DEVELOPMENT OF A PROBE OF EDDY CURRENT TESTING FOR DETECTION OF IN-PLANE WAVINESS IN CFRP CROSS-PLY LAMINATES

Koichi MIZUKAMI [1], Yoshihiro MIZUTANI [1], Akira TODOROKI [1], Yoshiro SUZUKI [1],
Akiyoshi SATO [2] and Kenshi KIMURA [2]

[1] Tokyo Institute of Technology, Department of Mechanical Sciences and Engineering
[2] IHI AEROSPACE Co., Ltd., Quality Assurance Department
2-12-1-I1-457, Ookayama, Meguro-ku, Tokyo, 152-8550, Japan
kmizukam@ginza.mes.titech.ac.jp

Abstract. When carbon fiber reinforced plastic (CFRP) parts are molded, defects can occur inside the CFRP. Fiber waviness is a deformation of carbon fibers in CFRP, and is one of the process-induced defects that occur in the molded CFRP. Waviness is induced by axial loadings of carbon fiber due to thermal residual stresses. Because fiber waviness causes significant degradation of compressive strength of CFRP structures, nondestructive technique for waviness detection is in great demand. In this study, eddy current-based nondestructive techniques for detection of in-plane fiber waviness in CFRPs are developed. Authors newly propose a test probe specialized for detection of in-plane fiber waviness in cross-ply CFRP. The proposed probe is sensitive to in-plane deformation of eddy current paths, can select inspected layers and the output signal is insensitive to lift-off. We carried out measurement on 20 layer cross-ply laminate with artificially induced in-plane waviness. It was found that the probe can detect waviness up to 18 layers away from the surface of cross-ply CFRP. The minimum size of the detected subsurface waviness has an amplitude of 1.4 mm and a length of 10.5 mm. We verified the effectiveness of the probe and clarified the mechanisms of changes in output signal obtained in the experiments using FEM analyses.

1. Introduction

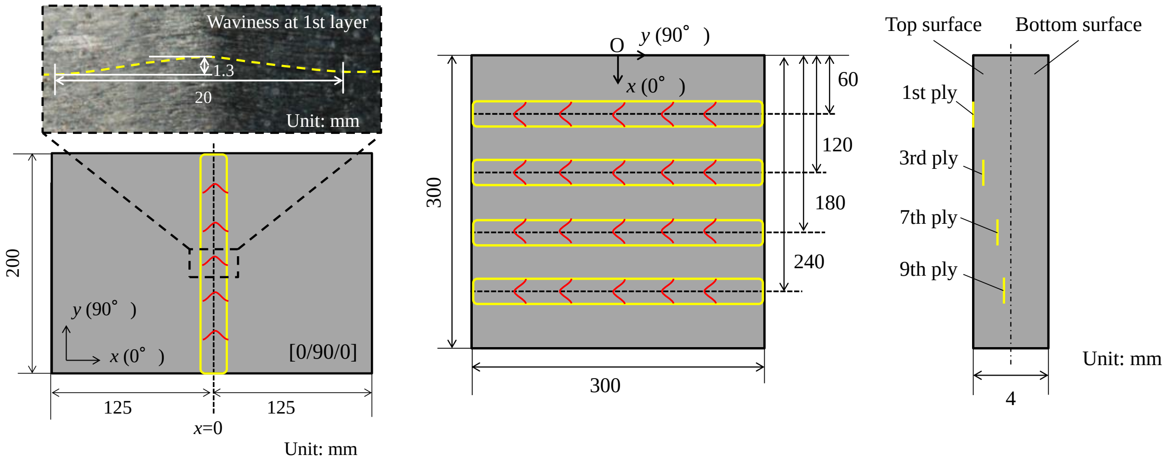
Carbon fiber reinforced plastics (CFRP) has attracted considerable attention in aerospace industries due to their high specific strength and stiffness. Fiber waviness is a deformation of carbon fiber, and is one of the process-induced defects that occur during manufacturing process. Process parameters which affect the development of waviness have already been studied [1-3]. It has been verified that difference in coefficient of thermal expansion between mold and CFRP is the primary cause of waviness development [1, 2]. It has also been reported that initial deflection of carbon fibers affect the initiation of micro-buckling during cooling process [3]. Hence, complete prevention of waviness development is quite difficult. Since waviness cause significant degradation of compressive strength, non-destructive testing method to detect waviness is in great demand. X-ray computed tomography (CT) is considered to be an effective non-destructive method to detect local fiber orientation due to its excellent detectability [4], and is currently in industrial use for waviness detection. Although X-ray CT can offer high sensitivity which is not achievable for other non-destructive methods, it is limited by the geometry of the tested material.

