The 7th World Conference on Structural Control and Monitoring, 7WCSCM,
July 22-25, 2018, Qingdao, China

Design and Numerical Simulation of Parted Crack Sensor Based on Patch Antenna

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Abstract

A passive wireless parted sensor based on patch antenna is designed and simulated to monitor the expansion of cracks in this paper. The crack sensor is attached on the surface of the structure, and its two parts will generate relative displacement when structural crack develops, which results in capacitance change and make further effect on resonant frequency shift. The finite element model of the patch antenna is established in HFSS and cracks propagation is simulated by applying relative displacement between the two parts of sensor. Then the resonant frequency is extracted from return loss coefficient curve to be fitted with crack width. So the change of the crack width can be monitored by detecting the resonant frequency shift of patch antenna.

Keywords: crack sensor, patch antenna, crack width, resonant frequency

1 Introduction

With the service load and environmental effect the performance of the structure will gradually degrade over time, so structure health monitoring has been extensively developed over the last few decades to monitor and evaluate the state of the structure[1].

Since cracks can directly indicate the state of damage the structure is suffering from, crack monitoring is significant in structure health monitoring. For reinforced concreted structure, lots of factors can induce cracks, such as temperature variation, differential settlement, loads and so on. Cracks will accelerate the carbonation of concrete and the erosion of steel bar, decrease the carrying capacity, and affect the appearance of building[2]. For steel structure, cracks are usually induced by fatigue under cycling load[3]. And the structure will failure and rupture when the dimension of crack over critical point.

The width of crack can be assessed by visual inspection with the help of binoculars, or by ultrasonic testing[4]. However, manual inspection should be conducted at fixed periods, which is time- and labor-consuming. In structure health monitoring, crack sensing technology is extensively used, such as fiber optical crack sensor[5] and vibrating wire crack sensor. The performance of these traditional crack sensors are reliable, but bulk of power lines and data cables are needed for power supply and data transmission for these sensors, respectively, which make installation and deployment of crack sensors difficult. What's more, wired crack sensors could not acquire data due to power failure or cable malfunction during extreme disasters.

In order to get rid of lines and cables entirely in the sensing system, the wireless passive sensors are developed and applied. Based on radiofrequency identification technology[6, 7], the antenna sensor can make the wireless detection of crack come true. The crack monitoring based on coil antenna was studied in 2003[8]. In 2011, Yi et al.[9] developed the smart-skin folded patch antenna senor for strain monitoring. Similarly, the sensor can also sense the deformation induced by structural cracks, so it can be used as crack sensor simultaneously. And other antenna sensors were researched as strain and crack sensors[10-12]. Due to the low profile and narrow bandwidth of patch antenna, Mohammad et al.[13] specifically propose a dual-resonant patch antenna for crack detection. Focusing on detection of crack dimension, 2D grid meander line dipole antenna[14] and 2D grid dipole antenna[15] are used to realize this task. The vector network analysis is required to obtain data for the former antenna sensor and wireless detection is completed for the latter.

For those crack sensors mentioned above, the deformation induced by cracks need to be transferred through substrate. Because of the negligible thickness of substrate, the transfer efficiency needs to be considered precisely. Additional, reliable connection between structure and crack sensor is very important to ensure coincidence of their deformation, which is unwarrantable under large deformation for common glue-connection. To solve this difficulty, crack sensors using mutual-coupling between two patch antennas[16, 17] were explored. The two patch antennas are located on both sides of crack, respectively. The phase changes with the alteration of distance between the two patch antennas. So the crack width can be obtained as long as the relationship is established between distance and phase. Nevertheless, the interrogation distance between the patch antennas and reader influence the relationship of the phase and crack width, so the reader position need to be fixed, which is not flexible in application.

