Eddy current non-destructive evaluation of manufacturing flaws and operational damage in CFRP composites

Robin James, Mohammad Faisal Haider, Victor Giurgiutiu, David Lilienthal
Eddy current non-destructive evaluation of manufacturing flaws and operational damage in CFRP composites

Robin James*, Mohammad Faisal Haider†, Victor Giurgiuțiu*, David Lilienthal‡
*Department of Mechanical Engineering, University of South Carolina, Columbia, SC, 29208;
†The Boeing Company, Charleston, SC
rj11@email.sc.edu

ABSTRACT

The manufacturing process of carbon fiber reinforced polymer (CFRP) composite structures can introduce many characteristic defects and flaws such as fiber misorientation, fiber waviness and wrinkling. Therefore, it becomes increasingly important to detect the presence of these defects at the earliest stages of development. Eddy current testing (ECT) is a nondestructive inspection (NDI) technique which has been proven quite effective in metallic structures. However, NDI of composite structures has mainly relied on other methods such as ultrasounds and X-ray to name a few, and not much on ECT. In this paper, we explore the possibility of using ECT in NDI of CFRP composites. We base our research on the fact that the CFRP displays some low-level electric conductivity due to the inherent conductivity of the carbon fibers. This low-level conductivity may permit eddy-current pathways that can be exploited for NDI detection. An invention disclosure describing our high-frequency ECT method is being progressed. We use multiphysics FEM simulation to simulate the detection of various types of manufacturing flaws and operational damage in CFRP composites such as fiber misorientation; waviness; wrinkling, etc. ECT experiments were conducted on CFRP specimens with manufacturing flaws using the Eddyfi Reddy eddy current array (ECA) system.

Keywords: CFRP; composites; characteristic defects; manufacturing flaws; operational damage; misorientation; waviness; wrinkling; ECT; air-cored eddy current sensor; impedance; ECA

1. INTRODUCTION

1.1 State of the art

CFRP composite materials are of extreme interest in the aerospace and automotive industries due to their light weight and high strength to weight ratio. Structures manufactured using CFRP composites must be made in a perfect state such that they do not introduce any dangerous risks. The manufacturing process of CFRP structures can introduce significant manufacturing flaws such as fiber misorientation, fiber waviness and wrinkling. Besides manufacturing flaws, the CFRP composite can also undergo operational damage during its service lifetime. These types of defects may lead to catastrophic failures if they are not detected at the earliest stages of development.

An assortment of nondestructive testing (NDT) methods exist that can be used for damage detection in CFRP composites. The method used for testing is selected after considering the cost, time involved, access to the composite and the ability of the method to detect the presence and the extent of the damage. The simplest and most common nondestructive testing method for CFRP composites is coin tapping [1]. This method involves tapping the composite with a coin and listening for changes in the sound which indicates the presence of damage. This method is not very reliable and is extremely time consuming. Visual tests [2] are performed by visually examining the composite and have the advantage of not touching the composite and are easy to execute. However, like the coin tapping, the accuracy of the method depends on the operator. To improve the method, dye-penetrant is used. Vibration based methods are used to measure the frequency response of composites. These methods can detect stiffness reduction which is evenly distributed over the composite [3]. A change in the natural frequencies is an indicator of stiffness change. Infrared thermography involves taking thermal images of a composite, which can provide information about its inner structure. This method can detect voids, foreign inclusions, delamination and impact damage in relatively short time [4]. In ultrasonic nondestructive evaluation and structural health monitoring, pulses of high-frequency sound-waves are transmitted into the composite and the time it takes for them to reflect back is measured. The method allows the detection of disbands and delamination in the composite ([5]-[8]). Microwave nondestructive evaluation methods have begun to be explored...
and utilized for the detection of corrosion damage precursors in Al-CFRP composites ([9], [9]) and for the prediction and detection of low velocity impact damage in aerospace composites ([11], [12]). High resolution and wideband microwave synthetic aperture radar imaging [13] and a microwave nondestructive testing system [14] have been developed for damage detection in multilayered CFRP composite materials.

