Detection and evaluation of damage in aircraft composites using electromagnetically coupled inductors

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Abstract

The paper presents a quantitative damage evaluation of carbon-fibre reinforced polymer (CFRP) plates using a non-contact electromagnetic (EM) sensor. The EM sensor with coupled spiral inductors (CSI) is employed here to detect both impact induced and simulated damage leading to an accurate evaluation of the location, depth and width of sub-surface defects. The effect of inspection frequency, standoff distance and signal power are also investigated leading to the development of an engineering circuit design tool that relates the set up and calibration of the sensor to its detection performance. It is found that the dynamic range of the transmission coefficient is the limiting factor in the original Salski CSI sensor and this problem is addressed by adding ferrite layers to reduce the reluctance of the magnetic circuit, improving damage sensing by 22%. The study leads to a further development of utilising an open ferrite yoke with a pair of encircling coils, which shows a 57 % sensitivity improvement and clearer identification of air gaps (voids) and delamination in CFRP laminates. The proposed EM yoke design CSI sensor is low cost and could be assembled into an array for non-contact, in situ mechatronic scanning of aircraft composite wings.

Keywords: carbon-fibre reinforced polymer (CFRP); non-destructive testing (NDT); coupled spiral inductors; damage evaluation; analytical modelling

1. Introduction

The proportion of fibre composite materials being used in aerospace, industrial, automotive and marine structures is increasing year on year. Continuously reinforced thermosets are currently the most popular composite systems, since they are offering better fatigue and corrosion resistance, higher specific stiffness and strength when compared to conventional metallic materials. They can be found in new aircraft such as the Boeing 787 Dreamliner and Airbus A350 XWB (extra wide body) [1], which are now at various stages in the design/manufacture/certification/delivery cycle. One of the most difficult problems to be overcome during the certification process of such aircraft by the civil aviation authorities for safe commercial use is to guarantee their structural integrity over the 30 years life of the aircraft [2]. This is technologically challenging for large integral composite structures, with wing spans of more than 25 m, fuselage barrel lengths of 50 m and diameter 5 m . Although carbon fibre-epoxy composites are used more extensively in civil aircraft structures [2], they remain vulnerable to impact damage (e.g., bird strike, hail, tyre rubber and metal fragments), due to their relatively thin composite skins and brittle behaviour. Continuous degradation can, in turn, affect structural performance over time, such that structural integrity is a major problem for the industry as it seeks a viable strategy for design and certification of large composite aircraft structures subjected to impact damage. Some types of fabrication defects and in-service damage cannot be identified or evaluated by a visual observation. Hence, various non-destructive testing (NDT) techniques have been employed to identify defects and damage in carbon-fibre reinforced polymer (CFRP) composites [3], for example, ultrasonic testing [4], eddy current technique (ECT) [5], thermography, X-ray tomography, optical fibre sensors, digital image correlation (DIC) [6], Lamb waves [7] and microwave techniques [8,9]. While, every NDT method has its own particular advantages, disadvantages and applications, some aspects (i.e., types of damage to be monitored, detection reliability, cost, portability, equipment setup, scanning time, safety concerns and measurement sensitivity) have to be selected and well understood by the user.

Among the existing NDT techniques, a group of electromagnetic (EM) techniques are receiving increasing attention in recent years [10,11], including eddy current, pulsed eddy current and microwave techniques. There are a number of attributes when applying the EM NDT, such as non-contact, one-sided scanning, no need for transducers or couplants, little safety hazard [12]. For this kind of electromagnetic non-destructive testing, special attention should be paid to the penetration depth of the signal into the sample, which is inversely proportional to the square root of the operating frequency and the conductivity of the sample [12].

Recently, Salski et al. [13–15] proposed a new type of electromagnetic sensor for CFRP composites. The designed sensor with coupled spiral inductors (CSI) exhibits several advantages, such as low power (~1 mW), low cost (less than £10), operator friendly and conformability. It operates at the radio frequencies where the penetration depth is comparable with the thickness of the composite [13]. The capability of detecting an air hole and cracks intentionally produced in a four-layer CFRP composite plate was reported.