Connected with those researches, this paper proposes a new parted crack sensor based on patch antenna. In other words, the crack sensor is composed of two parts which attached on both side of the crack respectively. And more reliable electro characteristics almost unaffected to interrogation distance are used as crack detection parameter, such as resonant frequency. The Second II introduces the design principle and measurement mechanism of the crack sensor. The Second III presents the results of numerical simulation. And the Section IV draw the conclusion of this paper.

2 Parted Crack Sensor Based on Patch Antenna

The common rectangular patch antenna consists of top microwave patch, bottom microwave patch, substrate and matched line, shown in Figure 1. According to the dimension change of top microwave patch, it was used to monitor structural deformation. In order to avoid the influence of substrate's deformation, the parked sensor is proposed by changing the deformation sensing unit.

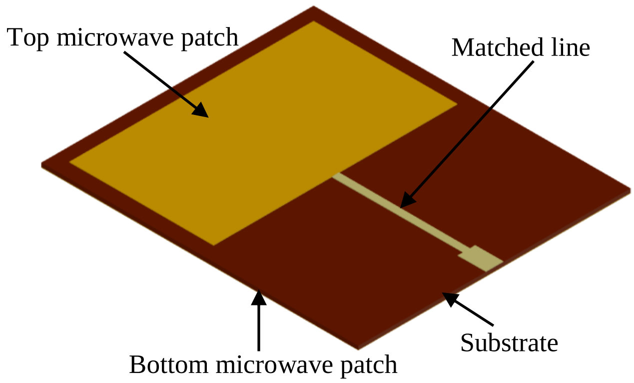
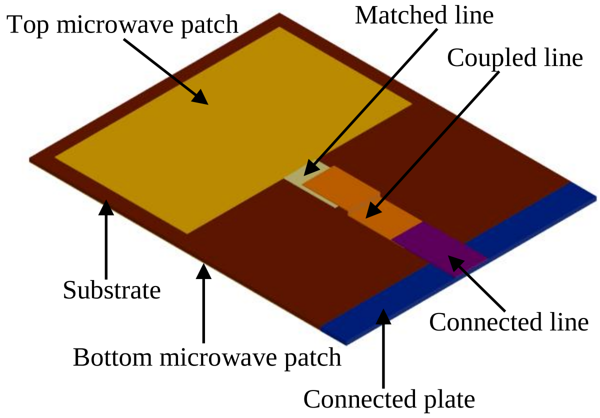


