Non-Destructive Assessment of Fiber Alignment in CFRP using Eddy Current Testing with Differential Type Probe

Hiroyuki KOSUKEGAWA¹, Yuki YOSHIKAWA¹, Ryoichi URAYAMA¹, Tetsuya UCHIMOTO¹, Toshiyuki TAKAGI¹
¹Tohoku University, Sendai, Japan
Contact e-mail: kosukegawa@wert.ifs.tohoku.ac.jp

Abstract. Carbon fiber reinforced plastic (CFRP) has been increasingly employed for various industries such as aviation and automotive. Therefore, the establishment of non-destructive testing for CFRP in various stages in its life cycle is required. Eddy current testing (ECT) could detect the defects related to carbon fiber such as misalignment of fiber, which are hardly detectable by ultrasonic testing (UT). Therefore, ECT has possibility to be a non-destructive diagnosis method for CFRP complementing UT.

The information of fiber alignment in CFRP is important to grasp the mechanical characteristics of composite and to repair damaged products. Because the density of fiber in transverse direction in CFRP is distributed, it is possible to detect the alignment of fiber by using a differential type probe even at relatively low frequency; ECT using an absolute type probe needs high frequency of 10 MHz ~ 100 MHz that inducing more noise because of low electrical conductivity of carbon fiber. In this study, we verify the detectability of alignment of carbon fibers in CFRP by ECT with a differential type probe.

Flat CFRP specimens with a thickness of 5 mm were fabricated by laminating 21 or 24 prepregs and by curing them with hot press at 130°C, 0.5 MPa. Eddy current signal amplitude by using a mutual induction-differential type probe with two pickup circular coils in one circular exciting coil was obtained by scanning the surface of CFRP specimens with a lift-off 0 mm at a frequency of 2 MHz. The arrangement direction of the two pickup coils were set in various directions with respect to the orientation of the fiber; 0 degree means the same direction of carbon fiber of the surface layer.

Eddy current signal amplitude obtained by C-scan of angle-ply CFRP laminates exhibits a complex image with significant contrast showing the alignment of fibers inside CFRP. By applying an inverse spatial Fast Fourier Transformation to the C-scan image, we can recognize the alignment of fiber at respective layers by separating orientation by angle.

Eddy current signal amplitude of CFRP with one orthogonal layer in 21 layers at 2 MHz also shows the significant contrast related to the fiber orientation. The variance of signal amplitude was evaluated. The fiber orientation near the surface layer can be identified well. Additionally, eddy current density simulated by finite element analysis can explain the detectability of ECT with a differential type probe.

These results indicate that the ECT with differential type probe has good detectability for assessment of fiber alignment at even relatively low frequency.
1. Introduction

Carbon fiber reinforced plastic (CFRP) has been increasingly employed for various industries as construction materials, with the viewpoints of its superior specific modulus and strength. Therefore, it is important to establish methods to maintain CFRP structures in durability, which induces an improvement of reliability of structure. These methods can be used at various stages in the lifecycle of CFRP.

Non-destructive testing (NDT), which detects various types of defects without breaking the material, is useful way to maintain structures. Ultrasonic testing (UT) is the most common method to detect the defects in CFRP. UT is mainly used for detection of delamination, foreign bodies and sometimes voids in CFRP. It is adequate for detecting the defects originated from matrix resin. UT, however, is not suitable for defects deriving from carbon fiber such as rupture, misalignment and shortage of carbon density due to its low resolution. Especially, assessment of alignment of carbon fiber is important to grasp the mechanical characteristics and to repair the damaged bodies. Therefore, a method supplementing these drawbacks of UT is required.

Eddy current testing (ECT), which can sense difference of electromagnetic properties by induction current, has possibility to detect the defects originated from carbon fiber. ECT is sensitive for the change of electrical resistance in target material. Then, it can detect the defects related to carbon fiber in CFRP because variation of carbon fiber may affect the electrical properties. Furthermore, ECT is also sensitive for the change of electrical resistance on the surface of material whereas UT is not suitable for detection of the defects near the surface.