In this paper, the Salski CSI sensor [13] has been reproduced with design improvements on impedance matching and configuration. It is used to detect six subsurface grooves that simulate manufacturing defects (seen as air gaps, voids) and delaminations in CFRP composites. A thorough discussion on the quantitative description of the damage, location, size and interaction is presented. Subsequently, some parametric studies investigating the effects of inspection frequency, standoff distance and signal power are conducted. Based on the parametric study, the proposed equivalent circuit model provides an engineering design tool that relates the CSI geometry (e.g. number of inductor turns) and setup (e.g. frequency and standoff distance) to detection performance. Further, the application is extended to the detection of the barely visible impact damage (BVID) on a CFRP composite plate. The magnetic reluctance of the CSI sensor is reduced by adding ferrite layers that improve its sensing by 22%. Finally, a refined design with a ferrite yoke and a pair of encircling coils improves the detection by 57%. The effective detection of a delamination layer is then demonstrated.

2 The CSI sensor

2.1 Mechanism of the sensor

Two coupled planar spiral inductors are fabricated on the underside of a printed circuit board (PCB). As presented in Fig.1, using vias (electrical connections), each inductor is connected to a coplanar transmission line on the top side to make a two port sensing device. In the present work, Salski's design is optimised to ensure impedance matching by setting the characteristic impedance of the coplanar transmission line to that of two SMA (SubMiniature version A) connectors (standard 50 Ω) [16] , which are used for Radio Frequency (RF) signal input and output. The final dimensions of the sensor are 38.40 mm long by 7.80 mm wide, with the inner coil diameter of 2.00 mm, width of the track on top side as 1.00 mm, spacing between the tracks, two coils and each turn as 0.20 mm, and 5 turns for each spiral inductor. The thicknesses of the substrate and the copper coatings on both sides are 1.50 mm and 35 μm. The distance between the via and the centre of the SMA connector is 11.30 mm.

The principle of the detection is based on the measurement of the scattering transmission coefficient (S_{21}) that is described in section 4 for the CSI sensor and is considered as one of the basic S-parameters in microwave engineering [17]; the reflection coefficient is symbolised by S_{11}. The transmission coefficient is defined as the relative power transmitted from the primary spiral to the secondary spiral. S_{21} is selected rather than other S-parameters because a higher signal-to-noise ratio (SNR) can be provided. When a conductive material is placed in the vicinity of the CSI sensor, the reference S_{21} is obtained. A defect (dent, crack and delamination) in the material under test disturbs the coupling and perturbs S_{21} to enable detection and evaluation.

2.2 Experimental setup

The EM sensor is mounted on an XYZ scanning stage and connected by two coaxial cables to HP8753B vector network analyser (VNA) used for the S_{21} measurement. As schematically illustrated in Fig.2, the personal computer (PC) is connected to the controller of the stepper motors with the positioning accuracy of minimum 1 μm. The logic control for the stepper motors is managed by the PIC18C452 Microchip® microcontroller. All the movements are controlled by the PC using VEE software® for precise and reproducible movements. In addition, the analyser is connected to the PC by the IEEE-488 connection for data acquisition.

3 Damage detection and evaluation using the CSI sensor

3.1 Non-contact detection of the intentionally produced grooves

Subsurface grooves are machined on a 2D woven CFRP strip. The cross section of the composite strip is illustrated in Fig.3, where six groves were machined on the bottom side. The ability of detecting the presence of the underneath defects is examined. The thickness of the strip is 2.58 mm, while the depths of the grooves from the left to right are 1.18 mm, 1.66 mm, 0.80 mm, 1.28 mm, 1.76 mm and 1.12 mm, respectively; the six grooves are separated by 21.00 mm.