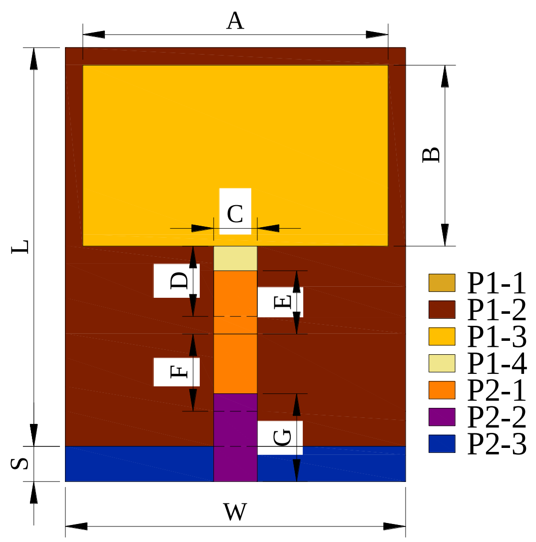
Figure 1. The model of patch antenna

2.1. Design of Crack Antenna Sensor

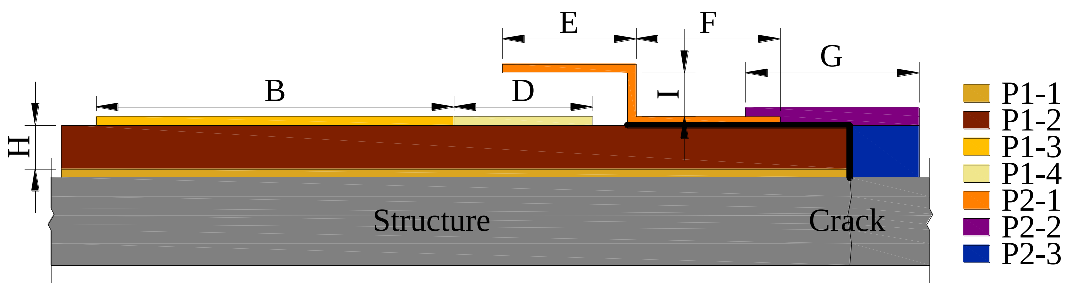
The crack antenna sensor is based on patch antenna which is split into two parts by adding a capacitor in the potrion of matched line, as shown in Figure 2. The bold wire is the boundary of the two parts in the longitudinal cutaway view of crack sensor (Figure 2(c)).



(a) The 3D view of crack sensor model



(b) The plan view of crack sensor model



(c) The cutaway view of crack sensor model

Figure 2. The model of crack antenna sensor

The first part consists of bottom microwave patch (P1-1), substrate (P1-2), top microwave patch (P1-3) and matched line (P1-4). The bottom/top microwave patch and matched line are made of copper cladding. The RT/duroid® 5880 is adopted as the material of substrate because of its low dielectric attenuation. The second part is composed of coupled line (P2-1), connected line (P2-2) and connected plate (P2-3). The coupled line is made of thin copper sheet. The consideration of selecting the material of connected line and connected plate is that the dielectric constant needs to be close 1, such as cystosepiment. In the case, the connected line and plate will not affect the distribution of electromagnetic field generated by patch antenna. The parameters of crack sensor are shown in Figure 2 and the corresponding dimensions are listed in Table 1.

Table 1: The dimensions of the crack sensor(Unit:mm)

Parameters	*L*	*W*	*S*	*A*	*B*	*C*	*D*	*E*	*F*	*H*	*I*
Dimensions	45.4	39	4	35	20.6	5	8	7.2	8.8	0.5	0.5

2.2. Measurement Principle of Crack Antenna Sensor

The patch antenna of crack sensor can be seen as a circuit shown in Figure 3. The top microwave patch acts as the power source. The overhanging portion of the coupled line constitutes a capacitor with the overlapped portion of matched line, so these two lines can be equivalent to the combination of resistance and capacitance, acting as load. The patch antenna can receive the electromagnetic wave emitted by RFID reader and transmit the power to the load, and the current is generated in this process. But a portion of power is reflected so that it can not be utilized by load. The reflection coefficient is defined as:

$$\eta(f) = \frac{P^-}{P^+} = \left| \frac{Z_L - Z_0^*}{Z_L + Z_0} \right|^2 \tag{1}$$

Where P^- is the reflected power, P^+ is the input power, Z_L is the impedance of the load, Z_0 is the impedance of the patch antenna, and Z_0^* is the conjugate of the impedance of the patch antenna, which are the function of the operating frequency. When the impedance of antenna and load match each other best, $\eta(f)$ takes minimum value and corresponding operating frequency is defined as resonant frequency.

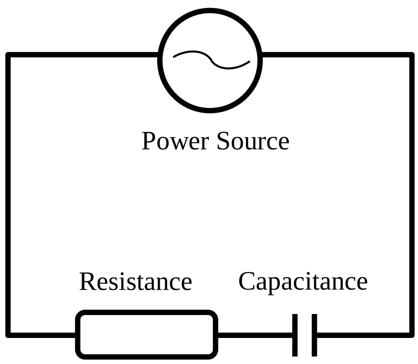


Figure 3. The equivalent circuit of patch antenna

The coupled line is bonded with connected line by super glue. The coupled line and connected line are contacted with the substrate and can move freely on the surface of substrate with the connected plate. As shown in Figure 4, when crack develops, the relative displacement occurs between the two parts of crack sensor located on both sides of crack respectively. Then the effective overlap length t_0 of two electrical plates of capacitor decreases lending to the change of capacitance and Z_L. In this case, the impedance of patch antenna needs change to match altered load impedance by changing operating frequency and the resonant frequency shifts consequently. The crack width $\triangle t$ is equal to the change of effective overlap length of capacitor, and the load impedance will change regularly. If the resonant frequency shift has the clear relationship with the change of load impedance, the crack width can be obtained by detecting resonant frequency of patch antenna.