In recent years extensive work has been done to understand the phenomena of eddy current testing in conductive materials and how it can be used to detect the presence of defects. A benchmark problem called the testing electromagnetic analysis methods (TEAM) workshop problem 15: rectangular slot in a thick plate has been described in [15] which involves an experiment where a circular air-cored coil is scanned, parallel to the x-axis, along the length of a rectangular slot in an aluminum alloy plate. Mook et al. [16] used high frequency eddy current sensors to characterize CFRP composites with various flaws such as fiber misorientation, delaminations and cracks. The eddy current (EC) distribution was reconstructed from the magnetic field in their work. Heuer et al. [17] claim that there is no efficient and reliable testing system for in-line and consecutive manual inspections of raw carbon fiber (RCF) materials and post laminated CFRP materials. The multi-frequency ECT system consisting of a scalable 16 sensor demonstrator line array developed at Fraunhofer IZF is used to detect missing carbon fiber bundles, fringes, missing sewing threads and fiber misorientation. They were able to obtain high-resolution eddy current images of visible even weaving threads. Mizukami et al. [18] have proposed a specialized EC probe to detect in-plane and out-of-plane fiber waviness in unidirectional CFRP. The proposed EC probe can detect in-plane fiber waviness in a thin unidirectional CFRP laminate at sufficiently high drive frequencies. Validity of their proposed method is verified through 3-D finite element method (FEM). Cacciola et al. [19] have proposed a ferrite core EC probe for the nondestructive evaluation of CFRP composites. The effect of the ferrite core is analyzed in order to focus the magnetic flux density on the investigated specimen. Eddy currents generated by high speed ferrite core probe movement were investigated using numerical simulation applying an FEM approach.

1.2 COMSOL simulation methodology

After the manufacturing process, the CFRP retains some of the conductive properties of the carbon fibers. These retained conductive properties of the carbon fibers in the CFRP composites create electrical pathways that can be exploited using high frequency ECT systems. In this paper, COMSOL multiphysics simulations were conducted to simulate the detection of various types of manufacturing flaws and operational damage in CFRP composites using an air-cored eddy current sensor to measure changes in its complex impedance. This change in the complex impedance of the coil can be measured in the impedance plane and the Lissajous curve can be plotted to indicate the presence of a defect. In addition, experimental ECT was also conducted on specimens with manufacturing flaws and operational damage using the Eddyfi Reddy ECA system.

In this paper, the TEAM workshop problem [15] is first used to verify the 3D FEM simulations conducted in COMSOL multiphysics. A good match is obtained between the experimental results obtained [15] and the 3D FEM simulations conducted in COMSOL multiphysics. A lift-off coil impedance plot was also generated which is similar to the lift-off curve obtained that is obtained by an EC device and then the NDT inspector manually adjusts the phase of the lift-off curve and makes the lift-off signal parallel to the horizontal axis to calibrate the instrument. The results obtained (Figure 1) indicate that we can proceed with a similar simulation strategy for a composite plate.

![Figure 1: (a) Coil impedance plot comparing simulation and experimental results; (b) Coil impedance plot with lift-off curve](image-url)
2. ECT SIMULATION OF THERMOSET CFRP COMPOSITES

An approach similar to the one described in the TEAM workshop problem [15] at the end of the previous section was used to model the behavior of eddy currents due to an air-cored coil placed on top of an eight-layer pristine thermoset CFRP composite with different stacking sequences. Three distinct stacking sequences were used: unidirectional, cross-ply and quasi-isotropic. Table 1 displays the characteristics of the air-cored eddy current coil. Table 2 displays the characteristics of the eight-layer CFRP thermoset laminate. Each lamina can be regarded as a homogeneous and anisotropic layer, and the conductivity tensor $\sigma_n$ of the n-th layer in the global coordinates x, y, z can be expressed as [20]:

$$\sigma_n = R_n^T \sigma_n R_n = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ \sigma_{yx} & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{zz} \end{bmatrix}$$  \hfill (1)

Where:

$$R_n = \begin{bmatrix} \cos \theta_n & \sin \theta_n & 0 \\ -\sin \theta_n & \cos \theta_n & 0 \\ 0 & 0 & 1 \end{bmatrix}$$  \hfill (2)

$$\sigma = \begin{bmatrix} \sigma_L & 0 & 0 \\ 0 & \sigma_T & 0 \\ 0 & 0 & \sigma_T \end{bmatrix}$$  \hfill (3)

Equation (2) is the rotation matrix that transforms the principal coordinates into the global x, y, z coordinates. $\theta_n$ is the rotation angle of the n-th layer. Equation (3) indicates the conductivity tensor with respect to the principal axes of the n-th layer. In equation (3), $\sigma_L$ is 20000 S/m and $\sigma_T$ is 20 S/m.

