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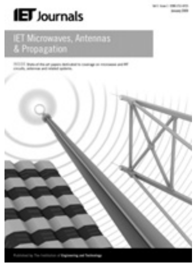

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Passive low-cost inkjet-printed smart skin sensor for structural health monitoring

B.S. Cook[1] *A. Shamim*[1] *M.M. Tentzeris*[2]

[1]*Department of Electrical Engineering, King Abdullah University of Science and Technology, Thuwal, KSA*
[2]*Department of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA*
E-mail: benjamin.cook@gatech.edu

Abstract: Monitoring fatigue cracking of large engineering structures is a costly and time-intensive process. The authors' present the first low-cost inkjet-printed patch antenna sensor that can passively detect crack formation, orientation and shape by means of resonant frequency shifts in the two resonant modes of the antenna. For the first time, the effect of non-linear crack shapes on the parallel and perpendicular resonant modes of a patch antenna is quantified with simulation and measurement. This study presents a step towards fully integrated, low-cost, conformal and environmentally friendly smart skins for real-time monitoring of large structures.

1 Introduction

The high costs and liabilities associated with large-scale structure failures has made real-time structural health monitoring (SHM) an integral and necessary security measure to ensure safe and reliable operation of dams, bridges, aircrafts and skyscrapers. Current engineering structures are susceptible to cyclic loading and harsh environments, which cause deterioration and stress fractures over the structures lifetime. To remain in service for long periods of time, these structures require constant inspections to detect and prevent potential structural problems. Failures or down time because of required inspections present significant costs in time and resources. Periodic manual inspections, which are primarily visual, are difficult and nearly impossible in some situations where there are hard to access areas or cracks underneath the paint. Smart skin wireless sensors are an attractive option for monitoring the structural health of these large structures.

According to Foong *et al.* 50–90% of large-scale structure failures are because of cracks caused by fatigue [1]. Several non-destructive sensing techniques such as ultrasonic interrogation, eddy-current sensors and comparative vacuum sensors have been discussed in [2] for monitoring crack formation and progression in load-bearing structures. However, these methods are expensive to implement on a large scale because of the labour and wiring costs as well as range-limited because of the power requirement. Recently, a new method emerged that uses a passive patch antenna to sense strain and crack development in structures by measuring the change in the resonant frequencies of a patch antenna [2–4]. The strain or crack in the structure to which the patch antenna is mounted changes the electrical length and/or width of the antenna leading to a resonant frequency change which can be detected by wireless interrogation. These patches can then be integrated into a smart skin, which can be interrogated in a zero-power way by an 'radio frequency identification (RFID)-like' reader and can be applied to these large structures at minimal cost.

Several methods have been studied, which use patch antennas for stress and crack sensing in structures. In [2], a patch antenna is fabricated on a flexible Kapton substrate and mounted onto a cracked ground plane. By stressing the ground plane and introducing a crack, a detectable change in the TM_{10} and TM_{01} modes of the patch antenna occurs. A second method demonstrated in [3] detects strain by measuring resonant frequency shifts caused by stretching of a Kapton-fabricated antenna mounted on a stressed ground plane. As the ground plane is stressed without introducing a crack, the antenna is stressed as well causing small dimension changes and therefore changing the resonant frequency. However, current studies have only quantified the effects of linear, or hairline cracks on the corresponding orthogonal mode of the patch. Effects of non-linear shaped cracks such as rectangle and pie-shaped cracks on the parallel and orthogonal modes have yet to be studied. Linear or hairline cracks have no effect on the parallel propagating mode, however, other crack shapes as will be demonstrated effect both modes, a property that is currently not exploited.