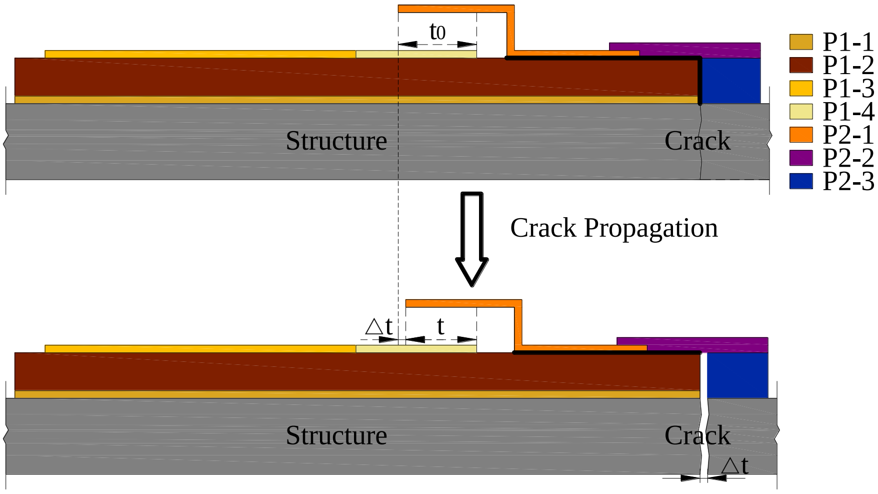


Figure 4. Operation principle of crack antenna sensor

3 Numerical Simulation of Crack Sensor

In order to obtain an accurate prediction about the performance of the RFID sensor for crack width detection, numerical simulation is adopted in finite element software.

3.1. The Finite Element Model

The finite element model is established in HFSS. The boundaries of top/bottom microwave patch, matched line and coupling line are set as perfect. The bonding between the top/bottom microwave patch and the matched line is assumed to be ideal with substrate. The coupled line can move freely on the surfuce of substrate. The connected line and connected plate do not appear in the finite element model based on the hypothesis that the electromagnetic field is impervious to these portion. The antenna sensor is placed inside an air sphere. The bottom and front sufures of patch antenna is overlapped with the surfaces of air sphere and the distance of thire other sufuces is about quarter wavelength corresponding to resonant frequency of patch antenna. At the outer surface of the air sphere, the radiation only is assigned. The finite element model is shown in Figure 5. The crack propagation is simulated by controlling the effective overlap length t_0 from 6.7 to 2.2mm at an increment step of -0.1mm,which makes the two parts of crack sensor generate relative displacement.

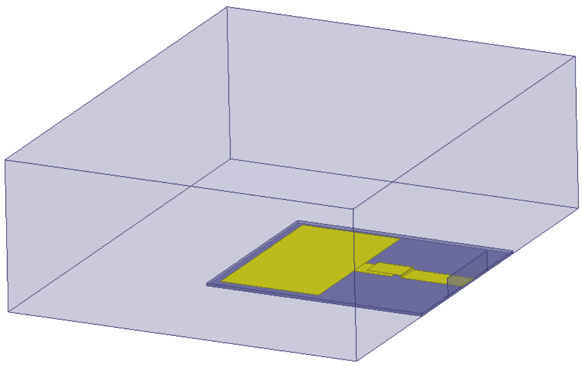


Figure 5. The finite element model of patch abtenna

3.2. Result Analysis

During the electromagnetic simulation, a frequency domain solver is used to calculate the return loss coefficient, which quantifies the impedance matching, and the efficiency of power transfer between load and the antenna. The return loss coefficient S_{11} can be calculated as following:

$$S_{11} = 10\lg\eta(f) \tag{1}$$

The return loss coefficient curve reaches its minimum value when patch antenna operates at resonant frequency according to the characteristic of function $\eta(f)$. So the resonant frequency can be obtained by picking the minimum of curve. The return loss curves of all steps are shown in Figure 6.

