Model-assisted eddy current inspection for enhanced detection sensitivity in CFRP

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Abstract

Having electrical conductivity in carbon fibre reinforced polymers (CFRP) could lead to the adoption of eddy current (EC)-based non-destructive testing for defects detection in CFRP. It is clear that with low electrical conductivity of carbon fiber embedded in matrix resin, the detection sensitivity of conventional eddy current technique is uncommonly poor. In this paper, attempts have been made for enhanced sensitivity using a model-based approach, with which the optimal design of a unique EC coil array as well as the resonance-based technique can demonstrate the potentialities of improving the sensitivity of detection.

Keywords: Eddy current, CFRP, disbond, model-assited, coil array, resonance-based

1 Introduction

Carbon fiber composite polymer (CFRP), which is well known for its mechanical strength and light weight, is currently dominating the aviation industry. Despite its multiple advantages, it is prone to defects during service due to its heterogeneous composition. For example, low energy impacts leave the superficial surface of a component unaffected; however it creates barely visible internal damage resulting in delamination/weak bond and fibre breakage. There are many effective and widely used NDT methods for CFRP inspection such as ultrasonic, shearography, pulsed thermography etc [1-3]. However, those techniques require stringent surface preparation of the test structure in order to achieve reliable detection [1-3]. Hence, an uncomplicated and quick inspection procedure capable for such detection could greatly benefit NDT community. The eddy current testing is one of the electromagnetic methods that is fast, simple and widely used for examining conducting structures. As carbon fibers and/or advanced nanocomposite in CFRP possess an amount of electrical conductivity, it is straightforward to think that EC method could be adopted for CFRP inspection. However, the detection level of conventional EC in CFRP may be very low due to low conductivity and CFRP famously anisotropic and inhomogeneous structure. Thus, the ability to boost the detectivity of EC for CFRP inspection will be crucial. Few studies so far have concentrated on specific defects and/or material [4-5]. The contribution of this paper is to develop a model that is able to simulate the EC response to CFRP structure with and without defects. This will aid the physical understanding and to provide guidelines for experimental procedures to further enhance the sensitivity of defects detection in CFRP. Leveraging on the developed model, we have proposed an appropriate configuration of EC
coil array operating near resonance regime of the system in order to significantly boost the signal above the noise level.

2 Model-based sensitivity enhancement

In this contribution, an efficient EC model for the simulation of response to CFRP structure with and without defects has been developed. As a proof-of-concept model, the delamination located close to inspection-side surface is considered as virtual defect to be detected.

Solving a multi-scale problem, which consists of a thin multi-layer anisotropic material (i.e. CFRP), in Finite Element Method (FEM)-based electromagnetic solver is intractable without using homogenization approach. The homogenized equivalent tensor of electrical conductivity of each elementary CFRP ply can be derived from [6]. For a unidirectional ply with fibre volume of 60 %, conductivity in fiber orientation is about $4.10^4$ S/m; the one in transverse direction and in z direction is approximately 8 S/m. The disbond model has been constructed based on [3] in such a way that ensures the circulation of current flowed uninterrupted, bypassing the defect; and the electrical conductivity is redefined to maintain the DC electrical resistance of the material similar to without defect. A CFRP consists of 8 plies, where the lay-up sequence is shown in Figure 1. The flaws were introduced in 2nd, 3rd and 4th plies of CFRP.

The key design parameters considered for EC modeling are the coils’ parameters, e.g. shape and size of coil, its operating frequency, and array configuration that can be optimally selected from optimization process to increase the output response, which is the coils’ impedance variation. It should be noted that making use of EC method for CFRP, the penetration depth is also dependent on fibre and epoxy ratio, number of fibres and the different fibre orientation.

A single EC coil, which is a square shaped (dimension of 1.5 mm), stranded coil having 225 turns of 0.08 mm diameter wire (AWG wire size 40), is used for the detection. The coil is excited with 1 A
alternative current source (internal resistance negligible) operating at frequency of 25 kHz, which is selected to satisfy the penetration depth (from few tens KHz to few MHz). The output impedance obtained is listed in Table 1. It is found that output signals may not be distinguished. Hence, the probability to detect the defects in CFRP using this conventional EC method is slim as such small variation may come from the noise level when EC testing is conducted in the real environment. A parametric study of different input design parameters (parameters of coil, defects’ parameters, and operating frequency within the bounded constraints) was investigated to evaluate their influence on the output response. It has been observed that by increasing the frequency, number of turns and coil dimension, higher impedance value can be obtained; and the impedance variation due to larger number of turns is much significant as compared to other parameters. However, there is trade-off between achieving higher output response with higher noise level due to higher frequency usage and larger size of coil. Hence, an optimization process needs to be carried out to identify optimized design parameters for enhanced detection sensitivity.

