Characterization of Carbon Fibre Reinforced Composite by Means of Non-Destructive Eddy Current Testing and FEM Modeling

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Abstract

The limitation of non-destructive methods for the inspection of carbon fibre reinforced plastic (CFRP) composites is a major problem for many practical applications of the material, especially in the aircraft industry. This paper presents a study which is directed towards non-destructive characterization of CFRP using eddy current methods. The relationship between the signal from different types of inductive probes and the microstructure of CFRP samples has been observed. The measurement of a bulk equivalent electrical conductivity of the material was based on the Deeds and Dodd's analytic solution, which provides the fundamentals for the prediction and detection of fibre fracture and material defects. Characterisation of the fibre direction has also been performed on unidirectional and multidirectional CFRPs using a highly directional probe. Finally, 3D finite element method (FEM) computer simulations have been developed to demonstrate the coupling of the probes and samples, and to support the experimental method.

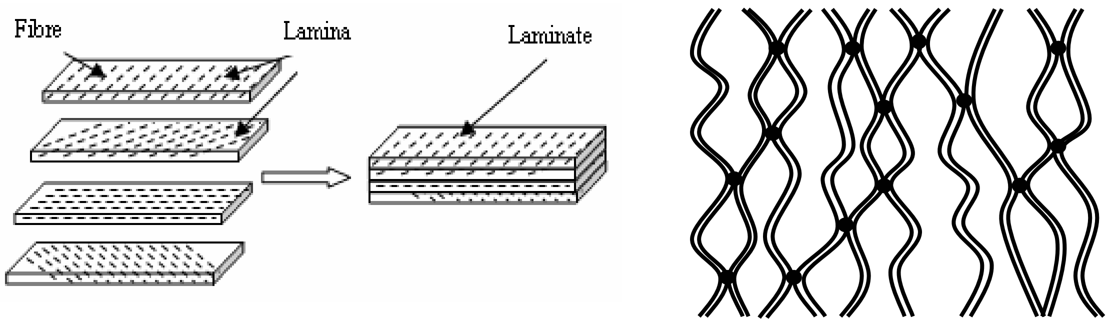
Keywords: Eddy current, FEM modeling, Non-destructive characterization, Carbon fibre reinforced plastic composites

1. Introduction

Carbon fibre reinforced plastics, CFRP are composites made with carbon fibres embedded in a polymer, commonly epoxy matrix. The fibres, which are usually 7 to 15 μm in diameter[1], are bundled together to form a tow, which can then be woven into a fabric or laid down unidirectionally to form a lamina. A single lamina has a thickness of about 0.05-0.2mm, and so in order to obtain usable mechanical engineering components, many laminae are stacked in same or different directions to form a laminate, as shown in Fig.1. This fibre directionaility contributes to the electrical anisotropy in CFRP which means the composite conductivity is typically much higher in the fibre direction and lower perpendicular to fibre direction[2], with the $0^o/90^o$ conductivity ratio being several orders of magnitude.

To non-destructively characterize CFRP structure and optimize its manufacturing, various inspection techniques have been studied and developed such as ultrasonics, scanning acoustic microscopy, embedded optical fibre, microwave technique scanning and DC or AC conductivity measurement. Eddy current testing has gained interest for in-service inspection and rapid quality control because of it is fast simple, and non-contacting[3,4].

Some recent work has been published [5-8].



(a) Stacking of individual lamina to form a laminate; (b) Schematic representation of layer with contact points between two parallel fibres[6]

Fig.1 Formation and structure of CFRP composite

This paper considers methods for applying eddy current inspection to different aspects of CFRP characterization. Various eddy current probes have been designed for composite conductivity testing. Both experimental and 3D FEM analytical results have confirmed the potential of this method.

2. Method and Testing Set-up

2.1 Probe and conductive material coupling

Eddy current testing is based on electromagnetic principles and simple electronic circuit can be used to model the situation of eddy current measurement of the materials. The two coupled coils in Fig.2 represent the eddy-current probe with inductance L_1 and the current loop in the material with L_2 and resistance R respectively. The probe and the material are coupled by the mutual inductance M

$$M = k\sqrt{(L_1 L_2)} \quad (1)$$

where k is the coupling factor which depends on the spacing between the probe and the material and on the design of the probe. Its value ranges from 0 to 1.