For distributed patch-based crack sensor networks to be an economical solution, they need to be low cost and easily mass producible. Currently published works use expensive photolithography methods on flexible substrates to fabricate the sensing antennas. By utilising inkjet-printing on a paper substrate to fabricate the sensors, low-cost green sensor networks become a viable solution for real-time SHM [5]. Inkjet printing also allows for an easy transition to mass production by means of reel-to-reel or roll-to-roll printing, which is a common industrial practice. These large-scale printing methods allow entire wallpaper arrays of sensors to be printed, which can cover large surface area structures such as bridges and dams. As SHM is a long-term application, the environmental resistance of the sensors is important as well and low-cost measures such as parylene and UV coatings can be applied post-printing which have been shown to increase sensor resistance to harsh environmental conditions. This paper contains the modelling and corresponding measurements of non-linear crack formation and progression using a low-cost paper-based inkjet-printed patch antenna with the intent of creating an economical solution for large-scale implementation of SHM crack sensors. This work assumes the patch antennas will be firmly affixed to metal structures with a strong adhesive which will cause cracks to form through the entire patch structure when cracks occur in the metal structure to which they are affixed.

2 Theory and simulation

Crack sensing using a patch antenna works by perturbing the TM_{10} and TM_{01} standing wave modes on the patch antenna as shown in Fig. 1. In the TM_{10} mode, the electric field is parallel to the length direction of the patch, whereas in the TM_{01} mode the electric field is parallel to the width direction. A thin crack in the length direction of the patch will not disturb current flow in the TM_{10} mode as it is in the direction of current flow shown in Fig. 1*b*. However, it will cause current to flow in a perturbed path in the TM_{01} mode (perpendicular to crack direction), which increases current path length and decreases the resonant frequency of the mode as shown in Fig. 1*e*.

The same occurs with a width-direction crack and the TM_{10} mode. However, if the crack is not very thin, it starts to affect the currents in the parallel propagation mode as well which has yet to be quantified in the literature and is the main focus of this paper. Different crack shapes will perturb the currents differently causing unique resonant shift characteristics to each crack shape as it propagates through the patch which becomes very useful in detecting structural fatigue cracking using dual-polarisation/mode sensing.

As a proof of concept and without loss of generality, the patch antenna used for this study, shown in Fig. 2, is a microstrip-fed patch that is designed for 1.9 GHz operation. As the antenna will be printed on a 250 μm thick lossy paper substrate which has a relative permittivity (ε_r) of 3.2 and loss tangent (tan δ) of 0.05 at 1.9 GHz [6], a 1.25 mm layer of polystyrene foam is inserted between the printed patch and the ground to decrease the substrate losses. The antenna is optimised using the CST (FDTD) solver and has final dimensions of 87 × 70 mm with inset feed dimensions of 7 × 13 mm and an input impedance of 50 Ω at 1.9 GHz.

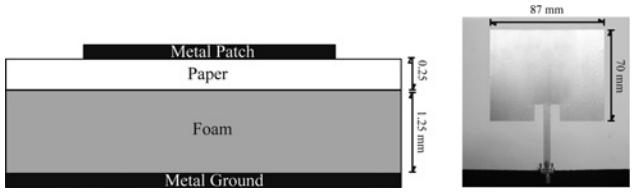

Fig. 2 *Fabricated patch antenna and antenna cross-section*

The spacing of the patch from the substrate edge is (λ/4) in all directions.

Initial simulations are performed with four different crack shapes: a rectangle, and a 5°, 10° and 15° triangular crack with the crack orientation parallel and perpendicular to the TM_{10} mode. Results from a parallel and perpendicular triangular crack are shown in Fig. 3*a*, where the crack in the parallel direction is 50% of the patch length and the crack in the perpendicular direction is 10% of the patch width.

The simulation results show that cracks in the parallel orientation generally will increase the resonant frequency, whereas cracks in the perpendicular orientation decrease the resonant frequency in the case of the crack breaking both the metallisation and substrate. However, when the crack only breaks the substrate, the resonant frequency will increase regardless of orientation.

