Non-contact detection of impact damage in carbon fibre composites using a complementary split-ring resonator sensor

Zhen Li*,**, Tianqi Wang*, Arthur Haigh***, Zhaozong Meng****, Ping Wang*,**

In this paper, a new non-contact method for detection of impact damage in carbon fibre-reinforced polymer composites with a complementary split-ring resonator sensor is proposed. The resonance frequency is evaluated as an indicator of the presence of damage. The resonator is made on a printed circuit board, and in the experimental setup it is positioned close to the area of interest. Electromagnetic models are built, and from the resonant responses the appropriate frequency range used for the test is determined. The active sensing element in the resonator is found from the analysis of the magnetic field distribution. The parametric study performed shows that a larger frequency change occurs for a wider impacted region, which is of great use for practical applications. The proposed method is validated by the experimental results, where a frequency shift of 65 MHz was observed for a 0.36 mm deep dent.

**Key words:** carbon fibre composites, impact damage, non-destructive detection, microwave sensor, complementary split-ring resonator, electromagnetic simulation

1 Introduction

Carbon fibre-reinforced polymer (CFRP) composites have been increasingly used in aerospace, automotive and marine structures year on year, owing to their superior stiffness and strength characteristics, good fatigue and corrosion resistance [1]. However, in the field carbon fibre composites remain vulnerable to impact, caused by objects and events such as hail stones, runway debris, collision with ground equipment, tool drops and bird strikes. The types of damage induced by impact include surface dents, delamination, matrix cracks and fibre breakage. And in many occasions, these happen internally and are hardly observed by visual inspection. Various non-destructive testing (NDT) techniques can be applied for damage detection, such as ultrasonic testing, acoustic emission, thermography, shearography, vibration testing, optical fibre sensing, guided waves (e.g. Lamb waves [2]) and digital image correlation (DIC). It is noted that each method has its advantages, disadvantages and fields of application [3, 4]. For example, in ultrasonics couplants are required, and the acoustic emission sensors shall be placed near the damage region. For thermography, the possibility of unwanted thermal damage caused during the inspection should be considered. In the setups of shearography and vibration testing techniques, mechanical loads need to be applied to the structure. In the optical fibre sensing systems, the possibility of failures in the wiring network, manufacturing and installation costs are some of the factors that should be paid attention to. Piezoelectric transducers used in the guided wave-based techniques should be attached on the surface of the structure under test. And before the DIC measurement, the sample surface should be speckled with black and white paints, which is not practical for large structures.

An alternative detection method is the microwave-based techniques. Microwaves can propagate in air and dielectric materials with low attenuation. There are a number of attributes when applying microwave testing, such as non-contact, no need for couplants or transducers bonded on the surface, operator friendly, relatively inexpensive and one-sided scanning [5–8]. Safety precautions are usually not necessary, as the signal power used is relatively low (few mW). In recognition of the growing interest in this technique, in 2014 the Microwave Testing Committee was established by the American Society for Non-destructive Testing (ASNT), and microwave testing was recognised as its own NDT method in the 2016 edition of the ASNT standards.

The existing microwave testing methods for CFRP composites can be categorised into five groups: self-sensing methods, near-field induction methods, near-field resonance methods, far-field methods and combination with other NDT methods [9]. Among these methods, the near-field resonance approach using a complementary split-ring resonator (CSRR) has attracted much attention in recent years, due to the distinct advantages of compact size, low cost, design simplicity, high sensitivity, etc.
The planar structure can be made on the ground plane of a microstrip line, which produces electric fields perpendicular to the resonator and consequently provides signal excitation. A schematic diagram of the scanning process is illustrated in Fig. 2, where the sensor is placed close to the sample so that any variation of the material properties and surface profile can affect the fringe fields. It is indicated that the CSRR sensing is a kind of near-field detection technique. When the sensor moves to an impacted region, the shape of the resonant fields is perturbed, resulting in a change in the resonance frequency. The resonance frequency shift can then be used as a damage indicator. Using the perturbation theory, the resonant frequency change can be estimated, assuming the perturbation is small, and the electromagnetic distribution remains the same [18]