The normalized impedance of probe is:

$$\frac{Z}{Z_0} = 1 - \frac{k^2}{1 - jR/(\omega L_2)} \quad (2)$$

where Z_0 is the impedance of the probe in air.

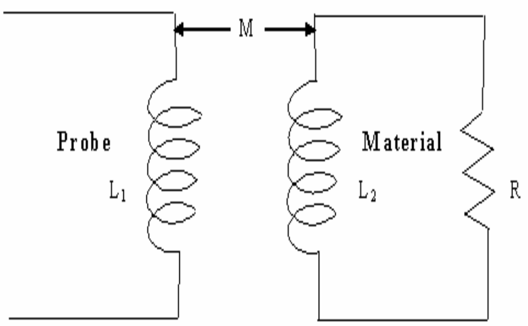


Fig.2 Circuit model for the eddy-current

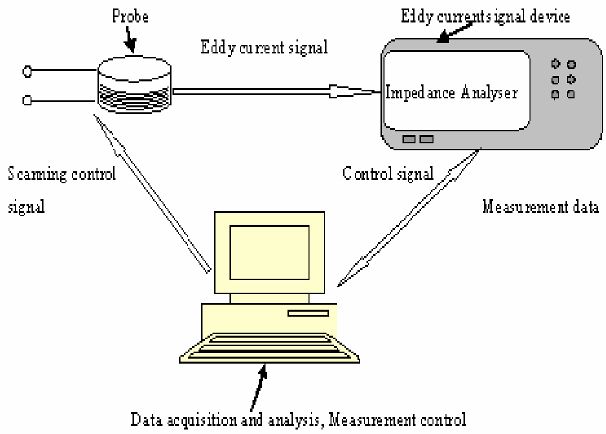


Fig.3 Basic eddy current testing system

2.2 Eddy current testing system

According to the relation between the probe impedance and material electrical properties, an eddy current testing system for the characterization of CFRP may be like Fig.3. The probe is controlled by PC to perform different scanning tasks and its design varies for different measurements and requirements. The eddy current signal device used here is an impedance analyser, in this case, a Solatron 1260. It has wide frequency range and can generate alternating current on the probe. The analyser is controlled and set by the PC through the interface software SMART. In this experiment, it works in frequency sweep mode from 100 kHz to 10 MHz. The PC plays role in scanning control, device specification, data acquisition and processing, and material structure imaging.

2.3 Composite conductivity testing

The conductivity of the composite is determined by the conductivity of individual fibres, the stacking sequence and the fibre volume fraction by the rule of mixture[9]. It has also been shown by experiments that the resistance of CFRP increases with the appearance of internal damage, such as fiber breakage and delamination[10]. These indicate that conductivity is closely related to other composite properties. To measure the bulk equivalent conductivity, a circular air-cored coil with specification in Table.1 was used above the composite to scan the inspected area, as depicted in Fig.4.

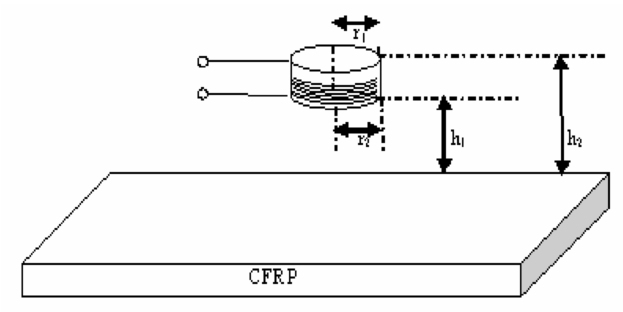


Fig.4 Conductivity testing

Probe Type	Turns	Inner diameter(r_1)	Outer diameter(r_2)
Circular air-cored	15	25mm	25.1mm