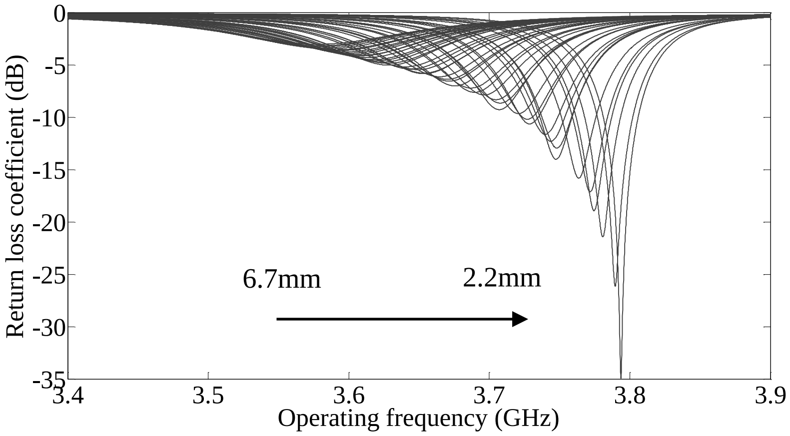


Figure 6. The return loss coefficient curves

Assuming that crack width is zero when the effective overlap length equal to 6.7mm, the return loss coefficient minimum and resonant frequency are extracted from curve under each step and plotted in the Figure 7 and 8. As can be seen in the Figure 7, the return loss coefficient changes with the decrease of effective overlap length at resonant frequency, which means that change of load impedance will influence $\eta(f)$ and resonant frequency. The resonant frequency of patch antenna is fitted linearly and quadratically with respect to crack width, and the results are shown in Table 2. The R-square of quadratic fit is more close to 1 than linear fit, so the quadratic expression is more precise in application. However, quadratic function is so complex that it is infeasible in engineering.