\[
\frac{f - f_0}{f_0} \approx \frac{\int_{V_1} \Delta V (\mu |H_0|^2 - \varepsilon |E_0|^2) \, dv}{\int_{V_0} \frac{\varepsilon |E_0|^2 + \mu |H_0|^2}{\varepsilon_{\varepsilon r}^2}}
\]

where \( f \) is the resonant frequency after perturbation, \( \mu \) and \( \varepsilon \) are the magnetic permeability and electric permittivity, respectively, and \( [E_0] \) and \( [H_0] \) are the original electric and magnetic fields, respectively. Here, \( V_0 \) is the original volume of the resonant region around CSRR, and \( \Delta V \) is the volume changed. It is indicated that the resonance frequency may either increase or decrease, depending on the location of the perturbation and whether the original volume is enlarged or reduced.

3 Design of a CSRR sensor

Here in the design, the CSRR is made on a printed circuit board (PCB), and the PCB fabrication technique is adopted. The substrate of the PCB used is FR4, the dielectric constant \( \varepsilon_r \) and dielectric loss tangent of which are 4.8 and 0.017, respectively. The thickness of the substrate \( t \) is approximately 1.5 mm, and the thickness of the copper coating is 35 \( \mu \)m. For impedance matching, the width of the signal line \( w \) is designed to achieve the same characteristic impedance \( 50 \Omega \) as that of the SMA (Sub Miniature Version A) connector (for signal input and output). The characteristic impedance of the microstrip line \( Z \) can be calculated as [19]

\[
Z = \begin{cases} 
\frac{60}{\varepsilon_{\varepsilon r}} \ln \left( \frac{\pi \varepsilon_{\varepsilon r}}{w} + \frac{w}{\pi} \right) & \text{for } w/t \leq 1, \\
\sqrt{\varepsilon_{\varepsilon r}(w/t+1.398+0.667 \ln(w/t+1.444))} & \text{for } w/t \geq 1 
\end{cases}
\]

where \( \varepsilon_{\varepsilon r} \) is the effective dielectric constant, which is a function of \( \varepsilon_r \), \( t \) and \( w \).

\[
\varepsilon_{\varepsilon r} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \sqrt{1 + 12w/t^2}. 
\]
Fig. 3. Photographs of the CSRR sensor designed: (a) – upper side, (b) – lower side

Fig. 4. Electromagnetic simulation model for the CSRR sensor designed

Hence, the width \( w \) is set to 2.8 mm. The values of the parameters related to the CSRR structure (Fig. 1) are listed in Tab. 1. The photographs of the CSRR sensor developed are presented in Fig. 3. On both sides there are thin green solder masks made of polymer for protection against oxidation.

4 Electromagnetic simulation

The performance of the CSRR sensor is evaluated using electromagnetic simulation software CST Microwave Studio. The model built is shown in Fig. 4. The strip line is 30 mm long, and the width of the PCB is 8.4 mm. The frequency domain solver is employed here for this electrically small structure. Based on the exponential fitting function given in [16], the resonance frequency of the resonator designed can be around 3.7 GHz, so a frequency range from 2 GHz to 4 GHz is used in the modelling.

The resonant response with air surrounding is presented in Fig. 5, which shows that the resonance frequency is around 2.5634 GHz and the minimum attenuation reaches −54.78 dB. Hence, in the simulation cases followed, a frequency range of 2–3 GHz is adopted for better description and quicker computation. The difference between the resonance frequency given by the estimation and simulation is primarily due to the fact that the empirical expression in [16] is only suited to the Rogers RO4350 substrate, while it can still be used as an initial guess for the frequency range setting in the simulation.

![Resonant magnetic field distribution around the sensor over a dent modelled](image)

Fig. 6. Resonant magnetic field distribution around the sensor over a dent modelled

Then, a composite plate is incorporated in the model. The distance between the sample and the sensor (ie standoff distance) is set to 0.1 mm. The composite is assumed homogeneous, and permittivity of 46–j15 [20] is adopted over the frequency range investigated. In addition, a half-sphere dent with a radius of 0.5 mm is created in the top surface of the sample to simulate impact damage. In the present case the resonance frequency is shifted downwards to 2.2532 GHz, which is mainly due to the increased capacitance around the resonator. The resonant magnetic field in the cross-sectional plane perpendicular to the feed line at the centre is shown in Fig. 6, where the maximum magnitudes exist at the short traces (black circled) connecting the inner conductor to the outer ground plane. Hence, it is suggested that optimal sensitivity can be achieved when the impacted region is placed under the narrow traces.