Eddy current testing (ET) is a non-destructive testing method for electrically conductive materials including carbon fiber reinforced composites. ET has been recently applied to defect detection in CFRP. To detect local fiber orientation, earlier studies suggest in-plane rotation of a pair of driver and pickup coil [5-7]. Anisotropic nature of conductivity of CFRP could be identified by measuring the variation of pickup coil output during polar scanning. In addition, high frequency eddy current imaging has been successfully applied to detect local defects in thin CFRP laminates. The effectiveness of textural analyses carried out by high frequency eddy current imaging has been experimentally verified and it was reported that waviness in multidirectional laminates can be visible in that image [8].

In this study, a new eddy current probe specialized for waviness detection is developed. We used a probe which consists of driver coil and pickup coil orthogonal to each other. The probe can choose inspected fiber direction and has high sensitivity to in-plane waviness. Our study focuses on detection of in-plane fiber waviness in CFRP. Detection of out-of -plane waviness is relatively easier for eddy current testing than detection of in-plane waviness. Moreover, out-of-plane motion of fiber is limited in case of thin laminates. Effectiveness of the probe was experimentally investigated using cross-play CFRP specimens with artificially induced in-plane waviness. Moreover, the variation of magnetic field distribution caused by waviness was investigated using finite element method (FEM). Physical background of changes in pickup coil output obtained around waviness could be revealed through the numerical calculations.

2. Materials and method

Figure 1 shows specimens with artificial in-plane waviness used for experiments of eddy current testing. The specimens are cross-ply CFRP laminates. Specimen A shown in Fig. 1(a) is 3 layer cross-ply laminate with a stacking sequence of [0/90/0]. Specimen A has in-plane waviness at 1st layer along its center line. As shown in Fig. 1(a), length and amplitude of waviness at the center of specimen A are 20 mm and 1.3 mm, respectively. Specimen B shown in Fig. 1(b) is 20 layer cross-ply CFRP laminate with a stacking sequence of $[(0/90)_5]_s$. Specimen B has in-plane waviness at different depths. The waviness are induced in 0 degree layers in 1st, 3rd, 7th and 9th layer. The sizes of waviness in specimen B



(a) (b)

Fig. 1 CFRP specimens with artificially induced in-plane fiber waviness. (a) Specimen A, 3 layer cross-ply CFRP laminate [0/90/0]. (b) Specimen B, 20 layer cross-ply CFRP laminate $[(0/90)_5]_s$.

Table 1 Estimated sizes of in-plane waviness measured by X-ray computed tomography.

	Amplitude [mm]	Length [mm]
1st ply	1.9	15.5
3rd ply	3.9	18.8
7th ply	2.6	16.3
9th ply	1.4	10.5

were measured by X-ray computed tomography. Table 1 shows estimated sizes of waviness in specimen B measured along *x* axis in Fig. 1(b).

Figure 2 shows the eddy current probe to detect waviness. As illustrated in Fig. 2, the probe is composed by rectangular driver and pickup coils orthogonal to each other. The pickup coil is placed under the driver coil such that total magnetic flux from the driver coil that penetrates the pickup coil loop becomes zero. When the long side of the rectangular driver coil is directed in fiber direction of cross-ply laminates, eddy currents are induced in the layers of that fiber direction [9]. For example, when the long side of the rectangular driver coil is directed in 0 degree direction of a cross-ply laminate, eddy currents are concentrated in 0 degree layers and only 0 degree layers can be inspected. Hence, the probe can choose fiber direction to be inspected and identify the fiber direction with waviness. During scanning the probe on intact part of the material under test, output voltage of the pickup coil ideally becomes zero because total magnetic flux from the drive current and the eddy currents through the pickup coil loop is zero. On the other hand, when the probe comes around in-plane waviness, the eddy current path is deformed along waviness and the magnetic flux from the eddy currents through the pickup coil is not zero. Therefore, the output voltage of the pickup coil is generated around waviness zones. Since the total magnetic flux through the pickup coil is ideally zero at intact zones, proposed probe is not susceptible to lift-off variation.