<table>
<thead>
<tr>
<th>Table 1 Coil characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter (mm)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>3.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2: Laminate characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamina Thickness (mm)</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>0.125</td>
</tr>
</tbody>
</table>

2.1 Frequency response of air-cored EC coil

The frequency response of the air-cored coil was conducted by placing the air-cored coil in a fixed position above pristine thermoset CFRP composites of different stacking sequence and running a frequency sweep from 0.1 kHz to 10 GHz. The frequency response of the air-cored coil above composite plates of different stacking sequences was obtained as a Bode plot. It consisted of the log-log plot of the magnitude and the phase plot of the complex impedance varying...
with increasing frequency for different stacking sequences. The coil resistance and the coil reactance were combined to obtain the coil-impedance plot on a log-log scale which clearly identified three distinct zones as displayed in Figure 2 along with the schematic of the simulation setup in which an air-cored eddy current coil is placed over an eight-layer pristine CFRP thermoset laminate. In zone 1, it is observed that the coil resistance remains constant with increase in frequency. In zone 2 it is observed that as the frequency is increased there is a linear relationship between coil resistance and the coil reactance. It is also observed that there is a clear gap in the coil impedance between a unidirectional laminate and a cross-ply laminate. This zone is a zone of interest and the frequencies in this zone can be used to identify flaws such as fiber misorientation, fiber waviness. In zone 3, non-linear effects seem to be arising with increase in frequency.

Figure 2 (a) Schematic configuration of air-cored coil over eight-layer CFRP laminate; (b) Coil impedance plot for different stacking sequences for increasing frequencies

2.2 Fiber misorientation detection in a unidirectional thermoset CFRP composite

A \([0]_8\) unidirectional CFRP composite was modeled with a fiber misorientation domain in the second layer and an air-cored coil was placed above it to model the ECT detection of the misorientation zone at a frequency of 800 kHz. The misorientation zone was assigned different misorientation angles (\(\theta\)) and the material properties were calculated based on the conductivity tensor given by equations (1), (2) and (3). Table 1 displays the properties of the air-cored eddy current coil and Table 2 displays the properties of the unidirectional thermoset CFRP composite. Figure 3 displays the schematic configuration of the air-cored coil scanning over the eight-layer unidirectional CFRP composite with the fiber misorientation domain. Figure 4 displays the original coil impedance plot and the compensated coil impedance plot. From the results obtained, we can observe that as the air-cored eddy current coil is scanned from the top of the misorientation domain (0 mm) and away (18 mm) from the fiber misorientation the coil impedance begins to approach the origin of the Lissajous curve where both the real and imaginary part of the impedance is zero (pristine area).

Figure 3: Schematic configuration of air-cored coil over eight-layer unidirectional CFRP composite with fiber misorientation
2.3 Fiber waviness detection in unidirectional thermoset CFRP composite

A scenario very similar to the one described in the previous section was used to model the fiber waviness detection in a unidirectional thermoset CFRP composite. The fiber waviness zone was divided into four equal subdomains and assigned misorientation angles ($\theta$) of 45°, 30°, -30°, -45° to simulate an in-plane fiber waviness. The schematic configuration of modeling the fiber waviness is displayed in Figure 5 along with the compensated coil impedance plot with lift-off. We can observe that as the air-cored eddy current coil is scanned from the top of the fiber waviness domain (0 mm) and away (18 mm) from the fiber waviness, the coil impedance begins to approach the origin of the Lissajous curve where both the real and imaginary part of the impedance is zero (pristine area).