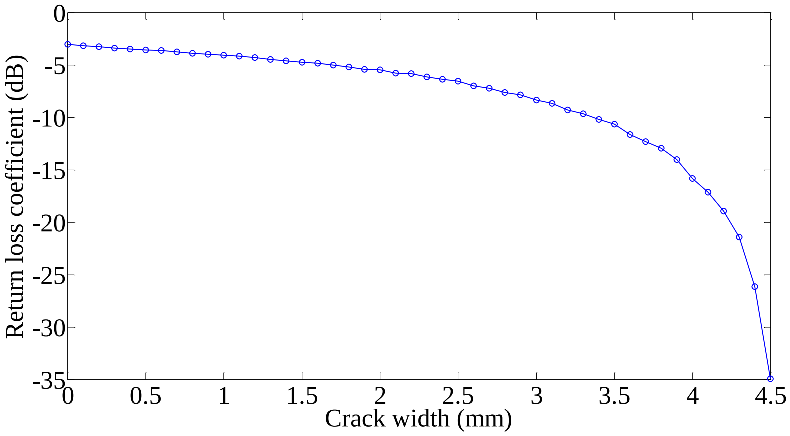


Figure 7. The return loss coefficient curves

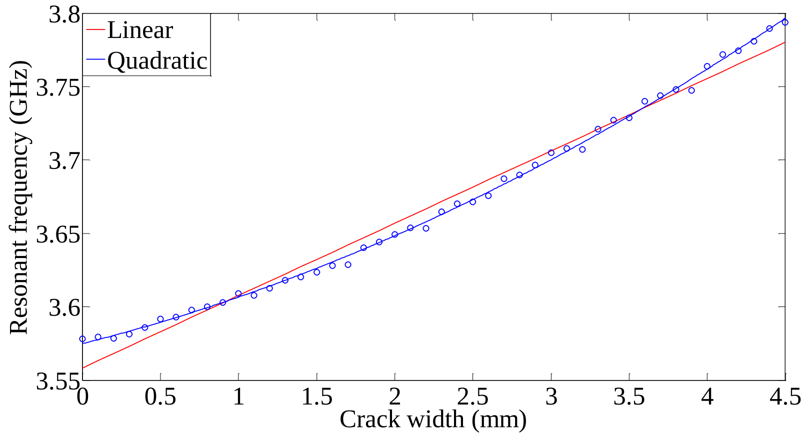


Figure 8. The crack width-resonant frequency fitted line

Table 2: The comprosion of diffrernt fitted line

	expression	*R-square*
linear function	f=0.0493w+3.5583	0.9840
quadratic function	f=0.005w2+0.0267w+3.5749	0.9984

To obtain linear relationship between resonant frequency of patch antenna and crack width, twenty-one continuous points are selected to be fitted ensuring that the measuring range is no less than 2cm. The selection principle is that the fitted line's R-square of the continuous points is maximum. The range from 5.2 to 3.2mm of the effective overlap length is adequate by comparison. Then the 5.2mm of the effective overlap length is designated as zero crack width by changing the length of connected line and the line is fitted renewedly as shown in Figure 9. The R-square 0.9930 indicates that the crack width has good linear relationship with resonant frequency. Therefore, the antenna sensor can monitor crack width accurately by detecting resonant frequency of patch antenna, and the relationship of them is simple to use in engineering.

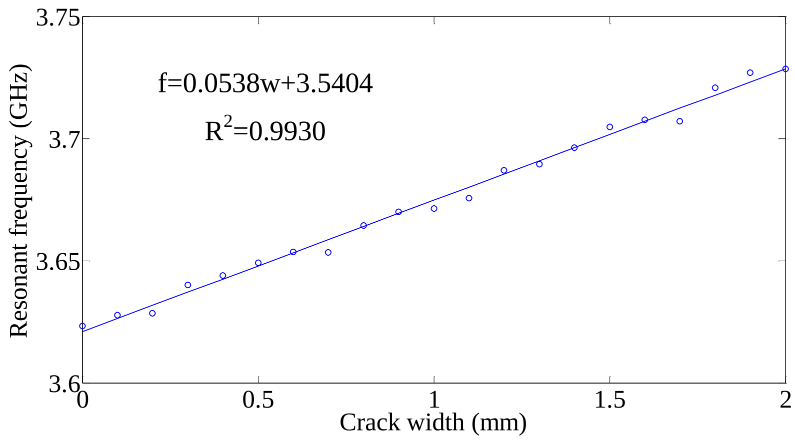


Figure 9. The crack width-resonant frequency linearly fitted line

4 Conclusions

This paper proposes a crack sensor based on patch antenna. The sensor is disconnected two parts by adding a capacitor in matched line. When crack devoples, the two parts of crack sensor attached on both sides of crack respectively will move relatively leading to the change of antenna load impedence, and resonant frequency will shift consequently. Base on this, a crack sensor is designed and simulated in finite element software. The result of numerical simulation indicates that the resonant frequency of patch antenna is related with the effective overlap length and has good linearty with crack width when the effective overlap length changes from 5.2 to 3.2mm.

Acknowledgement

This study was supported by the National Natural Science Foundation of China (Grant No.51478356), the Key Program of intergovernmental international scientific and technological innovation cooperation (Grant No. 2016YFE0127600), and by the Fundamental Research Funds for the Central Universities.

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