Table.1 Specification of conductivity testing probe

A more practical detailed solution for a circular air cored coil above a conductive plate of at multi-frequencies as showed in Fig.4 is given by Deeds and Dodd' formulas[11]:

$$\Delta L(\omega) = K\int_0^\infty \frac{P^2(\alpha)}{\alpha^2} A(\alpha)\phi(\alpha)d\alpha \qquad (3)$$

where $$\phi(\alpha) = \frac{(\alpha_1+\alpha)(\alpha_1-\alpha)-(\alpha_1+\alpha)(\alpha_1-\alpha)e^{2\alpha_1 c}}{-(\alpha_1-\alpha)(\alpha_1-\alpha)+(\alpha_1+\alpha)(\alpha_1+\alpha)e^{2\alpha_1 c}} \qquad \alpha_1 = \sqrt{\alpha^2 + j\omega\sigma\mu_0}$$

$$K = \frac{\pi\mu_0 N^2}{(l_1-l_2)^2(r_1-r_2)^2} \qquad P(\alpha) = \int_{\alpha r_1}^{\alpha r_2} xJ_1(x)dx \qquad A(\alpha) = (e^{-\alpha l_1} - e^{-\alpha l_2})^2$$

where α- is an integration variable; ω-- angular frequency of excitation current;
μ-- the permeability of the conducting plate; μ_0 - the permeability of free space;
σ-- the conductivity of the conducting plate; c -- the thickness of the plate;
r_1 and r_2- inner and outer radius of probe; l_1 and l_2- height of bottom and top of probe;
$J_1(x)$- a first-order Bessel function of the first kind.

The real and imaginary parts of analytic result from the solution are shown in Fig.5.

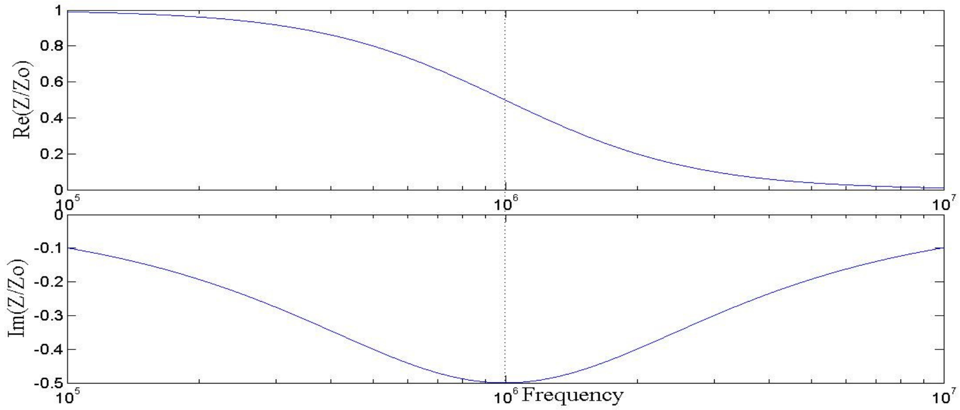
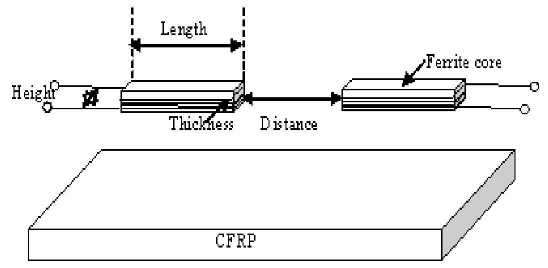


Fig.5 Analytic inductance of coil above a conductive plate

2.4 Detection of fibre direction

The anisotropy in conductivity, in particular of unidirectional composites, suggests that eddy current methods are ideally suitable to inspect the orientation of the fibres. Rotary eddy currents probes can be used to detect local fibres direction, shown in Fig.6. The probe is a ferrite-cored pair of rectangular coils with same dimensions and turns (Table.2). The coils are glued together to a base and used as transmitter and receiver pair.