![Figure 2: Parametric study - output response (real and imaginary part of coil impedance) vs. operating frequency (first row), number of turns (second row) and coil dimension (last row).](image-url)
Table 1: Output coil impedance - much less detection sensitivity using conventional EC method.

<table>
<thead>
<tr>
<th></th>
<th>Real Part</th>
<th>Imaginary Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Defect</td>
<td>0.00928</td>
<td>22.00004</td>
</tr>
<tr>
<td>Defect on 2(^{nd}) layer</td>
<td>0.00931</td>
<td>22.00546</td>
</tr>
<tr>
<td>Variation</td>
<td>0.3 %</td>
<td>0.03 %</td>
</tr>
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2.1 EC coil array

We have proposed a configuration, which consists of a horizontal excitation coil and a vertical pick-up coil as shown in Figure 3 for enhanced detection sensitivity. This configuration ensures that the magnetic flux generated by the driver coil penetrating the pick-up coil is minimal; thus the output voltage of the pick-up coil is not caused by the excitation coil [4]. Also, due to the way of eddy current passing around the disbond, the receiving coil could pick up higher magnetic field from the induced eddy current. In fact, an efficient optimization algorithm-based process, e.g. metamodel-based [7], plays an important role in effectively designing optimal coil configuration to achieve highest output response. It has been suggested that increasing operating frequency could lead to improved signal response [9]. However, the noise generated from equipment needs to be taken into consideration.

![Image of two-coil system above defected CFRP structure](image_url)

Figure 3: Two-coil system above defected CFRP structure (excitation horizontal and pick-up vertical coils); disbond introduced in 2\(^{nd}\) plies of CFRP.

2.2 Resonance-based technique

Enhanced response of eddy current signal via resonance can be achieved by incorporating the EM model into an equivalent lumped electric circuit to perform the system-level simulation of the eddy current NDT system, boosting the signal well above the noise level [9]. The effect of the co-axial cable, which connects the current source to the eddy current probe, was taken into account by its...
characteristic capacitance $C$. The equivalent circuit model is illustrated in Figure 4, where the Touchstone (TS) file accounts for the response of EM model; and the resistance $R$ is the internal resistance value of the coil. The electromagnetic coupling occurs between the eddy current coil and the component surface when the coil is in close proximity to a conducting structure. The defect-decoupling phenomenon can be observed with the presence of defects causing by the reduction in the coupling coefficient from that of the eddy current system coupled to an undamaged structure. This will result in a shift in the resonant frequency of the response signal [9].

![Electromagnetic (EM) modeling](Image)

**Figure 4: Coupled eddy-current probe equivalence circuit; TS file contains the coupling interaction from the 3D EM simulation.**

Before apply to CFRP testing, the concept of EM circuit co-simulation has been validated via the simulation of response of eddy current probe to sub-millimeter surface-breaking cracks (electrical discharge machining notch) in a Titanium test piece (Ti 6AL4V), whereby the result is shown in Figure 5. It has been seen that the detection sensitivity via resonant peak is enhanced up to ~300%. Good agreement between simulated and measured results from a developed eddy current data collection system can be seen with less than 0.4% error [10]. The extension of this EM circuit co-simulation model is planned for CFRP testing and the results will be shown at the conference.
Figure 5: Comparison of measured and simulated results obtained from - probe in the air and with Ti test piece.

3 Conclusions

A model, which can be used to simulate response to defects in CFRP structure, has been constructed. This can be used for the design optimization of a two-coil system for improved detection capability of eddy current inspection for CFRP, with which the sensitivity is problematic due to low electrical conductivity of CFRP composition, especially at low operating frequency (kHz). It is suggested to increase the frequency, where a promising resonance-based technique has been explored to achieve better detection sensitivity. Investigation of deeper disbond layers and even kissing bond can be considered in future study. The improvement of EC method would help for optimized equipment design to improve defect sensitivity and could lead to simple inspection procedures in NDT for CFRP.

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References