3 Inkjet-printed patch fabrication and measurements

The benchmarking antenna is printed onto a standard commercial photo paper using a Dimatix DMP-2800 (www.dimatix.com) inkjet printer and a silver nanoparticle-based ink from Cabot Corporation (www.cabot.com). Printing is done at a resolution of 1270 DPI, or drop spacing of 20 um to ensure good RF conductivity at 1.9 GHz. After printing, the antenna is cured in an oven for 2 h at 150°C in a Thermo Scientific oven to melt the nanoparticles together which results in a conductivity of near 1e7 [S/m] [6]. The paper is then cut and mounted onto the 1.25 mm thick extruded foam and ground plane using a light spray adhesive. SMA connectors are mounted using a two-part conductive epoxy from Chemtronics (www.chemtronics.com). The fabricated antennas return loss is measured using a Rhode and Schwartz 8 GHz VNA to verify correct operation of the patch before cracking the antenna. The results are shown in Fig. 3*a* and demonstrate that the antenna is operating as expected from the CST simulations.

The four crack types are propagated through the patch in parallel and perpendicular directions to the TM_{10} mode of operation. In the first case, the cracks cut through the patch metallisation, substrate and ground plane; and in the second

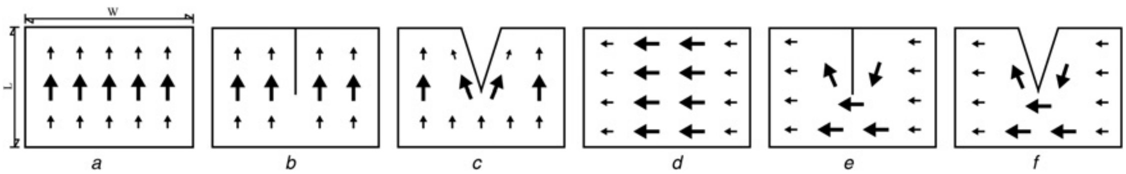

Fig. 1 *Patch surface currents for*

a TM_{10} mode
b TM_{10} mode with parallel hairline crack
c TM_{10} mode with parallel pie-shaped crack
d TM_{10} mode
e TM_{10} mode with perpendicular hairline crack and
f TM_{10} mode with perpendicular pie-shaped crack

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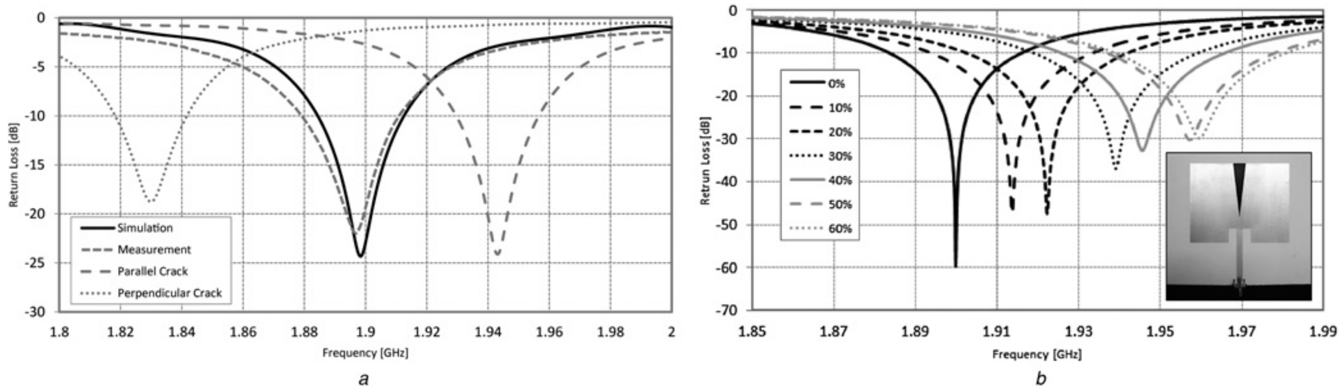

Fig. 3 *Graphs showing*

a Simulated return loss and measurement for original fabricated patch and simulation for parallel and perpendicular cracks to the TM_{10} mode
b Measured return loss for a 15° crack propagating through the patch in 10% increments of the patch length

case the crack is only cut through the substrate leaving the metallisation and ground plane intact. Each case is first simulated using the CST time-domain (FDTD) solver to predict the effects the cracks will have on the patch antenna.

