as the incomplete strain transfer ratio and insufficient bonding strength. These problems greatly limit the antenna sensor use in practice. In this regard, Xue et al. proposed a series of unstressed patch antenna sensors to avoid the problems of incomplete strain transfer ratio, which can detect the cracks or structural deformation by the relative movement between two antenna components, making the measurements of structural deformation and crack width more accurate [9,10].

In this paper, a patch antenna sensor for simultaneous crack and temperature sensing is developed, and its actual performance is tested. The proposed patch antenna sensor consists of an off-center fed underlying patch and an overlapping sub-patch. The sub-patch is attached to the underlying patch and moves as the crack width changes. The off-center feeding can activate the resonant modes of the integrated patch antenna in both transverse and longitudinal directions, and the resonant frequency shifts in two directions are used for temperature sensing and crack width sensing respectively. The theoretical analysis is conducted to study the relationships between the antenna resonant frequencies, the environment temperature, and the crack width. To demonstrate the effectiveness and feasibility of the proposed sensor, some experimental tests were conducted. The patch antenna sensors were fabricated to detect the crack widths, and several days of continuous monitoring obtained a series of measurements at different environment temperatures. The experimental results show that the sensor can accurately measure the temperature and crack width changes.

This paper is organized as follows. Section 2 introduced the methodology of the proposed patch antenna sensor and conducted the theoretical analysis. Section 3 presented the experimental design and the experimental results. Finally, the conclusion and future work of the proposed antenna sensor are discussed.

The patch antenna sensor for simultaneous crack and temperature sensing is shown as Figure 1. The underlying patch is off-center fed and partially covered by the overlapping sub-patch, and they are tightly attached to each other so that the electric current induced by interrogation waves can flow through the integrated patch. The antenna is dual-resonant since the off-center feeding of the patch antenna can activate the resonant modes in both transverse and longitudinal directions; thus, it has two fundamental resonant frequencies. The transverse fundamental resonant frequency of the patch antenna is only related to the environmental temperature changes. However, the longitudinal resonant frequency of the patch antenna depends on the environmental temperature and the overlapped length of the underlying patch and the overlapping sub-patch.

Methodology and theoretical analysis

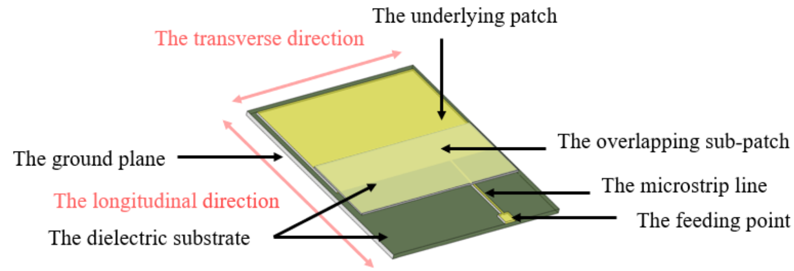

Figure 1. The concept of the proposed patch antenna sensor.

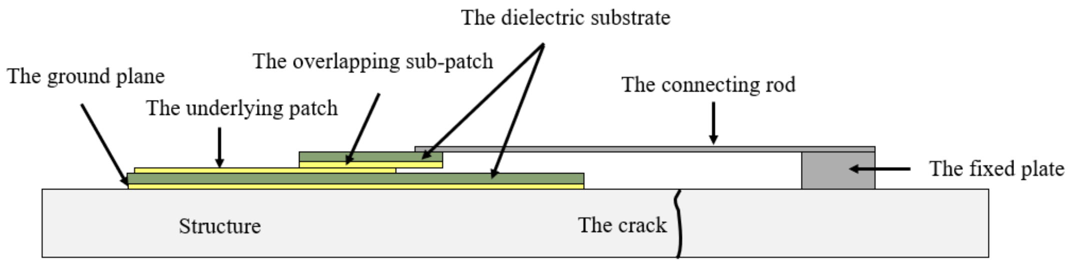

Figure 2. The patch antenna sensor installation diagram.

The patch antenna sensor is installed on the surface of the structure as shown in Figure 2. A connecting rod connects the overlapping sub-patch to the fixed plate, the underlying patch fastened to one side of the crack while the fixed plate is fastened to the other. As long as the crack width changes, the variation causes the relative movement between the two components of the antenna sensor. The sensing of the crack width can be achieved by measuring the relative movement between the underlying patch and the overlapping sub-patch. Thus, the longitudinal resonant frequency shift of the antenna can be used to measure the change of the crack width, and the resonant frequency shift in transverse direction is utilized for environmental temperature sensing.

