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Non-destructive testing of carbon-fibre-reinforced polymer materials with a radio-frequency inductive sensor

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ABSTRACT

A comprehensive experimental study of the non-destructive RF inductive testing technique, based on coupled spiral inductors, is presented in this paper. It is shown that the method can be applicable to the structural health monitoring of CFRP composite materials. The proposed technology is shown to be inexpensive due to simple dielectric printing technology applied to the development of sensors. The proposed technique allows speeding up the measurements substantially, as the application of the array of sensors is straightforward and incurs low cost. The throughput of the overall inspection is of essential importance in the case of large surfaces, like aircraft fuselage, which are still challenging to the alternative non-destructive testing techniques.

1. Introduction

Carbon-fibre-reinforced polymer (CFRP) materials have become increasingly popular among conventional well studied engineered materials due to advanced properties that they present, such as high strength to weight ratio, corrosion resistance, improved fatigue performance, etc. The above characteristics have led to the large increase of industrial applications of such composites to the development of wind turbines, aircraft fuselage, sport equipment, and many others. Nevertheless, contrary to the aforementioned advantages of CFRP materials, these can be impaired in several ways during fabrication, assembly and on-life stages by a series of different damages and/or structural failures. As a result, the wide applicability of these materials has created the need for the development of prompt and reliable systems for non-destructive testing (NDT), both for quality control during a manufacturing process as well as for condition monitoring of the structure in-service performance [1].

One of the common NDT techniques applicable to the inspection of defects in CFRP structures is ultrasonic testing (UT). The main principle of this technique is based on the propagation of an ultrasonic wave through a material under test (MUT) and the detection of the wave reflected from a defect. In a pulse-echo mode, the wave may be excited and received with a single transducer, while in a through-transmission mode the transmitted wave can be picked up by another transducer on the opposite surface of the MUT [2,3]. Saito and Kimpara [4] used ultrasonic C-scan images and cross-sectional photographs to reconstruct impact damages within CFRP laminates. The disadvantage of UT is the need of couplants (usually water-based), which enable efficient coupling of the transducer and the MUT, but is more feasible in laboratory studies than in-field tests. For the past decades, contactless UT techniques using lasers [5,6] and air-coupled [7] have been proposed to overcome the problem of using water-based couplants. However, the signal-to-noise ratio is significantly reduced in those techniques, and it still remains a challenge for defect detection in CFRP materials. In addition, all the aforementioned UT techniques require point to point scanning of the sample, thus, resulting in low measurement throughput.

Another common NDT technique used for the inspection of conductive materials is eddy current testing (ECT) [8,9] with an inductive coil placed in proximity to the MUT in order to induce eddy currents. Consequently, defects of the conductive material will affect the impedance of the coil, thus, enabling their detection. This type of ECT is known as an absolute mode of operation [10].

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There is also a differential mode of operation with two neighbouring coils placed above the conductive MUT. Both coils are driven in that method and a differential signal, which is supposed to be sensitive to the defects buried in the MUT, is measured [10]. The alternative to the differential mode is a coupled mode, where one coil is driven and the coupling signal is measured at the second coil [10].

ECT can operate in a wide frequency spectrum ranging from kHz up to a few MHz, where the largest sensitivity to defects buried in the conductive MUT is usually expected. The frequency applied in the measurement is usually adjusted to the conductivity of the MUT so that a penetration depth becomes comparable with the MUT's thickness. There are also extensions of ECT techniques that utilise the whole spectrum of the applied signal to the detection of buried defects, such as multi-frequency ECT [11] and pulsed ECT [12,13] techniques. He et al. [14] proposed automated defect classification in the pulsed ECT applied at kHz frequencies to multi-ply aluminium structures with interlayer gaps. It is clear in these studies that the method is sensitive to surface and subsurface defects although, due to the penetration depth decreasing with the square root of frequency, it is inapplicable to detect deeply buried defects. On the other hand, an increase of the upper frequency is challenging in ECT due to technological limitations.

Microwave and millimetre wave NDT techniques have also been investigated to detect and size the defects in CFRP structures but due to the substantially reduced penetration depth it is applicable only to very thin layers, like CFRP laminates on concrete surfaces [15,16]. Another NDT technique is shearography, an optical inspection technique using coherent light, which is extensively exploited in the aerospace industry [17,18]. Contrary to all the techniques described above, shearography is an indirect method where a load (vibration or heat) is required to be applied to the MUT in order to create a strain field (i.e. defect induced deformation of the surface). This technique is extremely sensitive to environmental conditions (e.g. vibration), so high mechanical stability of the MUT has to be assured in order to achieve the coherence of images.