A non-contact line scanning is conducted across the CFRP strip with the step size of 127 μm. The standoff distance between the sensor and the surface is kept constant at 250 μm. Total scanning distance is 139.20 mm. During the scanning, the output power of the signal is set to be 0.0 dBm (i.e. 1 mW). The performance of the sensor at 10 MHz is examined. The optimal frequency for inspection is investigated in section 3.4.1. By comparing the difference of the magnitude of the transmission coefficient (i.e. $|S_{21}|$) between the origin and the present position, the sensitivity $\Delta|S_{21}|$ at the selected frequency with respect to the scanning distance is shown in the left top of Fig.4. Six peaks of variable magnitudes indicating six grooves are accurately identified.

It is also shown that the variation of $|S_{21}|$ only happens when the coupling region (i.e. the space under the inductor) interacts with the groove, i.e. between two critical positions where the coupling region starts to move across and leaves the boundaries of the groove. For example, for the first groove, the size of the affected region is the sum of the narrow dimension of the coupling region (6.00 mm) shown in Fig.1 (b) and the width of the groove (4.00 mm). The interaction can be further decomposed, considering the relative distance between the centre and the groove. As shown in Fig.4 (b), the variations of the sensitivity between four critical positions (Position A, B, C and D) are analysed. Position A is in the centre of the sensor, where the coupling region starts to scan across the left boundary of the groove. In the measurement process, the data is stored at the central point of the coupling region.

In the sensitivity graph, the curve continues to rise until the coupling centre arrives at the left boundary of the groove (Position B), as the influence of the defect on the coupling becomes gradually prominent over this period. Afterwards, during the time when the coupling centre is still above the groove, the sensitivity value stabilises until the centre reaches Position C, where the centre comes to the right boundary of the groove. For symmetry reasons, the $\Delta|S_{21}|$ sensitivity drops as the centre moves away from the groove. At position D, the sensitivity declines to zero.

In summary, when the sensor scans across each groove, the sensitivity curve experiences three stages, i.e. increasing (denoted as Stage I) between Position A and Position B, temporarily stable (denoted as Stage II) between Position B and Position C, and decreasing (denoted as Stage III) between Position C and Position D. If the width of the coupling region is denoted as ℓ and that of the groove is described as w, then the widths of three stages are $\ell/2$, w and $\ell/2$, respectively. In addition, the middle part of Stage II coincides with that of the groove. It is seen that Stage II is more distinct than the other two stages. Therefore, for the subsurface defect that the width is larger or comparable to that of the coupling region, this platform characteristic of Stage II is considerably beneficial for the evaluation of the groove width.

3.2 Relationship between the magnitude of the signal and the subsurface depth

The highest peak exists at the location of the third groove counted from left to right, where the groove is the shallowest. While, the peak corresponding to the fifth groove is the lowest as expected. As listed in Table 1, there is a close relationship between the subsurface depth (h) and the average magnitude of the signal in Stage II (H). And in Fig.5 a linear line is offered by using regression analysis. The correlation coefficient R^2 =0.97 is given, which shows the high reliability of the approximation over the subsurface depth range investigated in the test.

3.3 Discussion on the spatial resolution

Spatial resolution of an imaging system is regarded as its capability to separate two closely spaced defects. In the present case, if two grooves are closely located, Stage I of one defect and Stage III of the adjacent defect would overlap. Attention should be paid to the fact that the amplitude of Stage II is dependent on the subsurface depth of the defect. Hence, the defects located at the same depth could not be separated from the sensitivity curve if the distance between the adjacent grooves is larger than the width of Stage III, which is $\ell/2$ (3.00 mm). However, two defects located at different depths can still be distinguished even though the separation is smaller than $\ell/2$, as long as the variation of the subsurface depth are detectable by the analyser.

3.4 Parametric study

3.4.1 Effect of the inspection frequency

Following Salski [13], the sensitivity of S_{21} in the range 0-100 MHz is examined. The six-groove CFRP strip was then scanned at 5,10 ,15 and 20 MHz, respectively. As Fig.6 (a) shows, the frequency response of Groove 1 where the highest sensitivity value is observed around 10 MHz. However, the second and fifth peaks become insignificant when the frequency is above 15 MHz, although other grooves are still detectable. The disappearance of the peaks can be explained by less penetration and the sensitivity response provided by the sensor as well. It should be noted that the selection of the inspection frequency should be determined case by case, as the penetration depth is highly depedent on the inspection frequency, which is be further explained in section 4.

