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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.

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

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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 ($\sim$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