4 Experimental setup

In order to induce cracks in the fabricated patch antennas, crack templates are constructed using plexiglass and a laser cutter. The templates are placed over the patch and a crack is cut into the patch with a blade, which follows the stencil to ensure accurate cutting. To simulate cracks that only disturb the substrate and leave patch and ground metallisation intact, a rectangular insert is cut from under the patch, the crack is cut into the insert, and the insert is slid back under the patch.

4.1 Crack parallel to TM_{10} mode

First, the four crack types are propagated through the metallisation, ground plane, and substrate parallel to the TM_{10} mode of operation and the results are measured. The return loss against crack length for a 15° crack is shown in Fig. 3*b*. It can be seen that the resonant frequency increases as the crack progresses through the patch. The measurement and simulation results for the four crack shapes are compared in Fig. 4.

As demonstrated, the rectangular crack has the effect of first increasing the resonant frequency by shortening the

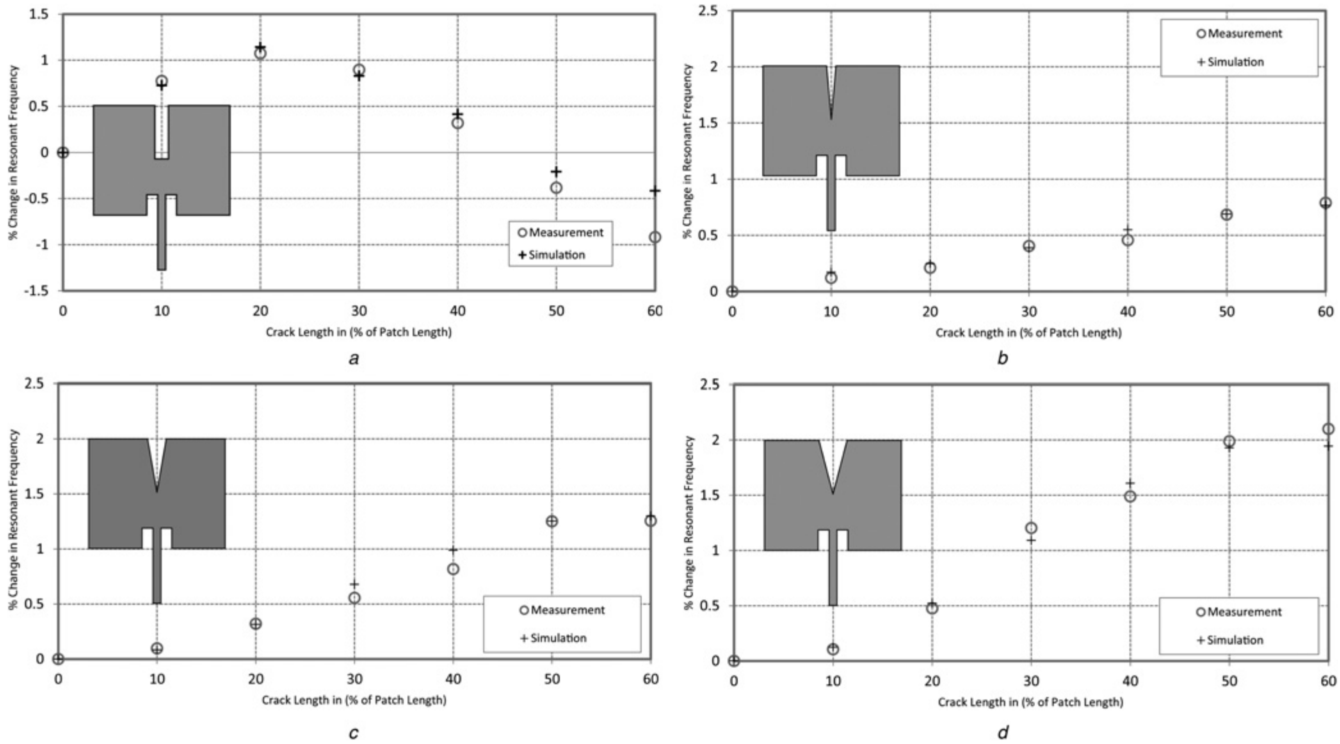

Fig. 4 *Crack through metallisation, substrate and ground for*

a Rectangular crack
b 5° crack
c 10° crack
d 15° crack

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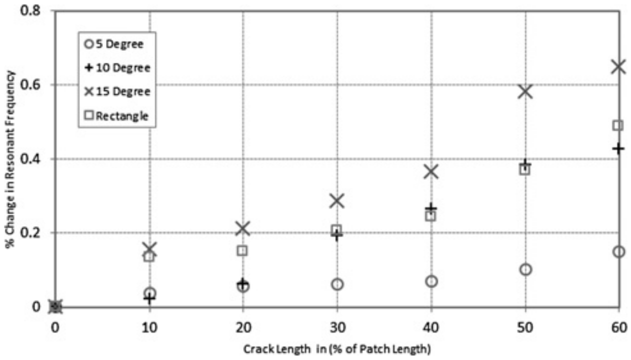

Fig. 5 *Measured resonant frequency change because of cracks forming in the patch antenna substrate parallel to the TM_{10} mode*

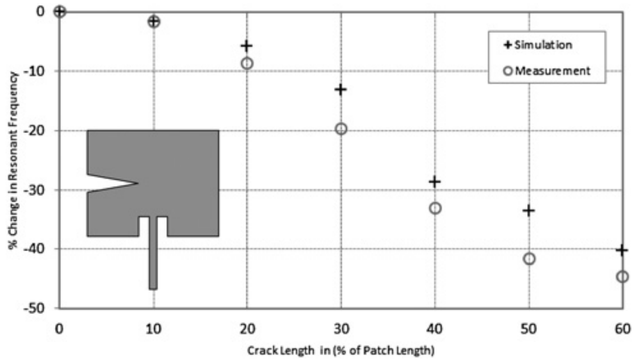

Fig. 6 *Measured and simulated resonant frequency change because of a crack forming perpendicular to the TM_{10} mode of propogation*

effective length of the patch as the antennas average length decreases. However, once the crack reaches 20% of the length of the patch, the currents are forced to flow around the crack which increases the mean current path length, which brings the resonant frequency down. This decrease in resonant frequency continues as the crack length increases.