3.4.2 Effect of the standoff distance

A parametric study in the absence of machined grooves is performed to evaluate $|S_{21}|$ as a function of the standoff distance. The change in the standoff distance is done by the stepper motor in the X-Y-Z stage, which is accurately controlled by programming. The results of the parametric study are shown in Fig.7, where the standoff distance is increased from 0 to 5 mm for three frequencies (10 MHz, 20 MHz and 50 MHz). Figure 7 illustrates that the magnitude of the transmission coefficient (i.e. $|S_{21}|$) increases with the standoff distance and this asymptotes to the free space condition, where the sensor's sensitivity $\Delta|S_{21}|$ is dramatically reduced.

3.4.3 Effect of the signal power

In this section, the influence of different power levels is also investigated with the fixed standoff distance of 100 μm, as the power consumption is also a critical factor for practical application in the field. It is found that the increase of the signal power induces small variations of $|S_{21}|$ (within 0.06 dB). It is suggested that the signal chosen at a lower power level is a beneficial factor for practical purposes (in this study 1 mW).

3.5 Detection of impact damage

Here the sensor is applied to detect the real impact damage on a 4 mm thick carbon fibre-epoxy +45/-45/0/90 quasi-isotropic plate. The BVID on the top surface was created by a drop-weight impact of 20 J energy. The diameter and depth of the dent observed by an optical microscope are approximately 3.85 mm and 44.3 μm, respectively. This dent could not be easily found during general visual inspection using typical lighting conditions.

A 2D raster scanning is performed at a standoff distance of 100 μm with a step size of 381 μm in both in-plane directions. A 2D image of the magnitude of S_{21} at frequency of 300 MHz is shown in Fig. 8. The median filtering and mean filtering are applied in the image post-processing for noise reduction and edge enhancement. The white area showing higher magnitudes (less negative $|S_{21}|$ dB) evidently indicates the presence, location and extent of the dent. Further work will be required to identify other resin microcracks and delamination depth or separate multiple delaminations that may occur during the impact event.

4 Equivalent circuit modelling

4.1 The circuit modelling

The purpose of this section is to derive an engineering design tool that can be used to estimate the S_{21} sensitivity of the sensor as a function of its geometry (e.g. number to turns of the coil), frequency and standoff distance. The geometry of the defect and electrical conductivity of the sample are also important. In the ECT, where the frequency is lower than 10 MHz [18] and in the microwave engineering field [17], the equivalent lumped circuit model is a well-established approach for circuit modelling. Here, the equivalent lumped circuit model shown in Fig.9 is also introduced.

According to the Kirchhoff's voltage law, the magnitude of the transmission coefficient $|S_{21}|$ for the present experimental setup can be derived:

$$|S_{21}| = \frac{MR_0}{\sqrt{[\frac{R_1(R_0+R_2)}{\omega} + (M^2 - L_1L_2)\omega]^2 + (R_1L_1 + R_0L_1 + R_2L_1)^2}} \quad (1)$$

Where $\omega = 2\pi f$ is the angular frequency while f is the operating frequency; R_1 and L_1 are the resistance and inductance of the feed coil, respectively; R_2 and L_2 are the resistance and inductance of the detector coil, respectively; R_0 is the matched load ($50\ \Omega$) at Port 2; M is the mutual inductance. Without losing generality, the value of M is set to be $M=kL_1$, where k is the coupling coefficient.

For the present sensor, the electromagnetic coupling involves the self-coupling between two inductors without the presence of the composite sample and the external coupling between the inductors and the conductive sample. For simplicity, these two kinds of coupling are considered as a whole. Hence, the presence of the conductive sample induces the variation of the mutual inductance. The coefficient k is linked to the standoff distance and conductivity distribution within the penetration depth as well. It is assumed that the resistance R and inductance L of the planar coils do not depend on the standoff distance when the coupling factor k changes [18].