Several researchers have reported the possibility and performance of ECT in NDT method of CFRP. Lange and Mook [1] describe usefulness of ECT for detection of orientation of carbon fiber in 1994. ECT can detect the orientation of carbon fiber due to its anisotropy of electrical resistance. Schmidt [2] and Heuer [3,4] also describe about the detection and evaluation of alignment of carbon fiber.

Schmidt describes in his paper [2] that the methods with half transmission probe and high frequency absolute probe are suitable for NDT method of CFRP. These methods, however, requires high frequency more than 10 MHz, and this condition needs a delicate mechanism and device which prevents the test signal from significant noises. It may reduce the accuracy of measurement.

We suggest ECT at relatively lower frequency with a mutual induction-differential type probe to detect alignment of carbon fiber. Differential type probe has low noise because two or more pickup coils can cancel mutual equivalent noise. In this study, the detectability of alignment of carbon fiber of laminated CFRP is investigated by using differential type probe at frequency of less than 10 MHz. Additionally, finite element analysis of eddy current distribution in laminated CFRP is also carried out to discuss ECT results.

2. Material and Methods

2.1 Preparation of CFRP specimens

Various flat specimens of CFRP laminates were fabricated by autoclave process and prepreg compression moulding (PCM) process according to the purpose in this study. Autoclave process was employed to fabricate a unidirectional oriented CFRP (UD-ply) and an angle-ply CFRP. Furthermore, CFRP specimens with one orthogonal layer in laminates were fabricated by PCM process.
In autoclave process, the preform was prepared by laminating 24 unidirectional prepregs (TR380G250S, Mitsubishi Rayon Co., Ltd.). The preform was cured at 130°C and compressed at 0.5 MPa for 120 min. The lamination pattern of angle-ply was [(+45/0/-45/90)]_S. The preform for CFRP with one orthogonal layer was prepared by laminating 21 prepregs. The preform was compressed at 0.5 MPa and cured at 130°C for 120 min. The orthogonal layer was set at 1st, 2nd, 3rd, 5th and 11th layer from the surface; these specimens were labelled as LP1, LP2, LP3, LP5, LP11, respectively. The orientation of other layers was same. The dimension of all specimens is 150 × 150 × 5.5t (mm).

2.2 ECT setup

The excitation signal was transmitted from a multifunction synthesizer (Wavefactory, WF1996, NF Co.) to exciting coil. The detection signal obtained by two pickup coils was amplified by a differential amplifier (5307, NF Co.). The amplified signal at specific frequency was selected by a lock-in amplifier (SR844RF, Stanford Research Systems). The ECT signal is an amplitude of induced electromotive force generated on pickup coils. A data acquisition device was used to convert the analog signal to digital one, and the data was obtained with a computer.

We used a mutual induction-differential type probe. The probe has one exciting coil with 185 turns and two pickup coils with 340 turns. The dimension of exciting coil is inner diameter of 4.0 mm and outer diameter of 4.5 mm, and that of pickup coils is inner diameter of 0.77 mm and outer diameter of 2.0 mm.

The two pickup coils were set inside the exciting coil. The signals obtained from these two coils cancelled out by mutual equivalent noise. When these two pickup coils are arranged parallel to the orientation of carbon fiber in UD-ply, the signal exhibits minimum intensity. As the angle of pickup coils and carbon fiber becomes higher, the signal amplitude shows larger. The significant difference in signal amplitude is observed more than 5 degrees as shown in Figure 1. The signal amplitude shows the maximum intensity when the pickup coils are arranged orthogonal to the orientation of carbon fiber in UD-ply.

The probe scanned the surface of CFRP in the area of 20 × 20 mm² on the center of the plate specimen. The edge effect of eddy current was sufficiently low. The scan pitch was 0.1 mm, and the measurement frequency was 2 MHz. The exciting voltage was 0.7 V. For CFRP specimens with one orthogonal layer other than LP1, the two pickup coils were arranged parallel to the orientation of carbon fiber of the 1st ply and scanned to the direction of the orientation of fiber of the surface layer. For LP1, the pickup coils were arranged orthogonal to the orientation of carbon fiber of the 1st ply.

