CRACK PROPAGATION MEASUREMENT USING A BATTERY-FREE SLOTTED PATCH ANTENNA SENSOR

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ABSTRACT

This research studies the performance of a battery-free wireless antenna sensor for measuring crack propagation. In our previous work, a battery-free folded patch antenna was designed for wireless strain and crack sensing. When experiencing deformation, the antenna shape changes, causing shift in electromagnetic resonance frequency of the antenna. The wireless interrogation system utilizes the principle of electromagnetic backscattering and adopts off-the-shelf 900MHz radiofrequency identification (RFID) technology. Following the same sensing mechanism, a slotted patch antenna sensor of smaller size is designed. The antenna detours surface current using slot patterns, so that the effective electrical length is kept similar as previous folded patch antenna. As a result, the sensor footprint is reduced and the antenna resonance frequency is maintained within 900MHz RFID band. To validate the sensor performance for crack sensing, a fatigue crack experiment is conducted on a steel compact-tension specimen. A slotted patch antenna sensor is installed at the center of the A36 steel specimen. For wireless interrogation, a Yagi reader antenna is placed 36 in. away from the antenna sensor to wirelessly measure the resonance frequency shift of the antenna sensor. The measurement is taken after every 10,000 loading cycles, till the specimen fails. Meanwhile, the length and width of the fatigue crack are also recorded. Finally, the resonance frequency shift of the antenna sensor is correlated with crack length and width at each loading stage.

KEYWORDS : *RFID, battery-free sensor, slotted patch antenna, fatigue crack.*

INTRODUCTION

Metallic engineering structures are vulnerable to repetitive fatigue load over their service lives. In particular, fatigue crack and fracture have been the main issues for steel bridge maintenance in recent years [1]. Early crack detection is essential for preventing catastrophic structural collapse and extending structural lifespan [2]. To ensure the safety of steel bridges in the Unites States, biennial bridge inspection is mandated by the Federal Highway Administration. However, current inspection is mainly visual [3]. Visual inspection is labor intensive and subjective. Small-size cracks can be difficult to find. To overcome these difficulties, numerous non-destructive evaluation (NDE) techniques have been developed to detect small crack in the early stage. Examples include piezoelectric sensors [4, 5] and acoustic emission sensors [6]. However, the application of these sensing systems is still limited, due to bulky installation and expensive maintenance of equipment.

Meanwhile, some researchers have investigated passive radiofrequency (RF) antenna sensors for wireless strain sensing and crack detection. The sensing mechanism is to correlate antenna resonance frequency change with strain and crack experienced by the antenna sensor. As a result of the electrical length change under strain, electromagnetic resonance frequency of the antenna changes accordingly [7]. During the operation, the RF reader emits interrogation signal to antenna sensor. If the antenna sensor is in the interrogation range, the sensor backscatters signal to the reader. However, passive (battery-free) antenna sensor application is usually limited due to its short wireless interrogation distance, which is typically within a few inches [8].

Our past research investigated radiofrequency identification (RFID) techniques for strain and crack sensing at relatively longer distance. Because the RFID chip in an antenna sensor modulates and improves signal-to-noise ratio, the maximum wireless interrogation distance can be improved. An RFID folded patch antenna is developed in our previous work [9, 10]. The dimension of the sensor is 61mm × 69mm, which may be too large for practical applications. In order to reduce the sensor dimension, a slotted patch antenna is developed. The sensor detours electrical current path through vias and surface slots in the conducting metallic layer. The dimension of the slotted patch is reduced to 48mm × 44mm. Tensile and compressive strain sensing performance of the slotted patch antenna sensor is first estimated by coupled simulation between mechanics and electromagnetic, and further validated by extensive experiments [9, 11, 12].

This paper presents crack sensing performance of the slotted patch antenna sensor. To validate the performance for fatigue crack sensing, the slotted patch antenna sensor is installed on an A36 steel specimen, which is designed and fabricated according to ASTM standard E647-11. Cyclic loads are applied to propagate a crack into the specimen. During the experiment, crack length and width, as well as antenna sensor resonance frequency, are measured after each loading stage (10,000 cycles). The rest of this paper is organized as follows. Section 1 presents the wireless operation of an RFID system and the design of the slotted patch antenna. Section 2 describes the crack sensing mechanism of the antenna sensor. Section 3 discusses laboratory experimental results for fatigue crack sensing. Finally, the paper is summarized with discussion of future work.