Recently, a new type of the NDT technique dedicated to the inspection of CFRP composites has been proposed [19], where coupling between two planar spiral inductors printed on a dielectric substrate is measured. Despite some similarities to the differential mode of operation of the ECT technique, it has been shown in [19] that the method does not belong to the category of the ECT techniques, where eddy currents play a dominant role. On the contrary, the coupling between the inductors in the technique proposed in [19] is mainly due to magnetic field components tangential to the MUT's surface. The radio-frequency inductive testing (RFIT) technique has several advantages when compared to alternative methods. First, it does not require water immersion like in the UT. Second, the cost of RFIT sensors is negligible as they can be manufactured on a raw printed circuit board (PCB), like FR4, the cost of which is less than 8 €/m^2. Third, the development of a conformable sensor array is inexpensive and straightforward as it can be printed on a flexible PCB, for instance, made of PTFE. Consequently, the inspection of large curved surfaces, like an aircraft fuselage, can be substantially simplified and speeded up. Moreover, the RFIT method allows determining the depth of defects buried below the surface on the basis of C-scans acquired at various frequencies [19]. However, the attention has been mainly focused in [19] on the proof of concept of that new NDT technique with a detailed theoretical study of its major properties.

In this paper, the overview of the RFIT technique is presented with the emphasis on its competitive properties and potential limitations. The method is validated experimentally against the UT technique, indicating its applicability to the detection of such defects as holes, cracks, delamination, and voids. In Section 2, CFRP composite samples selected for further inspection are characterised in terms of its internal composition as well as electrical properties at radio-frequencies (RF) and beyond. In Section 3, RFIT and UT measurement setups are discussed in details. In Section 4, samples with intentionally produced defects are thoroughly examined with both methods.

2. Characterisation

2.1. SEM imaging

Several CFRP composite samples are selected to undertake the validation of the RFIT technique. The composites consist of four layers of CFRP twill moulded in epoxy resin and coated with polyester gel as indicated in Fig. 1. According to the specification provided by the manufacturer of the samples [20], a volume fraction of carbon fibres in each CFRP layer is in the range $v_f = 50$–65%. Before the actual NDT inspection of the CFRP composites samples with the RF sensors will be undertaken, microanalytical studies are performed with the aid of a FEI Quanta 200 environmental scanning electron microscope (SEM), aiming to retrieve essential features of the samples with the major emphasis on the matrix-reinforcement distribution. Fig. 1 shows a four-layer gel-coated CFRP sample, which is cut into 4×0.5 cm^2 pieces. The cutting is performed using a precise cutting machine, alleviating potential risks of fibres misalignment.

Fig. 2 shows SEM images of the selected CFRP samples. As it can be noticed in Fig. 2(a), a gel layer used as a protective coating on the front surface of the composite can be clearly distinguished (red dotted frame). On the contrary, no clear distinction of four CFRP reinforcement layers can be done. Nevertheless, the results confirm the efficient aggregation of epoxy and carbon fibres during the fabrication of the samples. Additionally, it can be seen in Fig. 2(b) acquired at 4000× magnification that the diameter of individual fibres is approximately 5 μm. Furthermore, inspecting the representative test samples from their rear side, some areas with poor resin are detected as shown in Fig. 2(c). The presence of those voids allowed the visual inspection of the fabric twill revealing no substantial misalignments of carbon fibres (see Fig. 2(d)).

2.2. Electrical imaging

Subsequently, the CFRP samples are the subject of electrical characterisation, which is of essential importance in the evaluation of a frequency range where the penetration depth becomes comparable with the thickness of those samples. For that purpose, a single-post dielectric resonator is applied [21], which allows precisely evaluating the conductivity of materials. The resonator operates at $f = 5$ GHz and estimates the conductivity of the

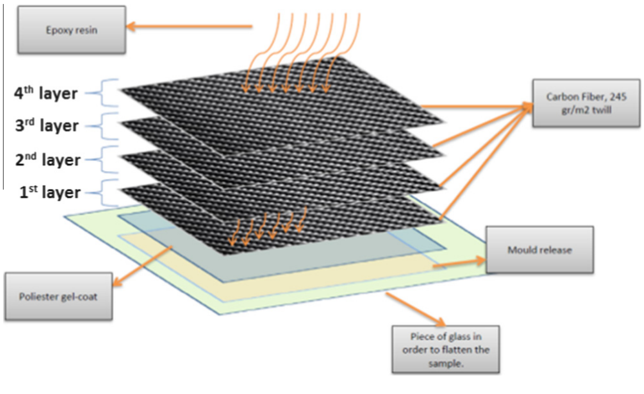

Fig. 1. Four-layer CFRP sample coated with polyester gel [20].