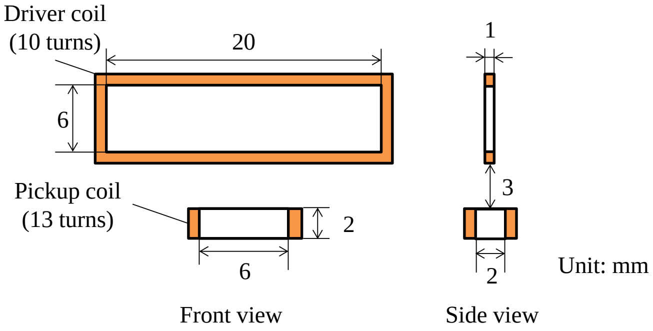


Fig. 2 Schematic of the proposed probe to detect waviness.

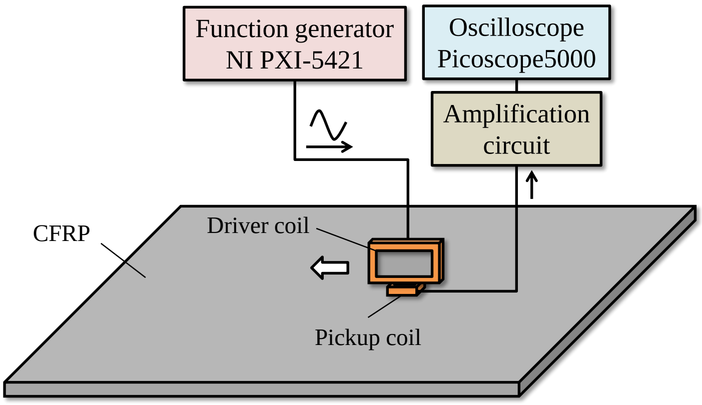
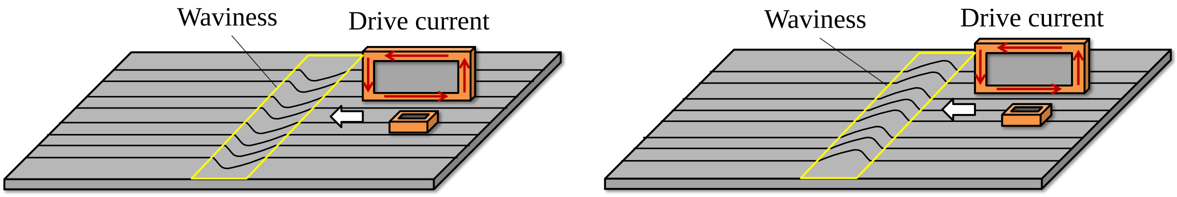


Fig. 3 Experimental setup used for eddy current testing for waviness detection.

Figure 3 shows experimental setup used for waviness detection. Long side of the driver coil was directed in 0 degree direction of CFRP because both specimen A and B have in-plane waviness in 0 degree layers. Sinusoidal voltage with constant amplitude was applied to the driver coil from arbitrary waveform generator (National Instruments, NI PXI-5421). Output voltage of the pickup coil was amplified by 100 times using amplification circuit and measured by oscilloscope (Pico Technology, Picoscope 5000 series). The probe was scanned in *x*-direction in Fig. 1(a) and (b) at 2.5 mm interval. In the measurement for specimen A, drive frequency was 3 MHz and lift-off of the probe was 3 mm. To investigate the effect of waviness direction on variation of pickup coil output, the probe was scanned for two cases shown in Figure 4. For specimen B, drive frequency and lift-off were 500 kHz and 0.5 mm, respectively. Measurements were carried out on the top and bottom surfaces of specimen B to investigate the detectability of subsurface waviness.



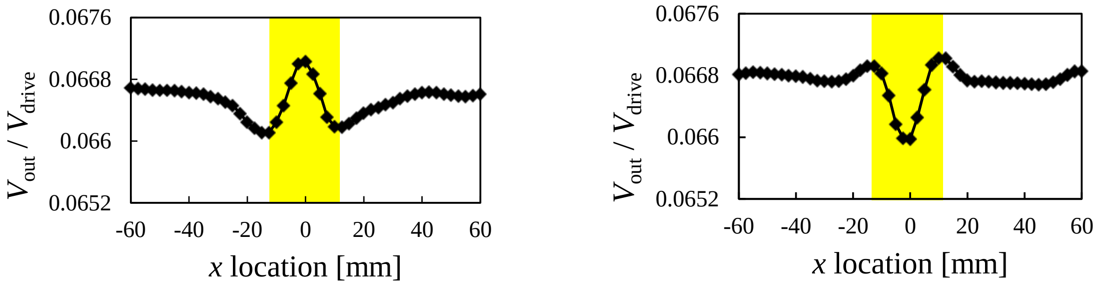
(a) (b)

Fig. 4 Relationship between drive current and waviness direction during testing specimen A. (a) Case 1. (b) Case 2.