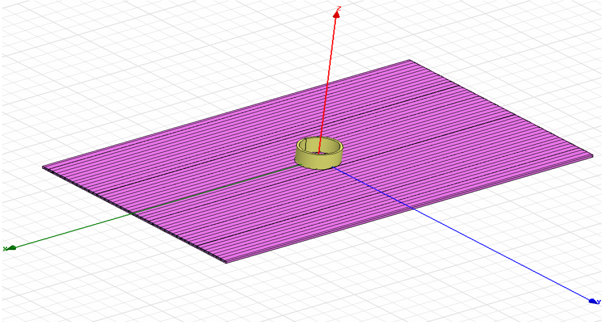
Type	Turns	Height	Length	Thickness	Distance
Ferrite-cored pair	5	5mm	10mm	1mm	10mm

Fig.6 Figure 3.6 Fibre direction detecting

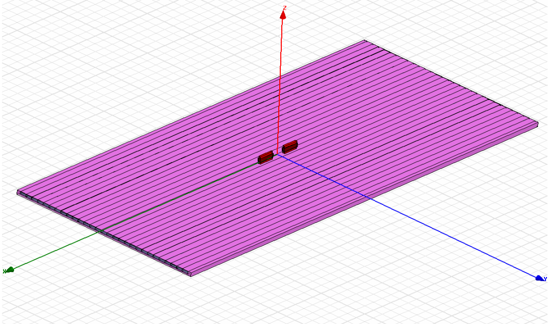
Table.2 Specification of direction detecting probe

3. Experiment and Simulation Results

The sample used for conductivity testing is a piece of cross woven CFRP, while for fibre direction detection is a 2-layers unidirectional piece, both of which are from industry. The simulations running in 3D FEM analysis use the models (seen in Fig.7) designed according to the real samples, eddy current probes and excitation. Taking the sensitivity, signal to noise ratio and electrical coupling between the fibres into consideration, a frequency range from 100k to 10MHz was chosen for conductivity testing and fixed frequency at 10MHz for fibre direction detection. In the simulatios the fibre bundles are specified as straight bars without contacts between each other.



(a) Model of conductivity testing

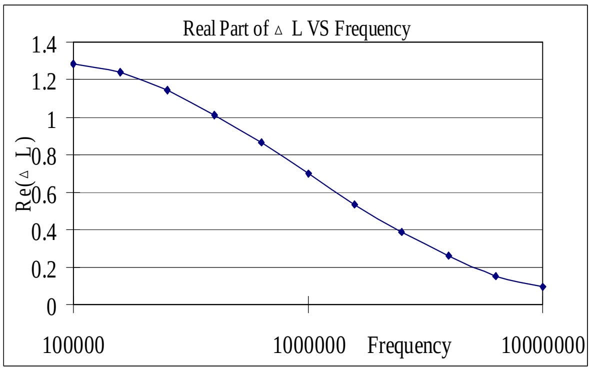


(b) Model of fibre direction detection

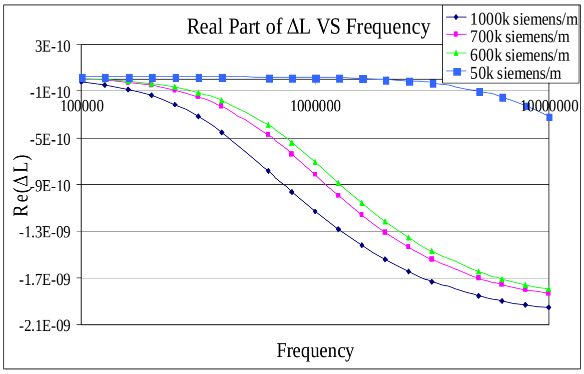
Fig.7 Simulation models in 3D FEM analysis

3.1 Composite conductivity testing

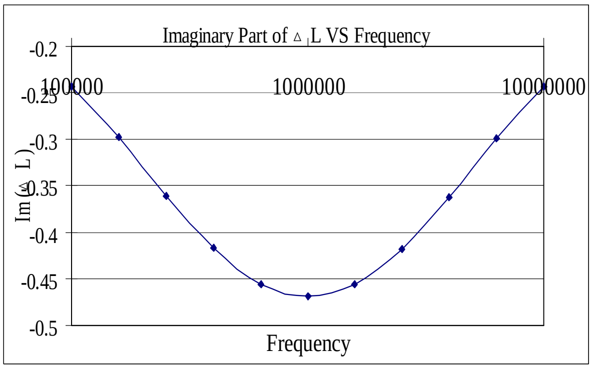
As can be seen from Fig.8, both the experimental and simulation results show good agreement with Deeds and Dodd's analytic solution. What's more, we can see clearly in the simulation results how the change of the conductivity of the fibre affects the results, which implies that the eddy current method is also sensitive to structural modification due to fibre fracture and inter-layer delamination for example.