The pie-shaped cracks do not demonstrate the same behavior as the rectangular cracks on the parallel resonant mode as current flow is not forced to flow around the sharp edges of the rectangular crack. This creates a constant increase in resonant frequency with crack length because of an effective average shortening of the patch length. As crack width increases, the effective shortening becomes more prominent and the resonant frequency increases at a larger rate with crack length. This becomes apparent in Figs. 4*b*–*d*. Generally, the measurements compare well with the simulations, however there are slight discrepancies, which can be described as follows. As the patch is fabricated using a photo paper and foam substrate, manufacturing tolerances on thicknesses and substrate homogeneity are not nearly as strict as those for standard RF substrates, which makes perfect modelling difficult.

The same crack shapes are then only propogated through the substrate without disturbing the ground and patch metallisation. As the substrate has a higher dielectric constant than air, cracking in the substrate will decrease the effective dielectric constant of the patch. The patch resonant frequency is related to substrate permittivity by (1) where $\varepsilon_{r_{\text{eff}}}$ is the effective permittivity of the microstrip patch structure, c is the speed of light in free space, L is the patch length, and ΔL_{oc} is the added patch length because of fringing capacitance [2]. This means that as the crack increases in area under the patch, the effective dielectric constant will decrease in turn increasing the resonant frequency of the patch

$$f_{10} = \frac{c}{2L\sqrt{\varepsilon_{r_{\text{eff}}}}} - 2\Delta L_{\text{oc}} \qquad (1)$$

It is expected that the resonant frequency of the patch will increase for all crack shapes as crack size increases since current paths are not affected by any cracked conductors in this case.

Fig. 5 shows the effects of different shaped cracks propagating through the substrate. As shown, the crack area is the determining factor on the resonant frequency shift. The larger cracks cause a larger shift as the effective dielectric constant incurs a greater decrease thus decreasing the electrical size and increasing the resonant frequency of the patch. However, the frequency shift is much smaller than cracks that cut both the metallisation and substrate.

