

Investigation of Eddy Current Nondestructive Testing for Carbon Fiber-Reinforced Plastic (CFRP) Based on Electromagnetic Field Analysis

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Abstract: CFRP (carbon fiber reinforced plastic) is used extensively in aircraft and spacecraft structures, because of its excellent mechanical properties. Ultrasonic testing, which is used as a non-destructive testing technique for CFRP, requires a contact medium. In contrast, eddy current testing does not require a contact medium, and when used for CFRP testing it has advantages not available with other techniques. CFRP is a laminate, with each layer being anisotropically conductive, and the distribution of the induced eddy current is yet to be determined. Here, to determine the eddy current distribution in the detection of flaws in cross-ply CFRP (0°/90°) by using a cross-point probe, we performed an FEM (finite element method) analysis of electromagnetic fields. We investigated the nature of the flaw signals and the differences in eddy current distributions between materials with and without flaws.

Key words: Nondestructive testing, eddy current testing, CFRP, flaw detection, FEM analysis.

1. Introduction

Composite materials present the combined advantage of high strength, high fatigue resistance and very low weight. They are used to a great extent in the aircraft and the aerospace industry. However, fiber-reinforced composite materials can show poor resistance to impact. In order to maintain the high level of quality and safety required by the aircraft and the aerospace industry, the use of non-destructive testing techniques is a major factor in the quality assessment for these new materials.

Eddy current testing method is one of the non-destructive testing techniques where electric induction is used. In this method, change of electric current in a test material by a test coil, where an alternating current is applied, is monitored as change of impedance of the test coil or electromotive force of another detecting coil. Distinctive feature of this

method is an ability of fast and contact-free inspection of flaws that affect local electric conductivity of the sample. Eddy current testing method has a potential to inspect the flaws of CFRP (carbon fiber reinforced plastic), because carbon fiber in CFRP has electric conductivity [1-12]. There are several problems to be solved for applying eddy current testing method to CFRP such as proper selection of test frequency, shape of probe, or signal processing.

CFRP is a laminate, with each layer being anisotropically conductive, and the distribution of the induced eddy current is yet to be determined. Here, to determine the eddy current distribution in the detection of flaws in cross-ply CFRP (0°/90°) by using a cross-point probe, we performed an FEM (finite element method) analysis of electromagnetic fields. We investigated the nature of the flaw signals and the differences in eddy current distributions between materials with and without flaws. Furthermore, we conducted an experiment of flaw detection.

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2. Detection of CFRP Flaw by Using a Cross Point Probe

Because CFRP contains carbon, it is electrically conductive, although the conductivity is lower by a factor of approximately 10^4 to 10^6 than that of metals. Eddy current testing can be carried out by making use of this conductivity. However, because of the low conductivity compared with metals, for which eddy current testing is generally conducted, and because of the anisotropic conductivity of the material, it is difficult to apply conventional eddy current testing methods to CFRP. Appropriate application of eddy current testing to CFRP requires an eddy current probe that is suitable for detection of flaws in CFRP and signal processing. Various eddy current probes with high detection performance are now available.

Fig. 1 shows the cross point probe, which is constructed with a rectangular exciting coil positioned upright and a detecting coil positioned normal to the exciting coil, used for detecting flaws in CFRP. The exciting coil induces eddy current in the winding direction of the coil, and magnetic flux caused by the eddy current in the winding direction of the detecting coil due to abnormalities in the test material generates electromotive force in the detecting coil, resulting in a signal.

When there is no flaw, as shown in Fig. 2, eddy current is induced in the winding direction directly under the exciting coil. This does not result in eddy current in the winding direction of the detecting coil, and hence does not generate any signal. By placing the exciting coil of the cross point probe in the same direction as the carbon fiber, eddy current is induced in that direction. Since the detecting coil is positioned normal to the carbon fiber direction, there is no eddy current in the winding direction of the detecting coil, and thus no signal is generated. In other words, the noise in cross-ply CFRP ($0^\circ/90^\circ$), which was an issue with the conventional probe, will not occur in principle.