4.2 Empirical expression for the coupling coefficient

From the detection results of the subsurface grooves, it has been shown that the sensitivity decreases as the depth from the sample's surface increases. An exponential trend showing the variation of $|S_{21}|$ with respect to the standoff distance is presented in Fig.7. It was demonstrated by Salski et al [13] that the sensor was also sensitive to the electrical conductivity of the panel. Therefore, standoff distance (s), subsurface depth (h) and conductivity (σ) of the sample are taken into account, as shown in Fig.10.

The exponential decay function is introduced here as this kind of function is fit to the description of the coupling coefficient as mentioned above, which is written as:

$$k = k_{\mathrm{air}}[(1-\alpha)\beta(\gamma-1)+1] \tag{2}$$

Where

$$\left.\begin{aligned} \alpha &= e^{-C_1 \frac{h}{h_{max}}} = e^{-C_1 h\sqrt{\pi f \mu\sigma}} \\ \beta &= e^{-C_2 s} \\ \gamma &= e^{-C_3 \sigma} \end{aligned}\right\} \quad (3)$$

α , β and γ are the coefficients considering the effects of h, s and σ . C_1, C_2 and C_3 are three exponential decay constants. The computation of these three constants will be demonstrated in the next section. The variable, h_{max}, is the maximum penetration depth of the electromagnetic waves into conductive materials, which is defined as [17]:

$$h_{max} = \sqrt{\frac{2}{\omega\mu\sigma}} = \frac{1}{\sqrt{\pi f \mu\sigma}} \quad (4)$$

Where μ is the magnetic permeability of the material. Here, μ of the carbon fibre composite material is equal to that of the free space μ_0 (i.e. $4\pi\times10^{-7}\,\mathrm{H}\cdot\mathrm{m}^{-1}$), as the CFRP is nonmagnetic.

4.3 Constant setting

a) Setting for the equivalent circuit model

In the present case, due to symmetry, the resistance and inductance of the feed coil are equal to those of the detector coil, i.e., R_1=R_2, and L_1=L_2, respectively. By substituting the parameter values of the inductors into the expressions for planar spiral inductances [19], the inductance is obtained, that is, L_1=L_2=122.81 nH. The experimental results presented in the section of the parametric study are utilised to compute two unknown parameters, i.e. R and k. By the brute-force algorithm [20], the combination of $R = 31.75\ \Omega$ and k=0.24 is found to give the best fit to the experimental results. Furthermore, k=0.31 is found to be capable of simulating the case where the sensor is placed in the air surrounding. As illustrated in Fig.11, the results given by the equivalent circuit modelling agree well with the experimental data.

b) Setting for the empirical expression of k

The values of three exponential decay constants, C_1=3.80, C_2=0.80, and C_3=0.13, are determined based on the experimental results. For the contact case with no damage underneath, the factor α considering the effect of the depth is neglected and s=0. Hence, Eq. (3) becomes

$$k_{\text{contact}} = \gamma k_{\text{air}} = e^{-C_3\sigma} k_{\text{air}} \quad (5)$$

So, the constant C_3 can be computed by substituting the conductivity of the panel, and the coupling constants k_{air} and $k_{contact}$.

$$C_3 = -\frac{\ln(k_{\text{contact}}/k_{\text{air}})}{\sigma} \quad (6)$$

For the calculation of C_3, the measurement of the electrical conductivity of the sample is required. It is known that the electrical conductivity of the CFRP is anisotropic [21,22]. In the external coupling, the induced currents mainly flow along the carbon fibres. The average bulk conductivity for calculation is measured, which is 2289 S/m.

4.4 Prediction of the maximal detection depth

In this section, the proposed model is applied for the prediction of the maximum detection depth at a fixed standoff distance, which is hardly obtained from Eq. (4). As shown in Fig.12, the sensitivity values at different subsurface depths are obtained by modelling, and a linear line is also obtained using the regression analysis. The maximum detection depth predicted by the modelling agrees well with that by the experiment, which demonstrates the accuracy of the proposed empirical expression for the coupling coefficient.