2.4 Embedded wrinkle detection in crossply thermoset CFRP composite

A [0/90]$_{25}$ crossply CFRP composite was modeled with an embedded wrinkle and an air-cored coil was placed above it to model the ECT detection of embedded wrinkle. The embedded wrinkle was modeled as a noodle along the width of the composite with an elliptical cross-section and assigned a conductivity tensor similar to the 90° laminas. The properties of the air-cored eddy current coil and the crossply thermoset CFRP composite are similar to the ones used previously. Figure 6 displays the schematic configuration of the air-cored coil scanning over the eight-layer crossply CFRP composite with the embedded wrinkle domain along with the compensated coil impedance plot with lift-off. From the results obtained, we can observe that as the air-cored eddy current coil is scanned from the top of the embedded...
wrinkle domain (0 mm) and away (18 mm) from the embedded wrinkle the coil impedance begins to approach the origin of the Lissajous curve where both the real and imaginary part of the impedance is zero (pristine area).

**2.5 Embedded polymer canyon detection in crossply thermoset CFRP composite**

A scenario very similar to the one described in the previous section was used to model the embedded polymer canyon detection in a crossply thermoset CFRP composite. The embedded polymer canyon was modeled as a noodle along the width of the composite with a rectangular cross-section and assigned an insulator conductivity. The properties of the air-cored eddy current coil and the crossply thermoset CFRP composite are similar to the ones used previously. Figure 7 displays the schematic configuration of the air-cored coil scanning over the eight-layer crossply CFRP composite with the embedded polymer canyon along with the compensated coil impedance plot with lift-off. From the results obtained, we can observe that as the air-cored eddy current coil is scanned from the top of the embedded polymer canyon domain (0 mm) and away (18 mm) from the embedded polymer canyon the coil impedance begins to approach the origin of the Lissajous curve where both the real and imaginary part of the impedance is zero (pristine area).

**2.6 Out-of-plane fiber waviness detection in crossply thermoset CFRP composite**

A scenario very similar to the one described in the previous section was used to model the out-of-plane fiber waviness detection in a crossply thermoset CFRP composite. The fiber waviness zone was divided into 2 equal subdomains and...
assigned misorientation angles (θ) of 45°, 30°, -30°, -45° in the first subdomain and -45°, -30°, 30°, 45° in the second subdomain to simulate an out-of-plane fiber waviness. The properties of the air-cored eddy current coil and the crossply thermoset CFRP composite are similar to the ones used previously. Figure 8 displays the schematic configuration of the air-cored coil scanning over the eight-layer crossply CFRP composite with the out-of-plane fiber waviness domain along with the compensated coil impedance plot with lift-off. From the results obtained, we can observe that as the air-cored eddy current coil is scanned over the out-of-plane fiber waviness domain the coil impedance changes from pristine to damaged and then back to pristine reading in the Lissajous curve.

![Final position of Coil](image1)

![Out-of-plane Fiber waviness orientation](image2)

Figure 8: (a) Schematic configuration of air-cored coil over eight-layer unidirectional CFRP composite with out-of-plane fiber waviness; (b) Compensated coil impedance plot with lift-off

### 3. EXPERIMENTAL ECT OF THERMOSET CFRP COMPOSITES

#### 3.1 Experiments on crossply thermoset CFRP composite specimen with embedded wrinkle

A [90/0]_6 crossply composite was manufactured using the CYCOM ® 5320-1 epoxy resin system with the Hexcel IM7 12K fiber in a compression molding (hot press) machine with the manufacturers cure cycle. A wrinkle was introduced between the first and the second layer of the composite by rolling up prepreg into a noodle shape and aligning it with the 0° fiber direction (Figure 9).

![Figure 9](image3)

Figure 9: (a) Cure cycle; (b) Prepreg layup; (c) Final composite plate (355 mm x 355 mm x 1.5 mm) with embedded wrinkle
3.1.1 Experimental ECT

Experimental ECT was conducted on the [90/0]_6 crossply composite specimen using the Eddyfi Reddy Eddy Current Array (ECA) scanner connected with I-Flex probes. Figure 10 displays the Eddyfi Reddy instrument and the two types of I-Flex probes that were used for the experiments. The first I-Flex probe had a central frequency of 250 kHz and a maximum frequency of 525 kHz with a coverage width of 56 mm. The second I-Flex probe had a central frequency of 500 kHz and a maximum frequency of 800 kHz with a smaller coverage width of 34 mm. The four frequencies, 250 kHz, 525 kHz, 500 kHz and 800 kHz were explored for the detection of the embedded wrinkle in the crossply composite specimen. The experimental setup consisted of Eddyfi Reddy and an I-Flex probe chosen from the two available probes.