1 WIRELESS INTERROGATION AND SLOTTED PATCH ANTENNA DESIGN

This section introduces wireless operation of an RFID system, and the design of an RFID slotted patch antenna sensor. Section 1.1 describes the principle of passive (battery-free) RFID sensing system for wireless communication between sensor and reader. Section 1.2 presents the size reduction technique from the folded patch antenna [10, 13] and the concept of the slotted patch to achieve further size reduction [11].

1.1 Wireless operation of an RFID system

A wireless RFID system, including a reader and an antenna sensor, is illustrated in Fig.1. In this research, the RFID sensor is composed of an antenna and an RFID chip (SL3ICS1002 model manufactured by NXP Semiconductor). A Tagformance Lite unit from Voyantic Ltd. is used as the RFID reader [14]. During the system operation, the reader emits interrogation electromagnetic signal to the antenna sensor. The antenna sensor receives the power when the sensor is within the interrogation range. Part of the captured power is harvested by the RFID chip. If the harvested power is higher than the turn-on power of the chip (32μW), the sensor is activated. The RFID chip modulates a response signal, and transmits the modulated signal back to the reader. Finally, the reader demodulates the response signal to distinguish the sensor response from the reflection by the surrounding environment. The system is passive (battery-free) since the sensor operates on the harvested interrogation power from the reader, i.e. the sensor does not require its power sources such as batteries.

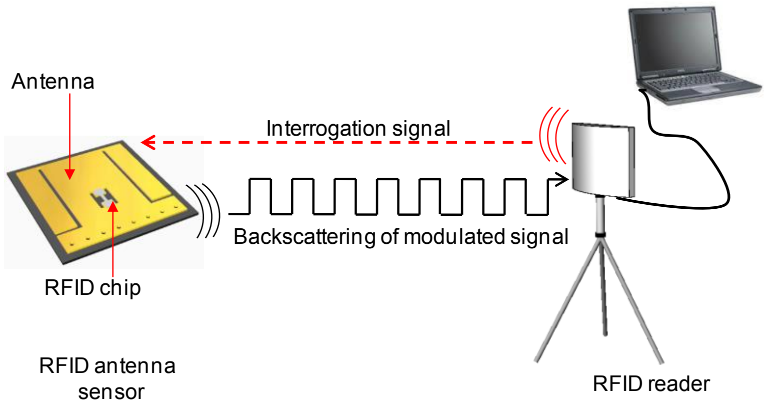


Fig.1. Wireless communication in a passive RFID system

1.2 Slotted patch antenna design

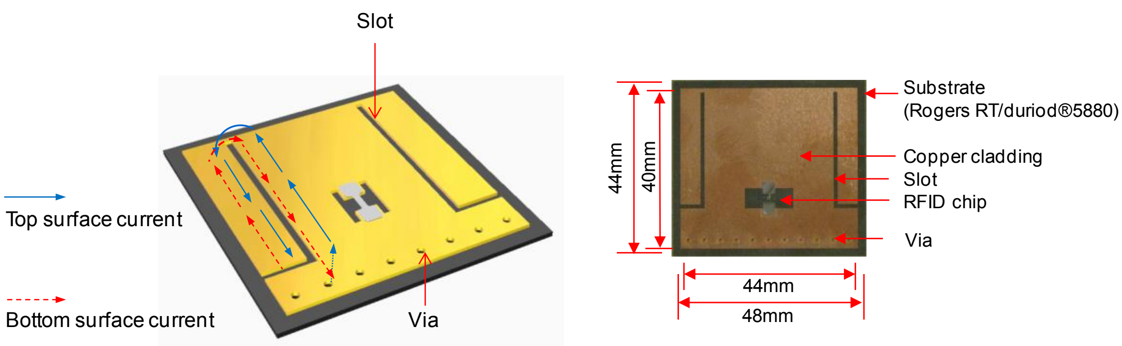
The operating frequency range of the RFID chip is around 900MHz. To utilize the RFID chip for signal modulation, the designed resonance frequency of the antenna sensor should also be around 900MHz. If a regular patch antenna used, the resonance frequency of the antenna can be estimated by:

$$f_{R0}^{Patch} = \frac{c}{2(L+L')\sqrt{\varepsilon_{reff}}} \quad (1)$$

where c is the speed of the light, L is the physical length of the antenna copper cladding (as metallic conductor of the antenna), ε_{reff} is the effective dielectric constant of the substrate, and L' is the additional electrical length due to fringing effect. According to Eq. (1), the length of the antenna sensor needs to be over 130mm, which is undesired in many engineering applications. To achieve size reduction, the slotted patch antenna design is shown in Fig. 2(a) [11, 13]. Vias go through substrate and connect top copper cladding with bottom copper (ground plane) to increase electrical length travelled by the current. Two slots are added on the top copper cladding to further detour surface current path. The resonance frequency of the slotted patch antenna sensor can be estimated as:

$$f_{R0}^{Slotted} = \frac{c}{8(L+L')\sqrt{\varepsilon_{reff}}} \quad (2)$$

As a result, the slotted patch antenna design achieves a smaller dimension of 48mm × 44mm (Fig.