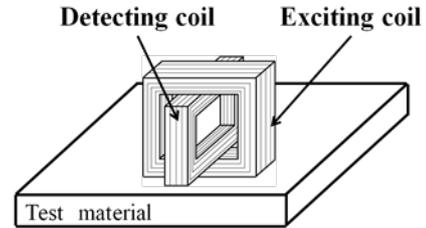


Fig. 1 Structure of cross point probe used for eddy current testing.

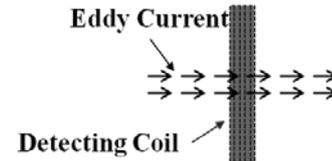
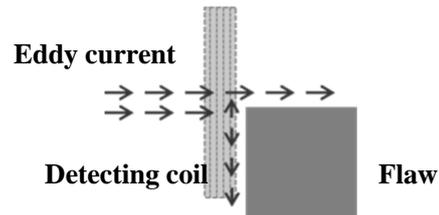
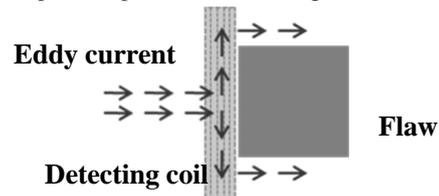


Fig. 2 Flow of eddy current without flaw.



(a) Flow of eddy current when a cross point probe is positioned at the edge of a flaw



(b) Flow of eddy current when a cross point probe is positioned at the middle of a flaw

Fig. 3 Principles of flaw detection in CFRP using cross point probe.

If there is a flaw, as shown in Fig. 3, the flow of eddy current will be disturbed at the edge of the flaw (Fig. 3a), and occur to generate a signal. Note, however, that if the cross point probe is positioned in the middle of the flaw, eddy current is generated in the detecting coil in the winding direction, but the flow will be in the opposite direction centering around the middle (Fig. 3b). In this case, the magnetic flux that interlinks the detecting coil becomes zero and thus electromotive force is not generated, resulting in no signal. Therefore, signals are generated at the edge of a flaw when using a cross point probe.

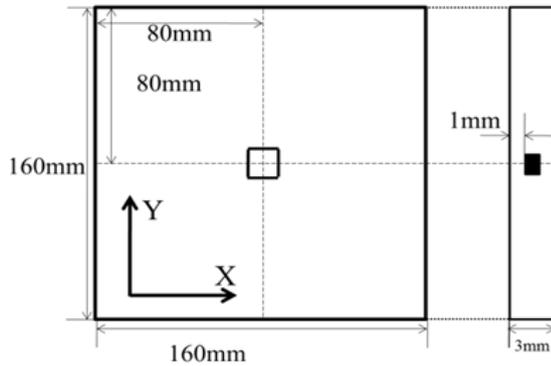


Fig. 4 Analysis model.

3. Method of Analysis and Experiment

First, eddy current distribution and flaw signal were obtained by FEM considering anisotropy of electromagnetic characteristics.

Fig. 4 is a model of the test sample of CFRP ($0^\circ/90^\circ$). Fifteen alternate 0° and 90° layers of 0.2 mm carbon fiber sheet were laminated into a 3 mm-thick sample. The conductivity of the 0° layer was set to 7,700 S/m in the X-axis direction and to 48 S/m in the Y-axis direction. The conductivity of the 90° layer was set to 48 S/m in the X-axis direction and to 7,700 S/m in the Y-axis direction. The conductivity in the Z-axis direction was set to 48 S/m for both the 0° layer and the 90° layer. These conductivities are measurement values of the manufacturing company of the CFRP specimen used in the experiment.

A 1-mm thick simulated square flaw with sides of 10 mm (conductivity 0 S/m) was placed 1 mm below the surface. The flaw was present in the 6th to 10th layers from the surface.

