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Research Article

Surface Crack Detection for Carbon Fiber Reinforced Plastic Materials Using Pulsed Eddy Current Based on Rectangular Differential Probe

Jialong Wu,[1,2] Deqiang Zhou,[1,2,3] and Jun Wang[1,2]

[1] *School of Mechanical Engineering, Jiangnan University, Wuxi 214122, China*
[2] *The Key Laboratory for Advanced Food Manufacturing Equipment Technology of Jiangsu Province, Wuxi 214122, China*
[3] *Wuxi G.S Precision Tool Co., LTD, Wuxi 214024, China*

Correspondence should be addressed to Deqiang Zhou; zhoudeqiang@jiangnan.edu.cn

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Aiming at the surface defect inspection of carbon fiber reinforced composite, the differential and the direct measurement finite element simulation models of pulsed eddy current flaw detection were built. The principle of differential pulsed eddy current detection was analyzed and the sensitivity of defect detection was compared through two kinds of measurements. The validity of simulation results was demonstrated by experiments. The simulation and experimental results show that the pulsed eddy current detection method based on rectangular differential probe can effectively improve the sensitivity of surface defect detection of carbon fiber reinforced composite material.

1. Introduction

In recent years, there has been an increasing interest in the use of composite materials, particularly carbon fiber reinforced plastic (CFRP), in the aerospace and renewable energy industries, because of the low weight and improved mechanical properties compared with metals. Components made from CFRP, such as wind turbine blades and aircraft fuselage, have to be tested for quality evaluation after manufacturing and monitoring during in-service operation to increase the component lifetime. To accomplish this, nondestructive testing and evaluation (NDT&E) techniques are used [1].

Stoessel and Burrows et al. used ultrasonic testing method to detect CFRP; it can clearly identify defects. However, this method suffered from a number of disadvantages, including the need for a couplant required for introducing acoustic waves and lack of sensitivity to shallow surface breaking defects [1, 2]. Cheng and Tian and He et al. applied pulsed eddy current thermal imaging method to test defects of CFRP; the defects of surface have been identified by comparing the temperature and thermal gap of imaging. The defects of 2 J and 4 J impacts cannot be detected, the hot area by impact with 6 J and 8 J was concentrated, and the hot area by impacts with 10 J and 12 J was like a circle [3, 4]. However, pulsed eddy current thermal imaging experimental equipment is very expensive with high cost and bad openness. So it is only used in the laboratory now. He et al. (2014) also used scanning pulsed eddy current technique to characterize the different types of defects in CFRP laminates. The results showed that the low energy impact from 4 J to 12 J can be effectively detected and the relationship between impact energy and the peak value of magnetic field intensity was nonlinear [5]. Mook et al. presented a method to reconstruct eddy current distribution in CFRP and a high-frequency eddy current sensor has been developed to detect CFRP. The results showed that rotary probes were capable of detecting fiber orientation, fiber fraction fluctuation, resin rich zones, delamination, and impact damages [6]. Schulze et al. applied an absolute half transmission anisotropic probe to the nondestructive testing of CFRP based on the multifrequency eddy current device. The results showed that the majority of defects of raw carbon fiber materials (RCF) or CFRP can be detected [7]. Koyama et al. proposed an eddy current testing probe named theta which could detect the impact damage of CFRP produced by the energy of 0.25 J with high signal-to-noise ratio [8]. Yin et al. used three multifrequency eddy current sensors to characterize CFRP. Three sensors were designed for bulk conductivity measurements, directionality characterization, and fault detection. The results showed that the conductivity of CFRP was anisotropic; the polar diagrams of the impedance on damaged areas and no damaged areas were different [9, 10]. Angani et al. studied the magnetic field distribution of cylindrical coil axis in the development of digital eddy current testing system. It indicated that the signal of the top of the central axis of cylindrical coil can be considered as the excitation magnetic field; the component of eddy current signal can be improved through the subtraction of top and bottom detection signal [11]. Zhang et al. compared the effect of defect detection of aluminum gear disk by using the absolute cylindrical probe and the differential cylindrical probe. The results showed that the defect detection effect of differential probe was better [12]. The literatures [5–12] mainly described the application of cylindrical probe in the field of NDT&E.