![Figure 10](image_url)

Figure 10: (a) Eddyfi Reddy; (b) First I-Flex probe with a coverage of 56 mm operating at 250 kHz and 525 kHz; (c) Second I-Flex probe with a coverage of 34 mm operating at 500 kHz and 800 kHz

ECT experiments were conducted from the top-side as well as the bottom-side of the CFRP specimen to see if the embedded wrinkle can be detected from both sides of the specimen. Figure 11 displays the results obtained from the top-side ECA scans for different probes and frequencies and Figure 12 displays the results obtained from the bottom-side ECA scans.

![Figure 11](image_url)

Figure 11: Top-side ECA scan of specimen with embedded wrinkle at (i) 250 kHz, (ii) 525 kHz, (iii) 500 kHz and (iv) 800 kHz
3.1.2 Ultrasonic immersion tank inspection

Ultrasonic C-scans were conducted in the ultrasonic immersion tank on the CFRP specimen with embedded wrinkle. A 10 MHz, 1" focused, 0.375" diameter transducer was used for conducting the C-Scans. The experimental setup is displayed in Figure 13. Post-processing of the data obtained from the ODIS software interface is able to give us a clear C-scan, B-scan and A-scans in the pristine and wrinkled area of the specimen as displayed in Figure 14.
3.2 Experiments on crossply thermoset CFRP composite specimen with embedded polymer canyon

A [0/90]_{2S} crossply composite was manufactured using the CYCOM ® 5320-1 epoxy resin system with the Hexcel IM7 12K fiber in a compression molding (hot press) machine with the manufacturers cure cycle. A polymer canyon was introduced between the first and the second layer of the composite aligning a polymer rod of 3 mm diameter with the 90° fiber direction (Figure 9).

3.2.1 Experimental ECT

Experimental ECT was conducted on the crossply [0/90]_{2S} composite specimen using the Eddyfi Reddy Eddy Current Array (ECA) scanner connected with I-Flex probes. Similar to the previous scenario, four frequencies, 250 kHz, 525 kHz, 500 kHz and 800 kHz were explored for the detection of the embedded polymer canyon in the crossply composite specimen. The experimental setup consisted of Eddyfi Reddy connected to an I-Flex probe chosen from the two available probes.

ECT experiments were conducted from the top-side as well as the bottom-side of the CFRP specimen to see if the embedded wrinkle can be detected from both sides of the specimen. Figure 16 displays the results obtained from the
top-side ECA scans for different probes and frequencies and Figure 17 displays the results obtained from the bottom-side ECA scans.

Figure 16 Top-side ECA scan of specimen with embedded polymer canyon at (i) 250 kHz, (ii) 525 kHz, (iii) 500 kHz and (iv) 800 kHz

Figure 17 Bottom-side ECA scan of specimen with embedded polymer canyon at (i) 250 kHz, (ii) 525 kHz, (iii) 500 kHz and (iv) 800 kHz
3.2.2 Ultrasonic immersion tank inspection

Ultrasonic C-scans were conducted in the ultrasonic immersion tank on the CFRP specimen with embedded polymer canyon. A 10 MHz, 1" focused, 0.375" diameter transducer was used for conducting the C-Scans. The experimental setup is displayed in Figure 13. Post-processing of the data obtained from the ODIS software interface is able to give us a clear C-scan, B-scan and A-scans in the pristine and wrinkled area of the specimen as displayed in Figure 14.

![Figure 18: (a) C-scan; (b) B-scan; (c) Pristine area A-scan (d) Damaged area A-scan](image)

3.3 Experiments on wrinkled CFRP composite specimens from Boeing

Three wrinkled specimens were supplied by Boeing, namely, Wrinkle 1 specimen, Wrinkle 2 specimen and Wrinkle 3 specimen. All the specimens have 48 plies with Wrinkle 1 and Wrinkle 2 specimens being unsymmetrical laminates and Wrinkle 3 specimen being a cross-ply laminate. The total thickness of Wrinkle 1 and Wrinkle 2 specimens was 8.84 mm. The average total thickness of Wrinkle 3 specimen was 8.27 mm. The L/d ratio of the wrinkle of these 3 specimens is displayed in the images in Figure 19 along with high resolution cross-sectional images of each specimen at 4800 dpi. The cross sectional scans are able to display the out-of-plane waviness caused by the embedded wrinkle and are also used to imply the clear meaning of the L/d ratio for the wrinkle of each specimen.