(a) Current detouring for size reduction (b) Dimension and components

Fig. 2. Slotted patch antenna sensor

2(b)). The substrate is made of 0.787mm-thick Rogers RT/duriod®5880 material, which has a low dielectric constant and a low loss tangent to improve interrogation distance and signal-to-noise ratio. Thus, the slotted patch antenna sensor achieves the size reduction compared to the normal patch antenna, while the antenna sensor maintains a resonance frequency around 900MHz for utilization of the RFID chip.

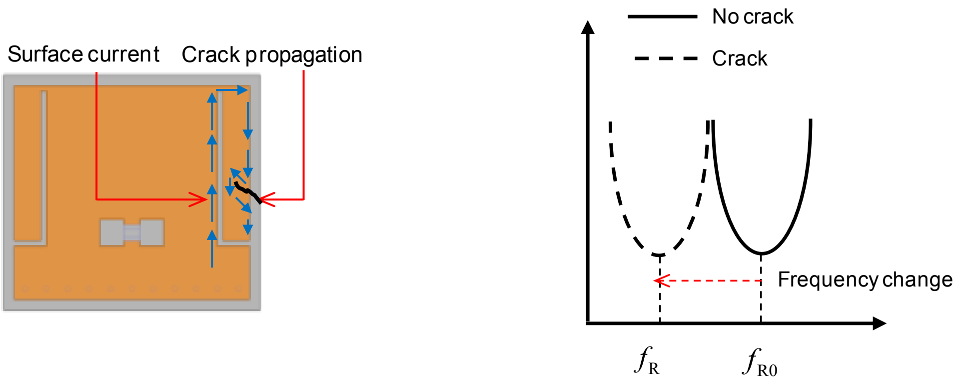
2 CRACK SENSING MECHANISM

Fig. 3 illustrates the relationship between resonance frequency change and crack propagation. The RFID reader sweeps through a predefined interrogation frequency range at a 0.1 MHz frequency step. At every interrogation frequency, the reader searches the interrogation power threshold that is the minimum amount of power needed to activate the RFID chip. After sweeping through the frequency range, the interrogation power threshold is plotted against interrogation frequency, as shown in Fig. 3(b). The resonance frequency is then identified from the minimum point in the plot [9]. If no crack occurs on the sensor, the resonance frequency is denoted as f_{R0}. After a crack on the ground plane or top copper layer propagates into the antenna sensor, the crack blocks current path and forces surface current flow to be further detoured along the crack (Fig. 3(a)). The increase in the electrical length reduces the resonance frequency to f_R, as shown in Fig. 3(b). Through wireless interrogation by the reader, the shifted resonance frequency f_R can be measured and provide information on crack growth.

3 EXPERIMENTAL RESULTS FOR FATIGUE CRACK SENSING

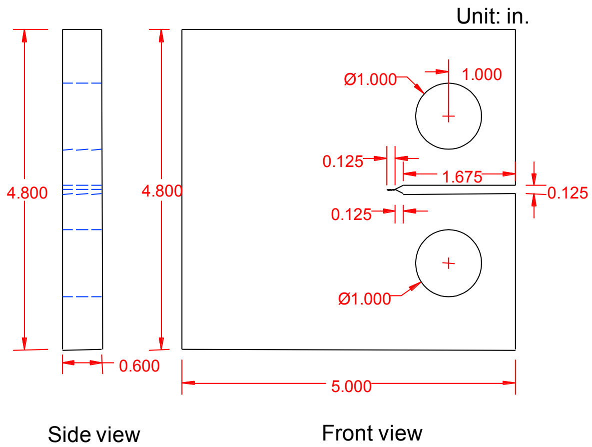
To validate the fatigue crack sensing performance of the antenna sensor, a compact-tension (CT) specimen is designed and fabricated according to ASTM standard E647-11. Fig. 4(a) shows the design drawing of the fatigue test specimen, and Fig. 4(b) shows a photo of the A36 steel fatigue specimen with the antenna sensor installed at the notch tip. Fig. 5(a) shows the fatigue specimen with sensor installed. A passive slotted patch antenna sensor is installed in the center of the specimen to measure crack propagation, which is to be initiated at the notch tip by cyclic loading. To measure crack opening of the specimen during cyclic loading, a magnetostrictive position sensor from MTS Sensors (CS-194-AV) is installed next to the notch. Fig. 5(b) shows the experimental setup for the fatigue test. An Instron 8802 machine is used to apply cyclic tensile load. A 900MHz Yagi antenna is used at the reader side and the interrogation distance is 36 inches.