When environment temperature changes ΔT , and the overlapped length changes ΔL_o , the fundamental resonant frequencies of the patch antenna under the influence of temperature and the overlapped length can be expressed as:

$$f_{10}(\Delta T,\Delta L_o)=\frac{c}{2(L_e+\Delta L_T-\Delta L_o)\sqrt{\varepsilon_e+\Delta\varepsilon_e}}\approx f_{10}+\frac{\partial f_{10}}{\partial T}\cdot\Delta T+\frac{\partial f_{10}}{\Delta L_o}\cdot\Delta L_o \tag{1}$$

$$f_{01}(\Delta T,\Delta L_o)=\frac{c}{2(W_e+\Delta W_T)\sqrt{\varepsilon_e+\Delta\varepsilon_e}}\approx f_{01}+\frac{\partial f_{01}}{\partial T}\cdot\Delta T \tag{2}$$

Where f_{10} represents the fundamental resonant frequency when the patch antenna is resonant at the longitudinal direction and f_{01} represents the fundamental resonant frequency at the transverse direction; c is the speed of light in a vacuum; ε is the relative dielectric constant of the dielectric substrate; L_e and W_e are the longitudinal electric length and transverse electric length respectively; ΔW_T and ΔL_T are the variations of the integrated patch size in the transverse direction and longitudinal direction caused by temperature variations; $\Delta\varepsilon_e$ is the variation of the dielectric substrate's relative dielectric constant.

Therefore, the environmental temperature can be determined using the resonant frequency shift in the transverse direction, and the temperature compensation of the longitudinal resonant frequency can be calculated simultaneously. Then, the resonant frequency shift in the longitudinal direction of the patch antenna can be used for the crack width sensing.

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Experimental study

A series of Experimental tests were conducted to illustrate the feasibility of the proposed patch antenna sensor for simultaneous crack and temperature sensing. The fabricated patch antenna with overlapping sub-patch is shown in Figure 3. The dielectric substrate of the antenna was selected as Rogers RT/duroid 5880 laminate, and the radiation sheets were made of copper. The patch antenna sensor was connected to the vector network analyzer (VNA) through the coaxial line.

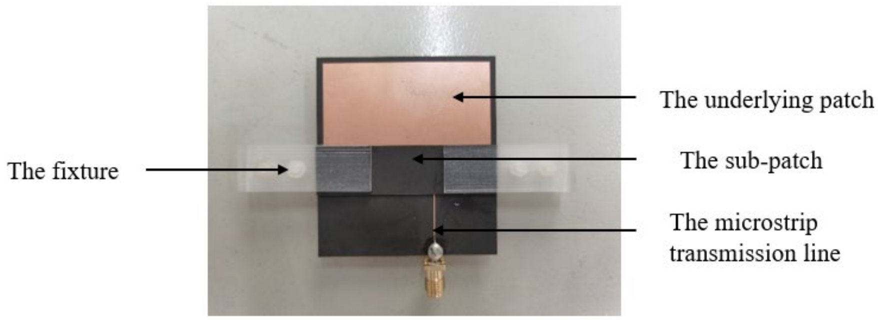

Figure 3. The fabricated patch antenna sensor.

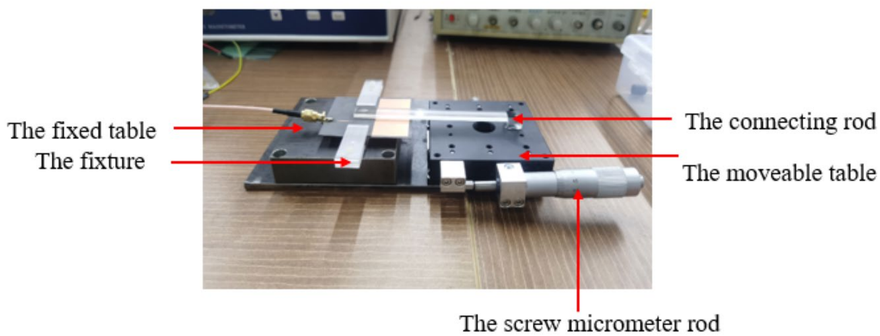

Figure 4. The crack extension simulator and experimental setup.

Figure 4 shows the crack extension simulator and experimental setup. The moveable table could be pushed by the screw micrometer rod and moved relative to the fixed table to simulate the crack width extension. The simulator simulates crack width extension from 0 mm to 3 mm with a 0.1 mm incremental step. Figure 5 shows the reflection loss curves S_{11} of the patch antenna, and Figure 6 shows the patch antenna's resonant frequency in the longitudinal direction with different crack widths.