4.2 Crack perpendicular to TM_{10} mode

After quantifying the effects of multiple crack shapes and sizes parallel to the direction of current propogation, the direction of the crack is changed to cut the patch perpendicular to the TM_{10} mode. As the crack is now directly in the path of the current, the resonant shifts will be much larger and cause a decrease in the resonant frequency because of an increase in path length required for the current to flow around the crack. Simulation results show that crack shape and width do not have a large effect compared to the crack length when the crack is perpendicular to the radiating mode. Therefore only a 10° crack is used in measurement for this case, which is displayed in Fig. 6.

As shown, the shifts in resonant frequency are much more dramatic with a crack perpendicular to the current direction than with a crack parallel to the current direction which is expected. While a parallel crack only produces 1–2.5% shifts depending on the crack size, perpendicular cracks can shift the resonant frequency by over 50%. The effects seen in the TM_{10} are flipped for the TM_{10} mode meaning a parallel crack for one mode is a perpendicular crack for the other. And, the effects seen in the TM_{10} mode are reciprocal to the TM_{10} mode for similar crack orientations. To separate out the two modes of operation in practice, the length and width dimensions of the patch antenna must be different to create different resonant frequencies for each mode.

5 Sensor implementation

As demonstrated, a crack in the length or width direction has a substantially different effect on both modes of the patch – an increase in resonant frequency is seen in the parallel resonant mode, whereas a strong decrease in resonant frequency is seen

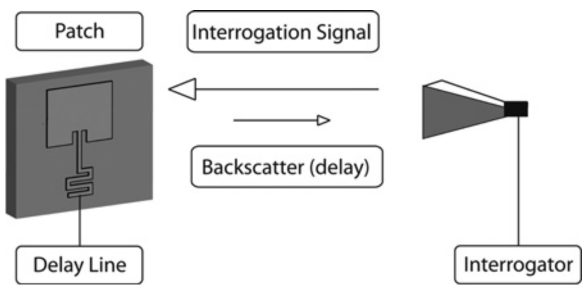

Fig. 7 *Implementation of crack sensor and CST simulation setup*

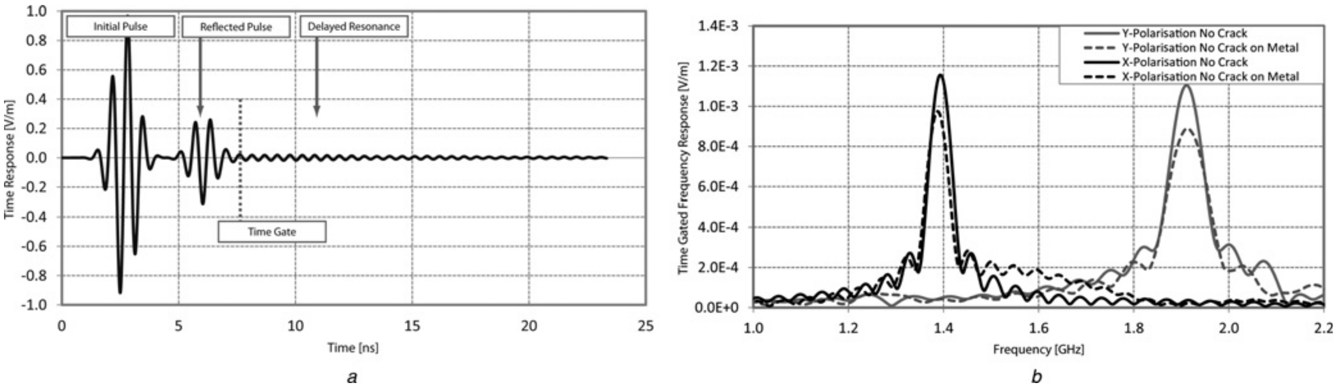

Fig. 8 *Results from interrogation*

a Time signal received at distance 0.5 m from the sensor
b Horizontal and vertical polarisation resonant frequencies extracted through time gating in MATLAB

in the mode perpendicular to the crack. This result can be exploited for remote interrogation of the patch structures as it mitigates environmental effects such as dielectric changes because of humidity or dirt films, which affect each mode equally.