For pre-crack opening, the specimen is subject to 5 Hz cyclic loading at 1.2 kips ~ 4.8kips. After pre-crack, the cyclic tensile load is reduced to a smaller range for each of the following nine cyclic loading stages, in order to keep constant crack growth ratio (around 0.1 inches per 10,000 cycles). Table 1 summarizes cyclic loading procedures and measurement results. At the end of every loading stage, the Instron machine is paused with a static load at 3 kips for taking

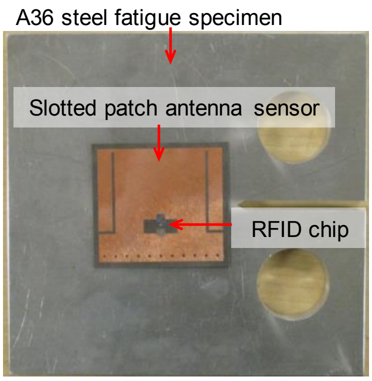


(a) Illustration of crack propagation (b) Illustration of frequency change due to crack

Fig. 3. Crack sensing mechanism



(a) Dimension of the A36 steel specimen

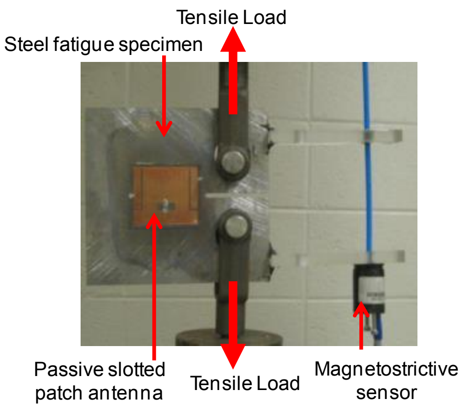


(b) Photo of the specimen with antenna sensor

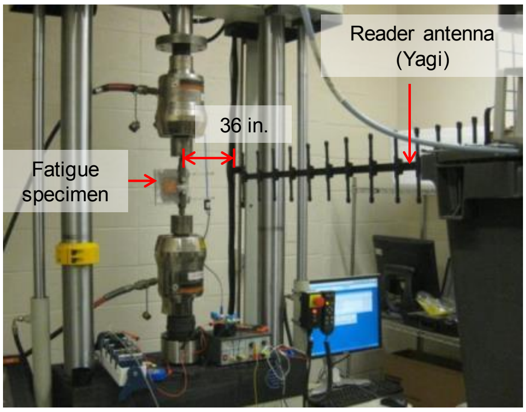
Fig. 4. A36 steel specimen design

measurements. Interrogation power threshold of the RFID antenna sensor is first wirelessly measured using the Tagformance Lite reader unit. After applying dye penetrant on the back side of the specimen, the crack length is measured by a caliper. Crack width listed in Table 1 refers to crack opening at the initial notch tip of the specimen, which is converted from magnetostrictive sensor data according to the specimen dimension. After all measurements are finished, the next cyclic loading stage starts. Fig. 6 shows representative photos from the back view of the specimen. The length of pre-crack is 0.082 inches and no fracture occurred on the sensor. After loading stage #3, the crack length propagates to 0.243 inches and the fracture occurs on the antenna sensor. Because the slotted patch antenna sensor stopped responding to the reader after loading stage #9, the fatigue test is terminated before the specimen is broken into two parts.

Fig. 7(a) plots the average interrogation power threshold of the antenna sensor at four representative crack lengths. The frequency shift from right to left is clearly observed as crack length increases. The resonance frequencies at all crack lengths are extracted from the power threshold figure, and plotted in Fig. 7(b) against crack length. Overall, about 3.5 MHz of resonance frequency decrease is observed in total, when the crack length increases to 0.688 in. Such large frequency decrease is easy to be measured in practice.