3. Results and discussion

Figure 5 shows results obtained in the experiment for specimen A. The horizontal axis denotes the *x* location of the center of the probe. The vertical axis denotes the amplitude of the pickup coil voltage divided by the amplitude of the drive voltage. The vertex of the waviness is located at $x = 0$, and $-10 \text{ mm} < x < 10 \text{ mm}$ represents the waviness zone. As shown in Fig. 5, variations of pickup coil output can be observed around the waviness zone. In Fig. 5(a), output signal has local minimum value at the edge of waviness zone and has local maximum value at the vertex of the waviness. To the contrary, in Fig. 5(b), output signal becomes local maximum at the edge of waviness zone and minimum at the vertex of the waviness. Those results show that the sign of changes in the pickup coil signal depends on the direction of in-plane waviness.

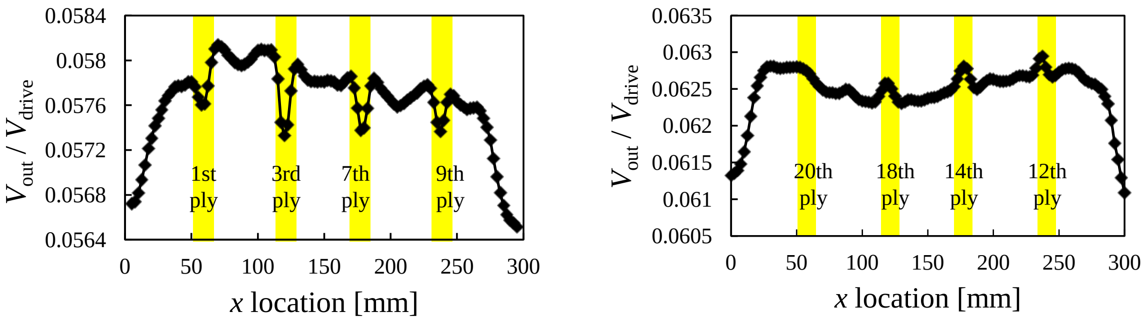
Figure 6 shows results obtained in the experiment for specimen B. The horizontal axis denotes *x* location of the center of the probe. The vertical axis denotes amplitude of the



(a) (b)

Fig. 5 Results obtained from the measurement for specimen A. (a) Case 1. (b) Case 2. (See figure 4.)

pickup coil output divided by that of the drive voltage. Fig. 6(a) shows the results of top surface scanning. Waviness are located at 1st, 3rd, 7th and 9th layer from the surface. Results of bottom surface scanning are presented in Fig. 6(b). In this case, waviness are located at 20th, 18th, 14th and 12th layer from the surface. Fig. 6(a) shows that pickup coil output has local minimum value in the waviness zone. Changes in the output voltage can be observed at the location of all waviness in specimen B. Low values of output signal around $x = 0$ and 300 mm are caused by edge effect. On the other hand, local maximum values of output signal can be observed at the locations of waviness at 12th, 14th and 18th layers. Signal change cannot be seen at the location of waviness at 20th layer. Therefore, the probe could detect waviness 18 layers away from the surface of cross-ply CFRP. In Fig. 6(b), sign of the signal change at the waviness zone is opposite to that in Fig. 6(a). This difference is same as that of Fig. 5 because waviness direction in the bottom surface measurement is opposite to that in the top surface measurement.



(a) (b)

Fig. 6 Results of measurement for specimen B. (a) Top surface. (b) Bottom surface.

Finite element method (FEM) analysis was implemented to verify the results obtained in the experiments. Figure 7 shows analytical model to investigate magnetic field distribution around waviness zone. In the analytical model, a rectangular driver coil was placed above a cross-ply CFRP. Origin of Cartesian coordinate (x, y, z) was set at the center