![Fig. 1. Relationship between ECT signal amplitude in UD-ply and angle of two pickup coils. The orientation of carbon fiber is set 0 degree.](image-url)
2.3 Signal processing

Since the differential signal obtained by two pickup coils has noise, then it was processed with spatial frequency filter by a two-dimensional fast Fourier transform (2D-FFT). The C-scan image was process with a two-dimensional discrete FFT, and the complex function $f(x, y)$ of ECT signal was obtained. The complex function was converted to another complex function, $F(u, v)$ by using the following equation (1):

$$F(u, v) = \frac{1}{MN} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x, y) \exp \left( -j2\pi \left( \frac{ux}{M} + \frac{vy}{N} \right) \right)$$  \hspace{1cm} (1)

Here, $M$ and $N$ are arbitrary natural numbers, $u$ and $v$ are the frequency component of the spatial wave in the $x$ direction and $y$ direction, respectively.

The signal was filtered with high-pass filtering on the picture elements at certain frequency. The C-scan image, which removes spatial noise, was obtained by performing an inverse 2D-FFT.

2.4 Variance of ECT signal

The variance $V$ of the ECT signal amplitude in the scanned area was calculated to evaluate the detectability for the orientation of carbon fiber by using following equation (2):

$$V = \frac{1}{n} \sum_{i=1}^{n} (X_i - \bar{X})^2$$  \hspace{1cm} (2)

Here, $n$ is the number of measured points, $X_i$ is the ECT amplitude at the measured points and $\bar{X}$ is the average of the amplitude.

2.5 Finite element analysis of eddy current density

To discuss the results obtained from ECT scan of CFRP with one orthogonal layer, numerical simulation of eddy current density in CFRP was performed. A commercial finite element analysis software PHOTO-Series EDDY jo (Photon Co., Ltd.) was employed for numerical simulation in this study. The frequency was 2 MHz. The full model was rectangular shape with a dimension of $100 \times 100 \times 2.4$ (mm), and the analysis area was a quarter region of the full model. The mesh number of the analysis area was 384,000 elements. The circular exciting coil was set on the center of the full model. The geometry and turn number of the exciting coil was the same as ECT experiment setup.

The CFRP model was composed of two kinds of layers: 0 degree and 90 degree orientation. These two layers have anisotropic electrical conductivity as shown in Table 1 [5]. The model has 10 layers with a thickness of 0.24 mm and each layer has 6 meshes in thickness direction.

<table>
<thead>
<tr>
<th>Table 1. Anisotropic electrical conductivity (S/m) of CFRP model in numerical analysis [5]. $\sigma_x$ and $\sigma_y$ is the electrical conductivity in the direction of x-axis and y-axis, respectively. $\sigma_z$ is the electrical conductivity in the direction of the thickness of CFRP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction of carbon fiber</td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>0 degree</td>
</tr>
<tr>
<td>90 degree</td>
</tr>
</tbody>
</table>
3. Results and Discussion

3.1 Identification of layers of angle-ply CFRP

We scanned an angle-ply CFRP laminate by using two pickup coils arranged in x- and y-axis (0º and 90º). The signals in both directions were filtered with spatial frequency filter, and the filtered results of both directions were added. Figure 2 (a) shows the C-scan image of angle-ply CFRP laminate after high-pass spatial filtering process along each axis. Figure 2 (b) shows the 2D-FFT image of Figure 2 (a). This image indicates that the angle-ply laminate is composed of four orientations of carbon fiber (+45, 0, −45, 90). An inverse FFT was applied to Figure 2 (b) to separate the respective orientation of carbon fiber.