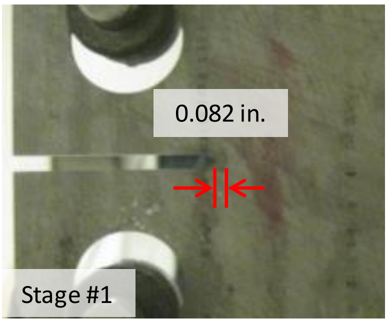


(a) Fatigue specimen with sensors

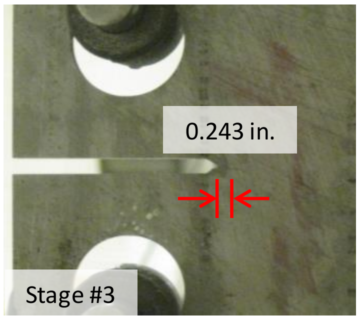


(b) Experimental setup

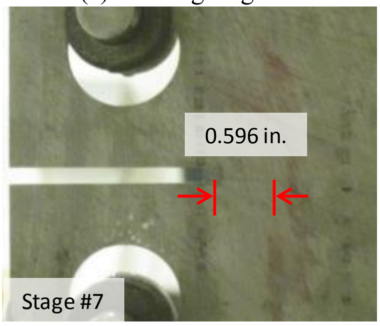
Fig. 5. Experimental setup for the fatigue crack test of the slotted patch antenna sensor



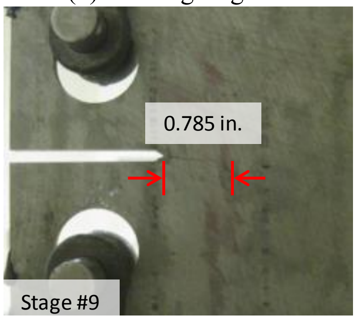
(a) Loading stage #1



(b) Loading stage #3



(c) Loading stage #7

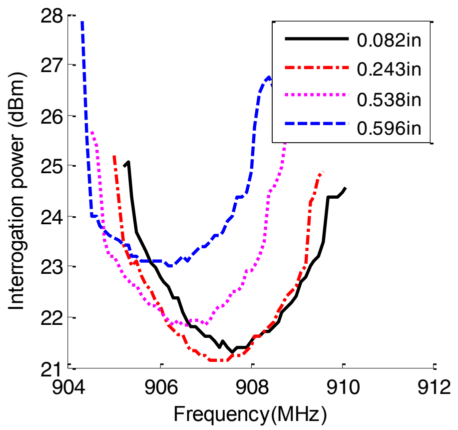


(d) Loading stage # 9

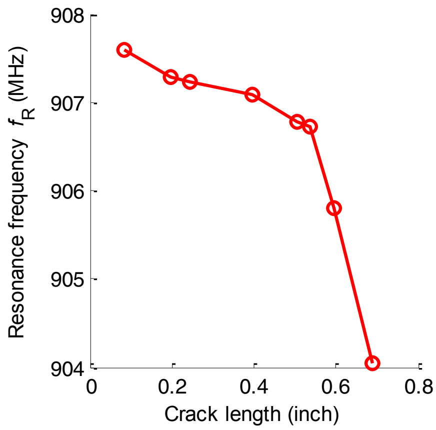
Fig. 6. Steel specimen photos at different crack length

Table 1: Cyclic loading procedures and crack measurements.

Loading stage #	Range(kips)	# of cycles	Crack length (in)	Crack width(in)
1	1.2~4.8	15000	0.082	0
2	1.5~4.5	25000	0.198	0.0009
3	1.5~4.5	35000	0.243	0.0010
4	1.7~4.3	45000	0.395	0.0011
5	1.9~4.1	55000	0.504	0.0012
6	1.9~4.1	65000	0.538	0.0012
7	1.9~4.1	75000	0.596	0.0013
8	1.9~4.1	85000	0.688	0.0014
9	1.2~4.8	95000	0.785	0.0016



(a) Average interrogation power and threshold



(b) Resonance frequency change with crack length

Fig. 7. Fatigue test results of the slotted patch antenna sensor

SUMMARY AND FUTURE WORK

This research presents a wireless crack sensing technique using the passive RFID system. The design of an RFID slotted patch antenna sensor is introduced. To verify the performance, compact-tension specimen is designed and a fatigue experiment is conducted. As crack propagates, the resonance frequency of the slotted patch antenna sensor reduces as expected. In the future, more extensive fatigue tests will be conducted with different loading conditions to validate sensing performance of the slotted patch antenna sensor. The interrogation distance limit will also be examined.

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