5 Further sensor development for sensitivity improvement

5.1 Attachment of the ferrite sheet

The configuration of the well-established PCB transformer [23,24] is similar to the CSI sensor. For the PCB transformer, two planar coils are fabricated separately on the top and bottom sides of the PCB. The ferrite sheet is attached on the coils for shielding. Different from the PCB transformer, here the ferrite sheet is only placed on the top side in order to reduce the reluctance of the magnetic circuit, thereby concentrating the magnetic field underneath. A sticky ferrite patch (IRJ04®) of dimension 20.00 mm ×7.00 mm ×0.25 mm and μ_r =40 was applied on the upper side.

A line scanning is conducted to detect the first groove underneath the CFRP strip shown in Fig.3. The standoff distance of 300 μm and the step size of 127 μm are adopted. The effect of the number of the ferrite layers is also studied. As presented in Fig.13, compared with the original CSI, the sensitivity provided by the added ferrite is improved. It is shown that the measurement results obtained from the sensor with three ferrite layers could provide better sensitivity improvement than other two ferrite cases. As the noise level is within 0.1 dB, the results show that the SNR value in the case with the introduced ferrite is increased by approximately 22% compared with that obtained by the original Salski CSI configuration.

5.2 The yoke sensor

5.2.1 Methodology

In the previous section, it is shown that the ferrite layers improved the sensitivity of the CSI sensor. A ferrite yoke arrangement schematically shown in Fig. 14 was constructed and applied. The yoke sensor consists of two coils and ferrite cores (two cylinders and one rectangular prism). Each coil is made up of 30 turns and one layer of the shellac coated copper wire with a diameter of 220 μm. The inductance of the coil with the presence of the ferrite core is 3.54 mH.

The whole sensor is mounted on the same substrate as the CSI sensor. The epoxy adhesive is used to glue each component together, such as the interfaces between the cylindrical ferrite cores and the flat ferrite sheet, the interface between the ferrite sheet and the surface of the substrate. Then the leads from the two coils are soldered to two SMA connectors.

5.2.2 Sensitivity comparison

a) Detection of subsurface grooves

For comparison, the yoke sensor is used to scan across the composite strip containing the six machined grooves. The CSI sensor with three ferrite layers is also employed. The performances of the sensors at the same frequency f=10 MHz are studied. As presented in Fig.15, the six grooves can be accurately picked up by three sensors. Specifically, the curves for two CSI cases (with and without ferrite patch) are similar, while the yoke sensor provides the highest sensitivity.

The relationship between the subsurface depth and the average magnitude of Stage II in three cases are shown in Fig.16. The regression analysis is also performed for sensitivity analysis. It should be noted that the measurement point using the Yoke sensor at the subsurface depth of 1.12 mm is an abnormal point for the regression analysis, which is ignored in the calculation. The linear relationship can also be found in the yoke sensor. It is demonstrated that the yoke sensor is more sensitive to shallower defects. For example, for the third groove with the subsurface depth of 0.80 mm, the sensitivity provided by the Salski CSI sensor is 1.27 dB, while that obtained by the yoke sensor is 2.00 dB, which shows the signal-to-noise ratio (SNR) is improved by around 57%.

b) Detection of simulated delamination

When composites are loaded in bending or under lateral impact, delamination (separation of neighbouring layers) can occur and this can be difficult to detect since it happens internally. Here the delamination set-up is arranged to demonstrate the potential detection using the newly developed sensor. Delamination is simulated by partially filling the machined grooves with small fillers of the same width 4.00 mm, creating an air gap (simulated delamination), as shown in Fig. 17.

The size of the air gap in the 2.58 mm thick CFRP sample is 0.82 mm and 0.34 mm, respectively. The line scanning is conducted across each groove at the standoff distance of 250 μm. Fig.18 shows the comparison of the sensitivity curve provided by the CSI sensor and the yoke sensor at the same inspection frequency 8 MHz. In both cases, the sensitivity of the yoke sensor is larger than that of the standard CSI sensor, which demonstrates a useful advantage in practice, especially when impact induced delaminations introduce a much smaller ply separation (air gap).