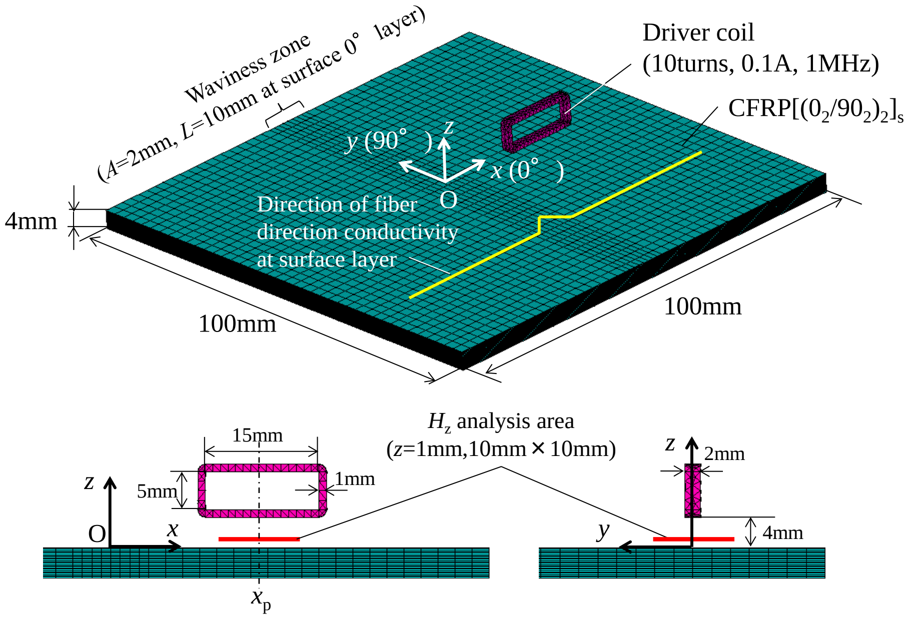
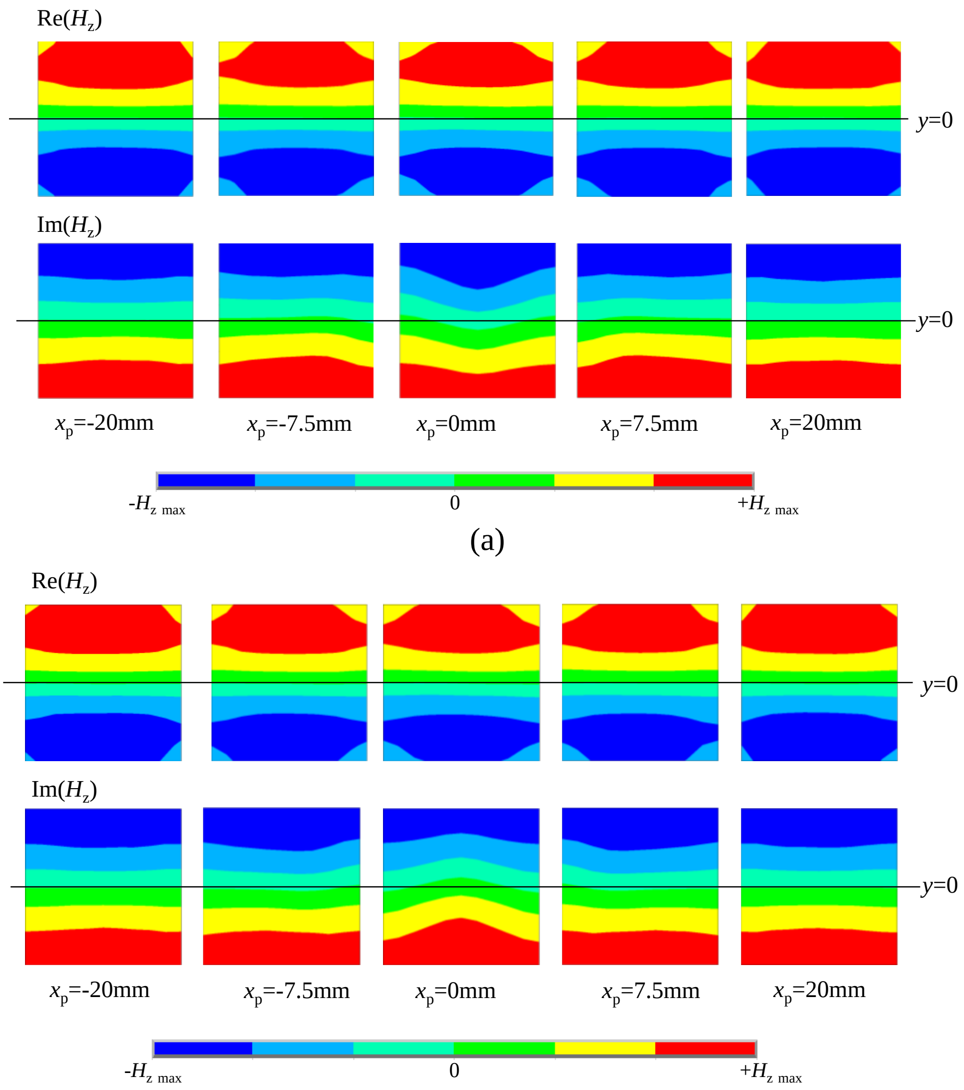