![Figure 19: (a) Wrinkle 1 specimen; (b) Wrinkle 2 specimen; (c) Wrinkle 3 specimen](image)
3.3.1 Experimental ECT

Experimental ECT was conducted on the three composite specimens using the Eddyfi Reddy Eddy Current Array (ECA) scanner connected with I-Flex probes. Two types of I-Flex probes were used for the experiments similar to the earlier scenarios. The four frequencies, 250 kHz, 525 kHz, 500 kHz and 800 kHz were explored for the detection of wrinkles in each of the three specimens. The experimental setup consisted of Eddyfi Reddy connected to an I-Flex probe chosen from the two available probes.

ECT experiments were conducted from the top-side as well as the bottom-side of each specimen to see if the wrinkles can be detected from both sides of the specimens Figure 20 displays the results obtained from the top-side ECA scans for different probes and frequencies used on Wrinkle 1 specimen and Figure 21 displays the results obtained from the bottom-side ECA scans. Figure 22 displays the results obtained from the top-side ECA scans for different probes and frequencies used on Wrinkle 2 specimen and Figure 23 displays the results obtained from the bottom-side ECA scans. Figure 24 displays the results obtained from the top-side ECA scans for different probes and frequencies used on Wrinkle 3 specimen and Figure 25 displays the results obtained from the bottom-side ECA scans.

![Figure 20: Top-side ECA scan of Wrinkle 1 specimen at (i) 250 kHz, (ii) 525 kHz, (iii) 500 kHz and (iv) 800 kHz](image)

![Figure 21: Bottom-side ECA scan of Wrinkle 1 specimen](image)
Figure 21: Bottom-side ECA scan of Wrinkle 1 specimen at (i) 250 kHz, (ii) 525 kHz, (iii) 500 kHz and (iv) 800 kHz

Figure 22: Top-side ECA scan of Wrinkle 2 specimen at (i) 250 kHz, (ii) 525 kHz, (iii) 500 kHz and (iv) 800 kHz
Figure 23: Bottom-side ECA scan of Wrinkle 2 specimen at (i) 250 kHz, (ii) 525 kHz, (iii) 500 kHz and (iv) 800 kHz

Figure 24: Top-side ECA scan of Wrinkle 3 specimen at (i) 250 kHz, (ii) 525 kHz, (iii) 500 kHz and (iv) 800 kHz
The embedded wrinkles in both the Wrinkle 1 specimen and Wrinkle 2 specimen were able to be detected at all frequencies using both the I-Flex probes. The embedded wrinkle in the Wrinkle 3 specimen was unable to be detected from the top-side scan using the first probe but was partially detectable using the second probe with high noise. The embedded wrinkle in the Wrinkle 3 specimen was successfully detected using both the probes from the bottom-side scan.

### 3.3.2 Ultrasonic immersion tank inspection

Ultrasonic C-scans were conducted in the ultrasonic immersion tank on the three wrinkled specimens. A 10 MHz, 1-inch focused transducer was used for conducting the C-Scans. Post-processing of the data obtained from the ODIS software interface is able to give us a C-scan, B-scan and A-scans in the pristine and wrinkled area of the specimen as displayed in f26, f27 and f28.

![Figure 25: Bottom-side ECA scan of Wrinkle 3 specimen at (i) 250 kHz, (ii) 525 kHz, (iii) 500 kHz and (iv) 800 kHz](image)

![Figure 26: (a) C-scan; (b) B-scan; (c) Pristine area A-scan (d) Damaged area A-scan](image)
Figure 27: (a) C-scan; (b) B-scan; (c) Pristine area A-scan (d) Damaged area A-scan

Figure 28: (a) C-scan; (b) B-scan; (c) Pristine area A-scan (d) Damaged area A-scan
4. SUMMARY, CONCLUSIONS AND FUTURE WORK

4.1 Summary

In this paper, the TEAM problem 15 [15] was used to validate the ECT simulation methodology and a good match between the simulation results and experimental results from was observed.