To practically implement the wireless interrogation of these patch antennas, an interrogation method has been demonstrated in [7] where the patch sensors are illuminated by polarisations in the directions of the two orthogonal modes of the antenna. If the patch antennas are not terminated with a matched load, the energy will not be absorbed and will reradiate out. Since the antenna is a high-Q structure, the resonance will continue for a period of time after the illumination signal, and time gating at the source can capture this delayed backscattering. The captured backscatter is a combination of structure and antenna backscatter, and so to separate out the antenna from the structure, a delay line can be introduced between antenna and terminating impedance to delay the backscatter from the antenna. By the resonant frequencies of each mode (TM_{01} and TM_{10}) detected back at the interrogation system, crack orientation and magnitude can then be estimated. Interrogation distances of several meters are possible with this method.

To demonstrate the crack interrogation in CST, a delay line is added to the patch which is illuminated with a wideband Gaussian pulse in polarisations parallel and perpendicular to the TM_{01} mode from a distance of 1 m as shown in Fig. 7. The reflected signal is received with linearly polarised probes to separate out the vertical and horizontal modes.

Fig. 8*a* shows the time signal received back at the probe when the patch is illuminated with a vertically polarised wave. It can be seen that there is an initial reflection of the Gaussian pulse, and then a delayed resonance which is caused by the patch re-radiating the energy that is reflected from the open circuit delay line stub. To extract the resonance of the antenna, the initial reflection is gated out, and then the remaining resonant signal is padded and an inverse fast Fourier transform is performed in matlab. Fig. 8*b* shows the results for the patch illuminated with vertical and horizontal polarisations. As shown, the vertical mode of the patch is at 1.9 GHz which is expected from the previous return loss simulations, and the horizontal mode of this particular patch is at 1.4 GHz. The patches are interrogated free standing, and on a large metal backing to simulate being mounted on a bridge. In both cases, the resonant frequencies of both modes are nearly the same with a slightly lower-power level because of the time that gating is applied to remove initial reflections.

This method is then used to simulate the interrogation effects of cracks in the directions parallel and perpendicular to the two orthogonal operating modes of the patch. First a 30% patch length crack is created in the vertical direction and the patch is illuminated with vertical and horizontal polarisation waves. As shown in Fig. 9*a*. the vertical polarisation mode which is parallel to the crack direction

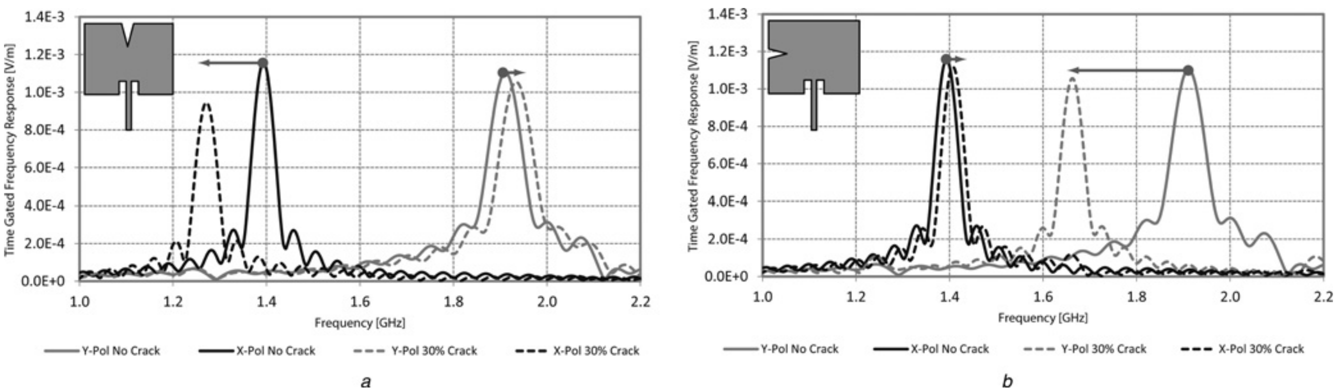

Fig. 9 *Interrogation of cracked patches with*

a Vertical 15° crack 30% of patch length
b Horizontal 15° crack 30% of patch width