Fig. 7 Analytical model to investigate magnetic field distribution in eddy current testing of the cross-ply CFRP with waviness.

of the CFRP surface. It was assumed that the stacking sequence of the CFRP was $[(0_2/90_2)_2]_s$. Long side of the rectangular coil was directed in 0 degree fiber direction. Waviness was simulated at the surface 0 degree layer of the CFRP over the width direction as described in Fig. 7. The waviness was approximately represented as a triangle wave and was simulated by modifying the direction of conductivities of elements along the triangle wave. The simulated waviness has an amplitude of 2 mm and a length of 10 mm. We calculated the distribution of the z-directional component of the magnetic field in the 10 mm × 10 mm area 3 mm under the driver coil. The x position of the driver coil was defined as x_p. The magnetic field was calculated for x_p = -20, -7.5, 0, 7.5 and 20 mm.

Figure 8 shows the results of FEM analyses. Re(H_z) and Im(H_z) represents real part and imaginary part of the z-directional magnetic field, respectively. Fig. 8(a) denotes the results for in-plane waviness in which fibers are displaced in $-y$ direction. Fig. 8(b) displays the results for fiber displacement in $+y$ direction. As shown in Fig. 8(a), real part of H_z is almost anti-symmetric with regard to $y = 0$ for all locations. This result indicates that pickup coil output is hardly affected by real part of H_z. On the other hand, imaginary part of H_z is



(a)

(b)

Fig. 8 Numerical results of distribution of z-directional magnetic field under driver coil at x_p = -20, -7.5, 0, 7.5 and 20 mm. (a) Results for in-plane waviness in which fibers are displaced in $-y$ direction. (b) Results for in-plane waviness in which fibers are displaced in $+y$ direction.

clearly affected by waviness. At x_p = –20 and 20 mm where the driver coil is away from waviness zone, Im(H_z) is anti-symmetric with regard to y = 0. Since both real and imaginary parts of H_z are anti-symmetric, output voltage of a pickup coil placed under the driver coil becomes 0 at non-defective zone. At x_p= -7.5 and 7.5 mm, where the driver coil is close to the edge of the waviness, Im(H_z) is positive value in the proximity to y = 0. When the driver coil is located right over the waviness zone at x_p= 0, distribution of Im(H_z) is deformed and not anti-symmetric. Moreover, Im(H_z) has negative value near y = 0 at x_p = 0. Those results indicate that phase reversal of pickup coil voltage occur during scanning the probe through waviness. Hence, variations of pickup coil output shown in Fig. 5 originate from the phase reversal of the magnetic field. In Fig. 8(b), the signs of the magnetic field near y = 0 at x_p= -7.5, 0, 7.5 mm are opposite to those in Fig. 8(a). Thus, sign of output signal changes depends on direction of waviness. This is verified by comparing the results shown in Fig. 5(a) and (b). Therefore, physical background of the changes in output signal of the pickup coil could by revealed through FEM analyses.

4. Conclusions

Eddy current probe which consists of rectangular driver and pickup coils orthogonal to each other is newly proposed to detect in-plane fiber waviness in cross-ply CFRP. The probe was used to detect artificially induced in-plane waviness in cross-ply CFRP laminates. Experimental results showed that output signal of the pickup coil has extreme value at the edge of the waviness zone and at the waviness vertex. Moreover, sign of change in output signal was dependent on the direction of fiber displacement in waviness. Detectability of detection of subsurface waviness was investigated using CFRP specimens with waviness at different layers. In-plane waviness 18 layers away from the CFRP surface could be detected by the proposed probe at 500 kHz. Minimum size of the detected subsurface waviness was 10.5 mm in length and 1.4 mm in amplitude. Physical background of signals obtained around waviness was investigated using FEM analysis. It was found that the distribution of imaginary part of the magnetic field was deformed around waviness. FEM analyses showed that phase reversal of pickup coil output occurs during scanning the probe through waviness zone. This result qualitatively agreed with results obtained in experiment. Moreover, results of FEM analyses showed that the sign of signal changes depend on the direction of fiber displacement in waviness.

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