By applying an inverse FFT, we can separate the C-scan image of an angle-ply CFRP laminate into four directions of carbon fiber. Figure 3 shows the inverse FFT image obtained by applying 2D-FFT filtering process to the image of C-scan of the angle-ply CFRP. Figure 3 indicates that we can identify the orientation of carbon fiber of not only the surface layer but also inner layers. The signals, however, may be influenced by some other layers with the same orientation. In order to identify each layer of the same orientation, it is needed to further separate the signal with other parameters.

![Fig. 2. (a) C-scan image and (b) 2D-FFT image of angle-ply CFRP laminates.](image)

![Fig. 3. Inverse FFT image obtained by applying 2D-FFT filtering the C-scan image of Figure 1: (a) +45 degree, (b) 0 degree, (c) −45 degree and (d) 90 degree.](image)

3.2 Evaluation of detectability by using CFRP with one orthogonal layer

We attempted to evaluate the detectability of the orientation of CFRP with one orthogonal layer with respect to signal amplitude. The C-scan images of CFRP with one orthogonal layer at 2 MHz are shown in Figure 4. When the position of orthogonal layer is deep, the difference of contrast describing carbon fiber shows insignificant. The variance of the
signal amplitude was shown in Figure 5. The variance of ECT signal amplitude indicates that ECT with differential type probe at low frequency can identify the orientation of carbon fiber near the surface layer of CFRP. On the other hand, the difference of variance becomes insignificant below 3rd layer. To realize the alignment of carbon fiber at deep layer, it is important to consider other parameters such as frequency and phase than amplitude.

![Figure 4. C-scan image of CFRP with one orthogonal layer at the frequency of 2 MHz. LP means “layer of perpendicular ply”.

![Figure 5. Variance of ECT signal amplitude of CFRP shown in Fig. 4.](image)

3.3 Numerical analysis of eddy current density of CFRP

Finite element analysis was performed in the case of CFRP with one orthogonal layer. Figure 6 shows the eddy current density on the surface of LP1, LP2 and LP3. The distribution of eddy current is anisotropic and elliptically stretched in accordance with carbon fiber direction of the surface layer. This phenomenon can be explained that eddy current path is stretched in the direction of high conductivity and tightened in the direction of low conductivity of the surface layer [6].

Figure 7 shows the lateral view of the eddy current distribution. Eddy current concentrates near the surface layer and does not penetrate into orthogonal layer. If two pickup coils are arranged orthogonal to the fiber orientation of the surface layer, differential signal amplitude can be affected the most by change of eddy current distribution related to carbon fiber alignment. On the other hand, the influence of orientation of carbon fiber seems not large when orthogonal layer is deeper than 2nd or 3rd layer. Considering the results of numerical analysis and variance of ECT signal shown in Figure 5, ECT using a differential type probe is suitable for assessment of the alignment of fibers near the surface even at relatively lower frequency.
Fig. 6. (a) Top view of analysis area and lateral view zone, (b) top view of eddy current density (A/m²) on the surface of CFRP with one orthogonal layer.

Fig. 7. Lateral view of eddy current density (A/m²) in the CFRP with one orthogonal layer. View areas of A-O and O-B correspond to the lateral view zones shown in Fig. 6. (a).

4. Concluding remarks

- Mutual induction-differential type probe can be used to detect the orientation of carbon fiber in CFRP even at relatively low frequency less than 10 MHz.
- The orientation of carbon fiber according to the layer in CFRP is identified by applying spatial frequency filtering process to a C-scan image.
- With the results of finite element analysis and the variance of the signal amplitude of CFRP with one orthogonal layer, ECT using a differential type probe at low frequency is suitable for assessment of the alignment of carbon fiber near the surface layers.

5. Acknowledgements

This work was partly supported by the JSPS Grant-in-Aid for Challenging Exploratory Research (15K14143) and the JSPS Core-to-Core Program, A. Advanced Research Networks, “International research core on smart layered materials and structures for energy saving”. CFRP specimens were provided by Dr. Motoi Fujishima of Akita Industrial Technology Center.
References