The first set of simulations was conducted on CFRP composite plates of different stacking sequences. The impedance was calculated and its frequency response was obtained over a wide frequency range, 100 Hz – 10 GHz. We found that the coil reactance \( X(\omega) \) varies almost linearly with frequency when plotted on log-log scale. We also found that the coil resistance \( R(\omega) \) has a much more interesting behavior which can be separated into three zones: Zone 1, in which the coil resistance hardly changes; Zone 2 (230 kHz–450 MHz), in which the coil resistance varies almost linearly with frequency on log-log scale for the unidirectional layup but nonlinearly for the other layups, and Zone 3 in which it varies almost linearly for all layups. Thus, it seems that Zone 2 is quite sensitive to CFRP composite layup, and, by implications, to deviations/defects in the actual layup when compared with the layup prescribed in the composite design specifications. Subsequently, we used ECT simulation to investigate detection sensitivity for various manufacturing flaws such as fiber misorientation, fiber waviness, embedded wrinkle, embedded polymer canyon, and out-of-plane waviness. It was found that these manufacturing defects induce changes in the impedance response that could be used to detect such flaws in a production environment. This methodology would also be applicable to operational damage.

This work also involved a large number of experiments. Experimental ECT scans were conducted on in house manufactured CFRP specimens manufactured with embedded wrinkle and a polymer canyon as well as on wrinkled specimens that were supplied by Boeing. Section 3 describes experimental ECT of several CFRP specimens with built in defects: USC embedded wrinkle specimen, USC embedded polymer canyon specimen, and Boeing out-of-plane waviness specimens. We used our Eddyfi Ready ECA equipment and I-Flex probes with a maximum frequency of 800 kHz. Besides ECT, we also performed ultrasonic water-tank inspection scanning of all specimens. We found the ECT was able to detect the flaws embedded in all specimens, in some situations even better that ultrasonic scanning.

4.2 Conclusions

The correctness of our ECT simulation using COMSOL software was successfully verified using the TEAM Workshop Problem 15 of an aluminum plate with a rectangular slot; the coil impedance changes moved over the rectangular slot towards a pristine region showed a good match with experimental data.

Frequency response plot indicated a zone of interest (zone 2) where there was a linear relationship between the coil resistance and the coil reactance with increasing frequency when plotted on log-log scale. This zone indicated a significant change in the coil resistance with staking sequence, e.g., between a unidirectional laminate compared with an angle-ply laminate. This difference is important for ECT detection of manufacturing flaws such as fiber misorientations, fiber waviness, wrinkling, etc and can be extended to the detection of operational damage.

ECT simulation of CFRP composite plates with simulated damages such as fiber misorientation, waviness, wrinkling, etc. indicated that the changes in coil impedance were sufficient to enable the detection of such manufacturing flaws; these impedance changes were observed as the coil was moved between pristine and flawed areas.

Experimental ECT scans confirmed the capability of detecting manufacturing flaws in specially built specimens. In these experiments, we investigated in house manufactured CFRP specimens with an embedded wrinkle and with a polymer canyon. We also investigated three out-of-plane wrinkled specimens supplied by Boeing. The ECT experiments were compared with ultrasonic scanning tests performed in the water tank. The results demonstrated the capability of our Eddyfi Reddy system with I-Flex probes to detect manufacturing flaws in CFRP composites.

Based on theoretical and experimental results presented in this paper, it appears that ECT is a promising methodology for detecting manufacturing defects in CFRP composites. In some cases, ECT was able to detect flaws that other NDI techniques, e.g., ultrasonics, were unable to detect.

An invention disclosure [21] covering our novel findings has been prepared and forwarded to Boeing.

4.3 Future work

The eddy current methodology and equipment currently existing for metals do not suit very well for CFRP composites. As shown by simulations described in this report, the use of eddy current testing in CFRP composites would be more...
sensitive to hidden defects if performed at much higher frequencies than available in the current equipment. Thus, a sustained R&D effort seems necessary to explore the development of novel eddy current equipment and methodologies more suitable for CFRP composites than those currently available.

Further work could be performed towards the practical application of the research results presented in this paper by exploring the possibility of eddy current nondestructive inspection to operational damage in CFRP composites. More computer simulations and equipment development could be conducted independently or in collaboration with an industrial partner.

ACKNOWLEDGEMENT

The financial support of The Boeing Company through SSOW-BRT-W0915-0005 is thankfully acknowledged.

REFERENCES