The exciting coil was 7 mm long and 9 mm high. The winding had a cross-sectional area of 1 mm^2 . The detecting coil had a 7 mm long, 7 mm high rectangular cross-section. The voltage was calculated from the magnetic flux crossing the rectangular cross-section of this single turn coil, and a flaw signal was obtained.

The winding direction of the exciting coil was aligned with the X-axis. The frequency was 1 MHz. The lift-off between the exciting coil and the test sample was set to 0.2 mm.

Next, in the experiment to detect flaw, the probe was moved over the surface of the test specimen. This involved two-dimensional movements of the probe of $\pm 25 \text{ mm}$ in the X and Y directions at intervals of 0.5 mm. The detecting coil used for the experiment is multi-layer winding, its cross-section is 1 mm^2 .

4. Eddy Current Distribution

In the 0° layer, which had high conductivity in the winding direction of the exciting coil, very little eddy current flowed in the Y-axis direction, which was the winding direction of the detecting coil. The eddy current in the 0° layer had a small effect on the flaw signal and could be ignored. The eddy current distribution in the 90° layer is shown below.

The eddy current in the 90° layer flowed strongly in the Y-axis direction, which was the winding direction of the detecting coil. Very little of it flowed in the X- and Z-axis directions, which were perpendicular to the Y-axis. The eddy current distribution in the absence of a flaw (Fig. 5a) was symmetric around the detecting coil, and the eddy current flowed in opposite directions. Therefore, no voltage occurred in the detecting coil.

When the probe in Fig. 5b was placed at (5, 0) mm in the X-Y plane, the eddy current was distributed vertically symmetrically with respect to the center of the detecting coil, and these eddy currents are opposite in polarity. Therefore, no voltage occurred in the detecting coil.

When the probe in Fig. 5c was placed at (5, 5) mm in the X-Y plane, the eddy current was distributed in such a way as to avoid the flaw; therefore, a voltage occurred in the detecting coil.

5. Flaw Signals by Analysis and Experiment

In the eddy current testing, a complex voltage of an in-phase component and a quadrature component is obtained. In-phase component is in-phase with the alternating current of the exciting coil. Quadrature component is 90 degrees phase advance to the alternating current of the exciting coil.

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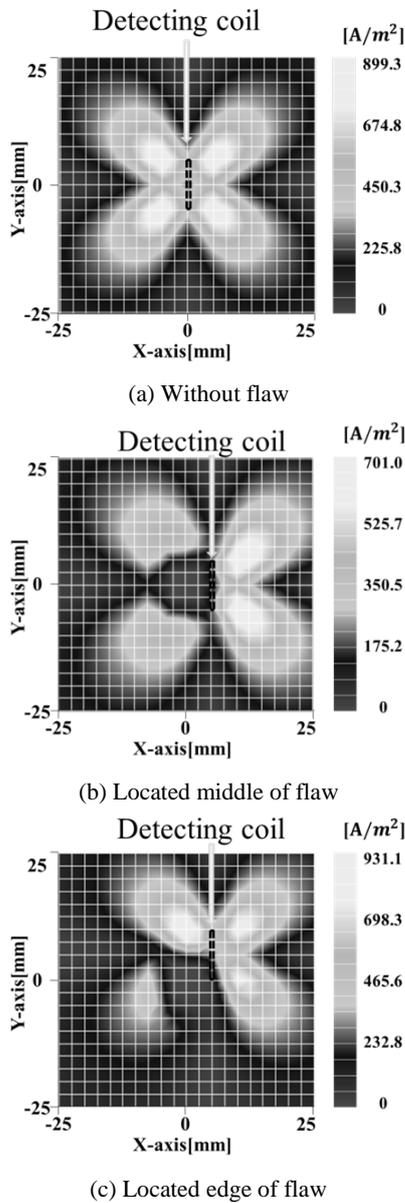


Fig. 5 Eddy current density of CFRP.