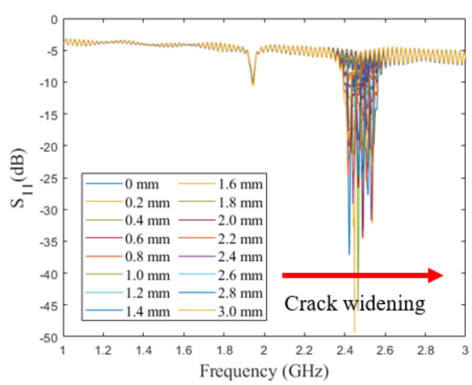

Figure 5. The S_{11} curves of the patch antenna sensor with different crack widths.

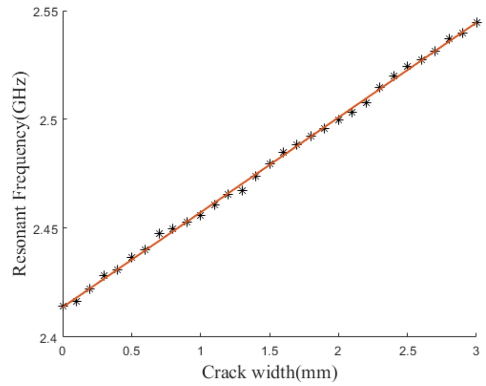

Figure 6. The resonant frequency in the longitudinal direction with different crack widths.

In order to verify the feasibility of the proposed patch antenna sensor for temperature sensing, the patch antenna sensor was installed at a fixed position in the room to monitor environment temperature changes over a period of time. Figure 7 shows the experimental setup. The patch antenna sensor was connected to the Nano VNA through the coaxial line, and the patch antenna senor was placed in a protective box made of acrylic, so as to avoid the interference of dust and other factors during long-term monitoring. A thermometer was placed near the patch antenna sensor to record the environment temperature and compare it with the measurements of the patch antenna sensor.

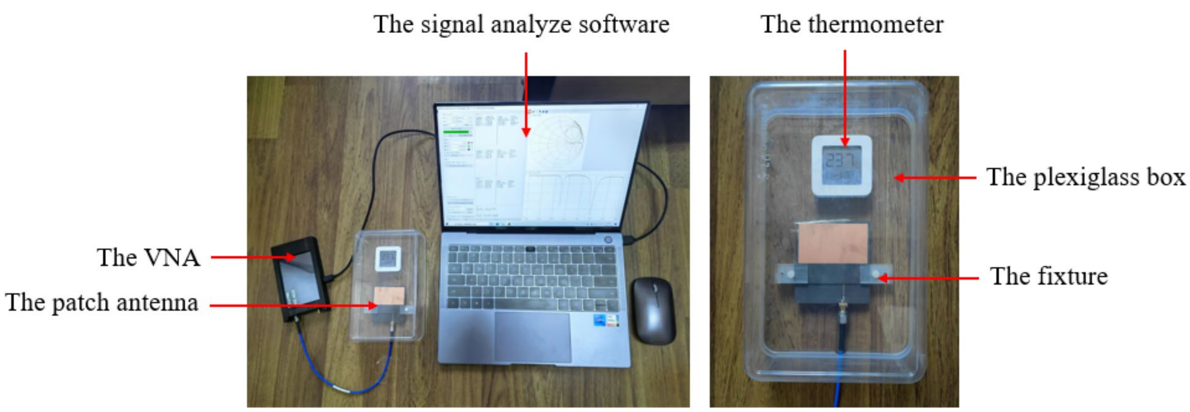

Figure 7. The environment temperature monitoring experimental setup.

Several days of continuous monitoring were performed to demonstrate the feasibility of the sensor for long-term temperature monitoring. The experimental results show that the resonant frequency in transverse direction of the antenna has a good correspondence with the temperature variation during the monitoring period, as shown in the Figure 8. To further illustrate the environment temperature sensing ability of the patch antenna sensor, the 24 hours temperature change in one day was selected to compare with measurements of the patch antenna sensor, shown as Figure 9. The results show that the environment temperature sensing according to the transverse frequency shift of the patch antenna is feasible.

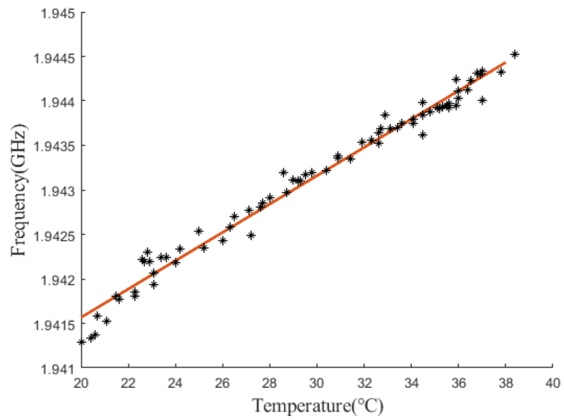

Figure 8. The resonant frequency in the transverse direction with environment temperature.