Parametric study is conducted to assess the effect of the damage size on the resonance frequency. As seen in Tab. 2, the resonance frequency is increased with increasing dent size. This trend is what can be expected according to the prediction by (2). It is also indicated

| Diameter of the inner conductor (\( d_{in} \) mm) | Diameter of the whole resonator (\( d_{out} \) mm) | Spacing between the trace and inner conductor (\( s_1 \) mm) | Trace width (\( s_2 \) mm) |
|-----------------------------------------------|-----------------------------------------------|--------------------------------------------------|-----------------|
| 4.8                                          | 6.0                                          | 0.2                                              | 0.2              |
Table 2. Comparison of the resonance frequency for different sizes of the dent simulated

| Radius of the dent (r_d, mm) | 0.4 | 0.5 | 1.0 | 1.5 | 2.0 |
|-----------------------------|-----|-----|-----|-----|-----|
| Resonance frequency (f, MHz) | 2245.0 | 2253.2 | 2258.6 | 2266.6 | 2296.4 |

Fig. 7. A composite sample with barely visible impact damage under test: (a) – photograph, (b) – 3D view of the impact image by chromatic confocal optical microscopy

![Image](image1)

Table 3. Changes in the resonance frequency and Q factor due to the impact damage

|                | Intact region | Impacted region |
|----------------|---------------|-----------------|
| f_R (MHz)      | 2230.0        | 2295.0          |
| Q factor       | 31.86         | 28.69           |

6 Concluding remarks

A novel approach for detection of impact damage in CFRP composites using a complementary split-ring resonator sensor has been demonstrated. During inspection, the resonator, the conductive composite material and the air space in between comprise a resonant region. When a dent produced by impact damage is in the near field of the sensor, the damage induces shape perturbation, resulting in resonance frequency change.

The design of a CSRR sensor developed has been described in detail. And electromagnetic simulation has been conducted, where a more accurate approximation of

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the resonant frequency is obtained, and the most sensitive sensing element is found. In addition, parametric study has been carried out to evaluate the effect of the damage size on the variation of the resonant frequency. It has been demonstrated that the larger the damage, the more variations it will cause, which is advantageous for practical applications. Detection of a barely visible impact damage in a composite plate was performed. An increase of 65 MHz in the resonance frequency and a decrease in the Q factor have been revealed. The proposed sensor can be extended to inspection of three-dimensional surfaces, where a flexible PCB substrate can be chosen.

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Zhen Li (Assoc Prof, PhD) received the BEng. degree from Nanjing University of Aeronautics and Astronautics (NUAA) and MEng. degree from Shanghai Jiao Tong University (SJTU), China, in 2010 and 2013, respectively, and the PhD degree from The University of Manchester, UK, in 2017. He is currently an Associate Professor with College of Automation Engineering, NUAA. He has authored and co-authored over 20 technical peer-reviewed papers in international journals and conference proceedings. His research interests include non-destructive testing of fibre-reinforced polymer composite materials and microwave testing.

Arthur Haigh (PhD) was born in Scarborough, North Yorkshire, United Kingdom (UK). He received the PhD degree from Manchester Metropolitan University, UK, in 1994. He is currently a Visiting Research Fellow with Department of Electrical and Electronic Engineering, The University of Manchester, UK. His industrial career was principally with Ferranti Ltd (UK). For the last nine years of his industrial career, he was with the Microelectronics Centre, responsible for the introduction of direct step-on-wafer lithography machines. As the Special Projects Manager, he managed the technical side of an ESPRIT II proposal involving 14 other European companies and a total budget of 30 million pounds. He left the industry in 1988, and for three years, he taught physics at Manchester Metropolitan University.