Fig. 6 shows image display of the flaw signal obtained by two-dimensionally scanning. Fig. 6a shows the analysis result, and Fig. 6b shows the experiment result. Flaw signals are obtained at the four corners of the flaw edge. Fig. 7 shows the flaw signal pattern for each scanning position in the direction of Y-axis. The voltage was highest when the detecting coil was placed near the edge of the flaw.

From these figures, it can be seen that the signals of the analysis result and the experiment result are in good agreement.

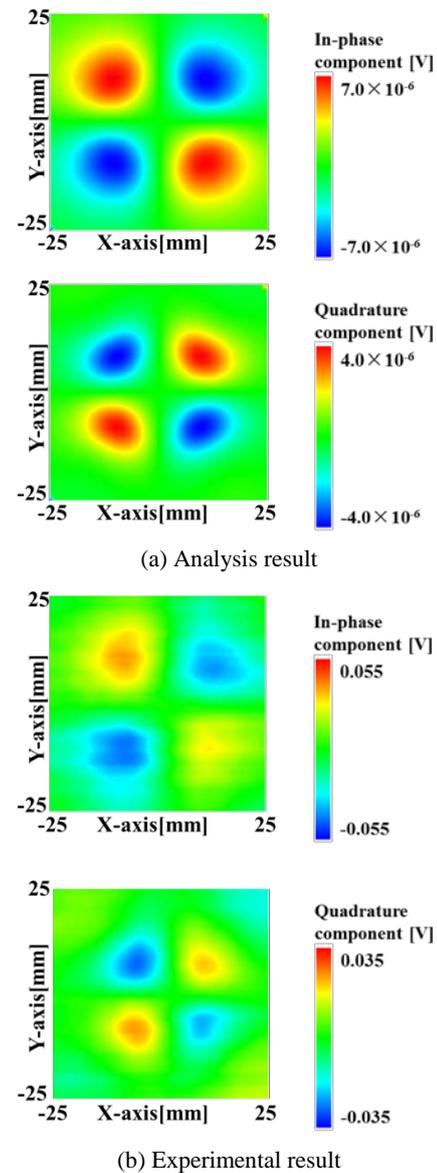
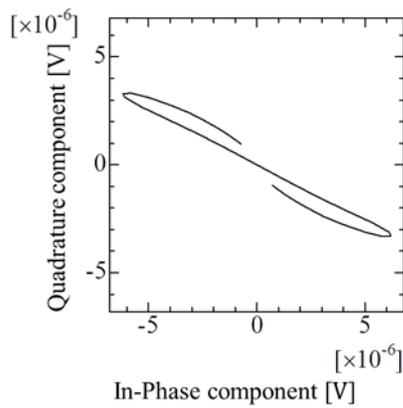


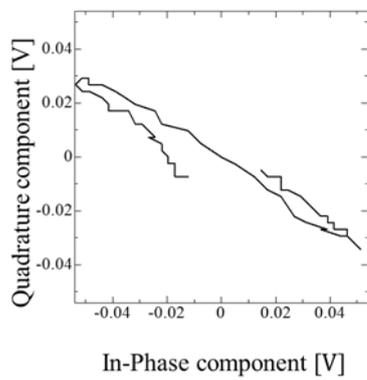
Fig. 6 Image display of flaw signals.

6. Conclusions

We used an FEM analysis to investigate the eddy current distributions in the electromagnetic fields induced in cross-ply CFRP ($0^\circ/90^\circ$) when an eddy current cross point probe was used. The difference in eddy current distributions between materials with and without a simulated flaw, and its relationship with the flaw signal of the detecting coil, were investigated. There was agreement between the analytical results and the flaw signal patterns in the test results. As a next step, we intend to investigate the relationship



(a) Analysis result



(b) Experimental result

Fig. 7 Detecting signal of cross point probe.

between the flaw signals for different flaw sizes and lamination positions and the eddy current distribution.

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