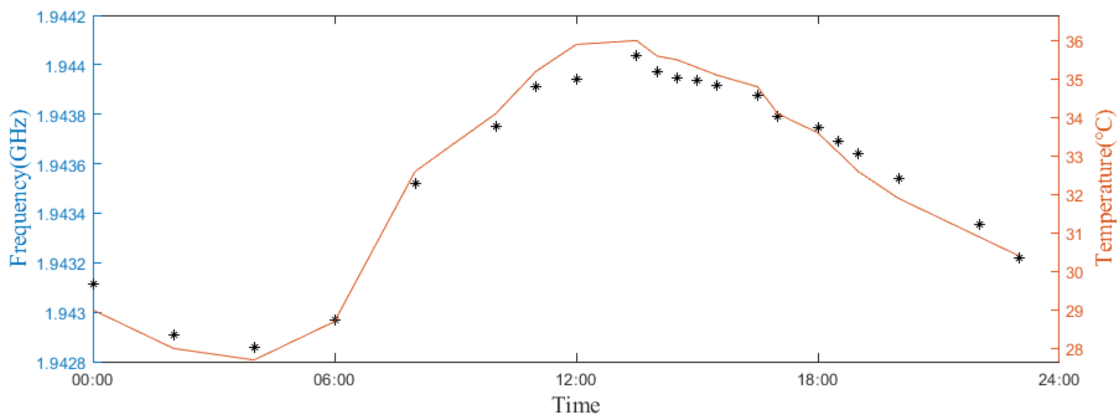

Figure 9. The patch antenna sensor 24- hour temperature monitoring results.

Summary

In this paper, a patch antenna sensor with overlapping sub-patch for simultaneous crack and temperature sensing is proposed. The patch antenna sensor is dual-resonant; thus, the patch antenna's resonant frequency shifts in transverse direction and longitudinal direction can be used to measure the environment temperature and crack width respectively. Theoretical study experimental tests were conducted to study the performance of the patch antenna sensor. Despite the encouraging results, some significant concerns such as the effective wireless interrogation technique still need to be investigated in future work.

References

[1] Taheri shima. A review on five key sensors for monitoring of concrete structures. Construction and Building Materials, 2019, 204: 492-509. https://doi.org/10.1016/j.conbuildmat.2019.01.172

[2] Han, tianran, Wu gang, Lu yong. Crack monitoring using short-gauged Brillouin fiber optic sensor. Measurement, 2021, 179: 109461. https://doi.org/10.1016/j.measurement.2021.109461

[3] Wang tao, Tan bohai, Lu mingge, Zhang zheng, Lu guangtao. Piezoelectric Electro-Mechanical Impedance (EMI) Based Structural Crack Monitoring. Applied Sciences, 2020, 10(13): 4648. https://doi.org/10.3390/app10134648

[4] Zhang jun, Tian guiyun, Marindra adi, Sunny ali, Zhao aobo. A Review of Passive RFID Tag Antenna-Based Sensors and Systems for Structural Health Monitoring Applications. Sensors, 2017, 17(2): 265. https://doi.org/10.3390/s17020265

[5] Yi xiaohua, Cho chunhee, Cooper james, Wang yang, Tentzeris manos, Leon roberto. Passive wireless antenna sensor for strain and crack sensing—electromagnetic modeling, simulation, and testing. Smart Materials and Structures, 2013, 22(8): 085009. https://doi.org/10.1088/0964-1726/22/8/085009

[6] Xue songtao, Zheng zhiquan, Guan shuai, Xie liyu, Wan guochun, Wan chunfeng. A Capacitively-Fed Inverted-F Antenna for Displacement Detection in Structural Health Monitoring. Sensors, 2020, 20(18): 5310. https://doi.org/10.3390/s20185310

[7] Li dan, Wang yang. Thermally Stable Wireless Patch Antenna Sensor for Strain and Crack Sensing. Sensors, 2020, 20(14): 3835. https://doi.org/10.3390/s20143835

[8] Tchafa mbanya, Huang haiying. Microstrip patch antenna for simultaneous strain and temperature sensing. Smart Materials and Structures, 2018, 27(6): 065019. https://doi.org/10.1088/1361-665X/aabd47

[9] Xue songtao, Yi zhuoran, Xie liyu, Wan guochun. Double-frequency passive deformation sensor based on two-layer patch antenna. Smart Structures and Systems, 2021, 27(6): 969-982.

[10] Xue songtao, Li xianzhi, Xie liyu, Yi zhuoran, Wan guochun. A bolt loosening detection method based on patch antenna with overlapping sub-patch. Structural Health Monitoring, 2021, 21(5): 2231-2243. https://doi.org/10.1177/14759217211055613