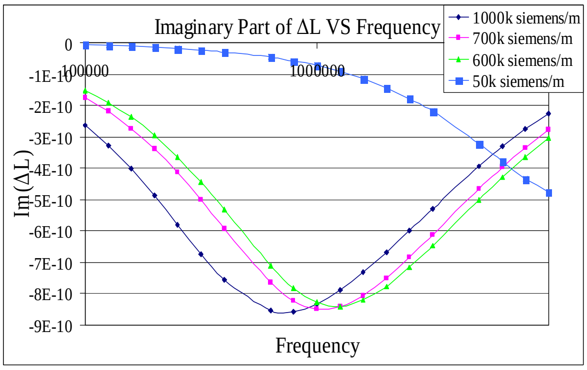
(a) Real part of experiment result



(b) Real part of simulation result



(c) Imaginary part of experiment result

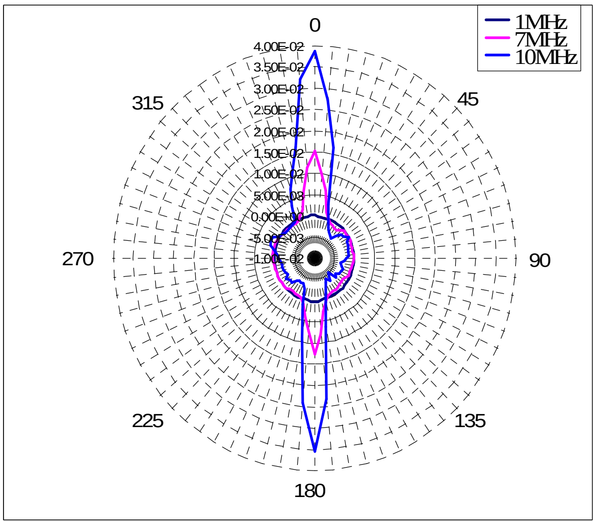


(d) Imaginary part of simulation result

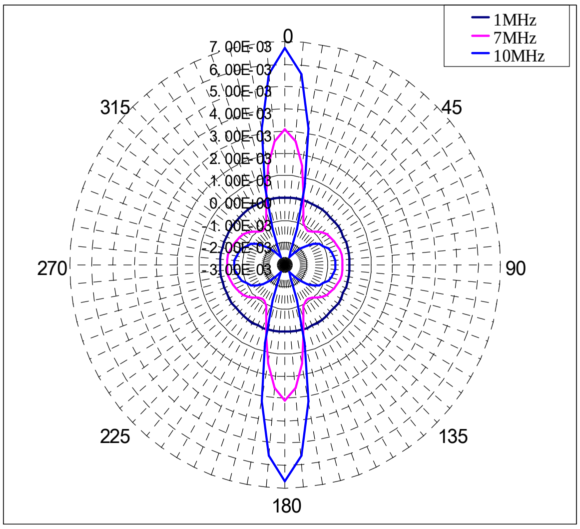
Fig.8 Results of conductivity testing

3.2 Fibre direction detection

During the measurement, the coils were rotated above the inspected area from 0^0 to 360^0 and the trans-impedance between the coils was measured. Plotting calculated data on polar plane, the fibre direction is clearly evident in Fig.9.



(a) Experiment result



(b) Simulation result

Fig.9 Results of fibre direction detection

The large lobes in the graphs indicate the fibre direction and the small lobes are caused by the shape of the coils. The imbalance occurring in Fig.9 (a) may result from fibre contacts and electrical coupling between fibres and layers. From Fig.9, it can also be seen that using higher frequency provides higher directionality.

4. Conclusion

Theoretical analysis, experimental results and a 3D simulation show the capacity of the eddy-current method to characterize CFRP non-destructively. Special probes are required to make use of the electrical anisotropy of CFRP in conductivity testing and fibre direction detection. Based on these, characterization of defects in CFRP is another potential application of eddy current method. Meanwhile, the practical problem is how to eliminate the effect of the noise and electrical coupling during the measurement especially at high frequencies.

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