In Figure 19 some preliminary results are presented for a 2D plain weave carbon fibre-epoxy laminate loaded in three-point bending. A long noticeable delamination can be seen in Fig. 19 (a). A line scanning is conducted with a standoff distance of 250 μm and step size of 127 μm. As shown in Fig.19 (b), the performance of the sensor at 5 MHz is tested and the crack is clearly identified. The trend of the curve agrees with the three-stage analysis by the previous study. The measured length of the crack at the edge of the sample is 4.98 mm, compared to 4.70 mm obtained by the MATLAB code developed for the sensor data extraction, giving confidence to the proposed electromagnetic based non-contact sensing system.

6 Concluding remarks

In this work, the electromagnetic CSI sensor has been successfully employed for damage detection and evaluation in CFRP composites. From the detection of subsurface grooves, it has been found that the width, location and depth of the groove can be easily obtained from the 3-stage analysis of the sensitivity curve. A linear relationship between the average magnitude of the second stage and the subsurface depths of the grooves has been revealed. In addition, the sensor has been employed to the detection of the real impact and three-point bending induced damage on a CFRP composite plate. The generated images strongly suggested the presence, location and extent of the induced damage. The parametric study that has been conducted to investigate the effects of the inspection frequency, stand-off distance and signal power on the performance. It has been revealed that the sensitivity declines as the separation of the sensor and the top surface increases; the sensor’s performance is independent of the signal power.

An equivalent lumped circuit model for the EM sensor has been proposed considering the effects of the stand-off distance, the subsurface depth and the conductivity. A good agreement with the experimental measurements is observed, which suggests that the analytical model could provide a practical tool for performance prediction and optimal design.

Two scenarios for the sensitivity improvement using ferrite material are provided. First, the ferrite sheet is attached on the top side of the CSI sensor for the concentration of the magnetic field. The results show that the introduction of the ferrite sheet contributes to the improvement of the performance. Second, a yoke sensor with ferrite and encircling coils is designed. It has been shown that the SNR parameter provided by the latter sensor is improved by 57%, which is considered as significant in the effort to identify impact induced damage in multi-layered composite plates. Further work is required to investigate the ability of the proposed sensor in identifying multiple, overlapping delaminations; these results will be reported in the near future publications.

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Figure captions

Fig.1. Schematic diagram of the CSI sensor. (a) Top side (b) Bottom side

Fig.2. Schematic diagram of the experimental setup for damage detection by using the CSI sensor

Fig.3. Cross section of the CFRP strip with six grooves on the bottom side (not to scale)

Fig.4. Analysis of the sensitivity curve obtained from the detection of the six subsurface grooves. (a) Sensitivity curve (b) Analysis of the interaction between the sensor and the defect

Fig.5. Relationship between the subsurface depth and the corresponding magnitude of Stage II

Fig.6. Parametric study of the effect of the inspection frequency. (a) The sensitivity spectrum at the position above the first groove. (b) Sensitivity curve for the six-groove detection at different frequencies

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Fig.8. The distribution of $|S_{21}|$ obtained by the detection of the BVID on the CFRP sample

Fig.9. Diagram of the two-port network in the equivalent circuit modelling for the CSI sensor

Fig.10. Three parameters considered in the expression of the coupling coefficient: standoff distance (s), subsurface depth (h) and conductivity (σ) of the sample

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Fig.15. Comparison of the sensitivity curves between three sensors for the detection of six subsurface grooves

Fig.16. Comparison of the relationship between the subsurface depth and the average magnitude of Stage II obtained by three sensors

Fig.17. Two cases with an artificial delamination created by partially filling the grooves. (a) Case I. (b) Case II

Fig.18. Comparison of the sensitivity curves for the detection of simulated delamination produced by the CSI sensor and the EM yoke sensor. (a) Case I. (b) Case II

Fig. 19. Detection of delamination in a 2D plain woven CFRP sample induced by three-point ending. (a) Photo of the delamination caused by bending. (b) Sensitivity curve

Table caption

Table 1 Summary of the subsurface depths of the grooves and the average magnitude of Stage II in the sensitivity curve