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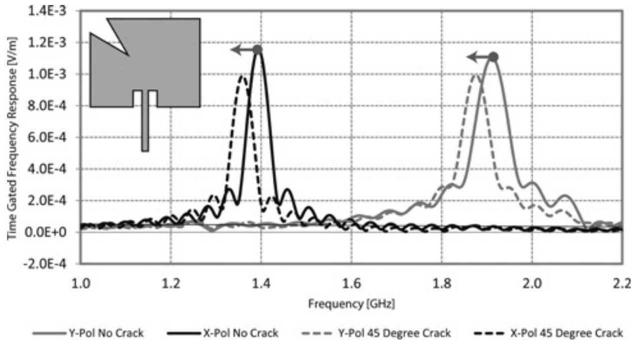

Fig. 10 *Interrogation of cracked patches with a crack along the diagonal*

experiences an increase in resonant frequency, whereas the horizontal mode experiences a decrease in resonant frequency. The frequency increase in the parallel direction is 1.5% which is similar to the S11 shift predicted in Fig. 4*d*. The frequency decrease in the perpendicular mode is 11% which is again very similar to the predicted shift in Fig. 6.

The crack is then interrogated in the horizontal direction at a length of 30% of the patch width. As shown in Fig. 9*b* a decrease in the vertical mode resonant frequency and an increase in the horizontal mode resonant frequency occurs, which is opposite to the effect of the vertical crack as expected. This allows for crack direction extraction through dual-mode measurement.

As a final test, a crack is created at a 45° angle through the diagonal of the antenna at a length of 30% of the diagonal. It can be seen in Fig. 10 that both the horizontal and vertical modes experience a down-shift in frequency as the crack creates a longer current path in both directions similar to the crack perpendicular to the propagating mode.

6 Conclusions

A paper-based inkjet-printed patch antenna for low-cost SHM has been demonstrated which is able to detect cracks parallel and perpendicular to the resonant modes of the antenna using an orthogonal polarisation interrogation method. Resonant frequency shifts because of different shapes and orientation cracks have been quantified with simulation and measurement results that are in close agreement. Crack propagation measurements over time can give insight into the length, shape and orientation of cracks because of characteristic resonant frequency shifts caused by different crack shapes and orientations as they progress through the patch antenna. The sensor can be interrogated passively requiring no power source and can be fabricated at affordable costs for large-scale implementation.

7 Acknowledgment

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8 References

1 Fong, C.H., Wiercigroch, M., Dears, W.F.: 'Novel dynamic fatigue testing device: design and measurements', *Meas. Sci. Technol.*, 2006, **17**, pp. 2218–2226
2 Mohammad, I., Huang, H.: 'Monitoring fatigue crack growth and opening using antenna sensors', *Smart Mater. Struct.*, 2010, **19**, pp. 1–8
3 Tata, U., Huang, H., Carter, R.L., Chiao, J.C.: 'Exploiting a patch antenna for strain measurements', *Meas. Sci. Technol.*, 2009, **20**, pp. 1–7
4 Mohammad, I., Gowda, V., Zhai, H., Huang, H.: 'Detecting crack orientation using patch antenna sensors', *Meas. Sci. Technol.*, 2012, **23**, pp. 1–9
5 Vyas, R., Lakafosis, V., Lee, H., *et al.*: 'Inkjet printed, self powered, wireless sensors for environmental, gas, and authentication-based sensing', *IEEE Sens. J.*, 2011, **11**, pp. 3139–3159
6 Cook, B.S., Shamim, A.: 'Inkjet printing of novel wideband and high gain antennas on low-cost paper substrate', *IEEE Trans. Antennas Propag.*, 2012, **60**, pp. 4148–4156
7 Deshmukh, S.: 'Passive RF sensors and wireless sensor interrogation'. Master's thesis, University of Texas at Arlington, 2010