Theodoulidis and Kriezis calculated the impedance of rectangular testing coils. They found that when rectangular sensors are placed horizontally, the distribution of eddy current becomes more intensive on both sides of the coil and the influence of the lift-off effect becomes smaller, so it was helpful to the detection of small defects [13]. Itaya et al. studied the effect of detection defects of cylindrical probe, square and rectangular probe by comparing the coincidence rate between the curve of the theoretical derivation and the distribution of defects point. He found that rectangular probe has a unique advantage in detection defects and the placement angle of rectangular probe relative to the direction of defects has bigger influence on the effect of detection defects [14]. He et al. applied rectangular pulsed eddy current sensor to identify surface defects and subsurface defects. They found that when sensor is on different position against the defect, peak waves of response signals presented the same shape in direction of magnetic induction flux, while they presented different shapes in direction of exciting current that improved the performance of defect classification [15].

From previously literatures, it was clearly found that the properties of rectangular probe exactly can be used to test the conductivity of CFRP due to the fact that it belongs to anisotropic materials. In authors' laboratory, Zhou et al. utilized pulsed eddy current rectangular sensor to study the conductivity of CFRP and detect the defects of CFRP. The results showed that pulsed eddy current rectangular probe can effectively identify defects in certain direction [16]. They (2014) also utilized pulsed eddy current rectangular probe to detect surface defects of CFRP. The results showed that rectangular probe could effectively identify the different width and depth of crack defects and with the increase of the notch depth or width, the peak value of defect differential signal increased [17]. However, the pulsed eddy current

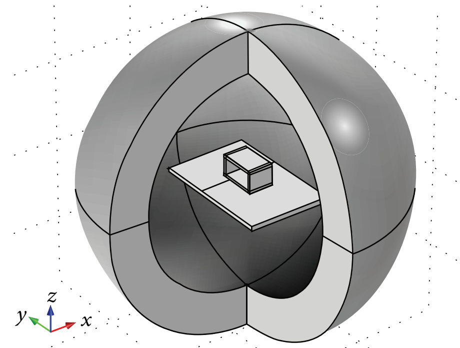

Figure 1: Differential simulation model.

rectangular differential testing probe applied to detection of CFRP is not very common. The main purpose of this paper is to apply this method to detect defects of CFRP.

The rest of the paper is organized as follows. Firstly, the direction of the rectangular coil placed is determined by simulation. Secondly, the differential principle of pulsed eddy current detection is analyzed by finite element simulation and the sensitivity of differential pulsed eddy current model is compared with direct measurement. Thirdly, the accuracy of the simulation results is validated by experiments. Finally, the defect recognition research is carried out.

2. The Establishment of Simulation Model and Analysis

2.1. The Establishment of Simulation Model. This paper established a three-dimensional eddy current testing rectangular probe model by using Comsol Multiphysics 4.4. In order to compare the defect detection sensitivity of differential and direct measurement detection, the differential detection model and the direct measurement model are established, respectively. Figure 1 shows the structure of differential eddy current testing probe. The difference between the two models is the position of incision. The position of incision on the carbon fiber reinfored plate of the direct measurement model is in the center. The model parameter settings are as follows: geometry size of carbon fiber reinforced composite material sample is 100 mm × 50 mm × 5 mm, which is separately engraved incisions of width (2 mm) with different depth (1 mm, 2 mm, 3 mm, and 4 mm) and depth (2 mm) with different width (1 mm, 2 mm, 3 mm, and 4 mm) in the samples. Due to the electrical conductivity of carbon fiber reinforced composite is anisotropic, so longitudinal conductivity is set to 10^4 S/m, transverse conductivity is set to 10^2 S/m, and cross direction conductivity is set to 10^2 S/m [18]. The length, width, and height of the rectangular exciting coil, respectively, are 50, 45, and 45 mm [19], square wave frequency is set to 100 Hz, enameled wire diameter is set to 0.3 mm, and the number of turns of coil is set to 1000 turns.

2.2. The Simulation Analysis

2.2.1. Select the Direction of Rectangular Probes Placed. Because carbon fiber reinforced composites are anisotropic

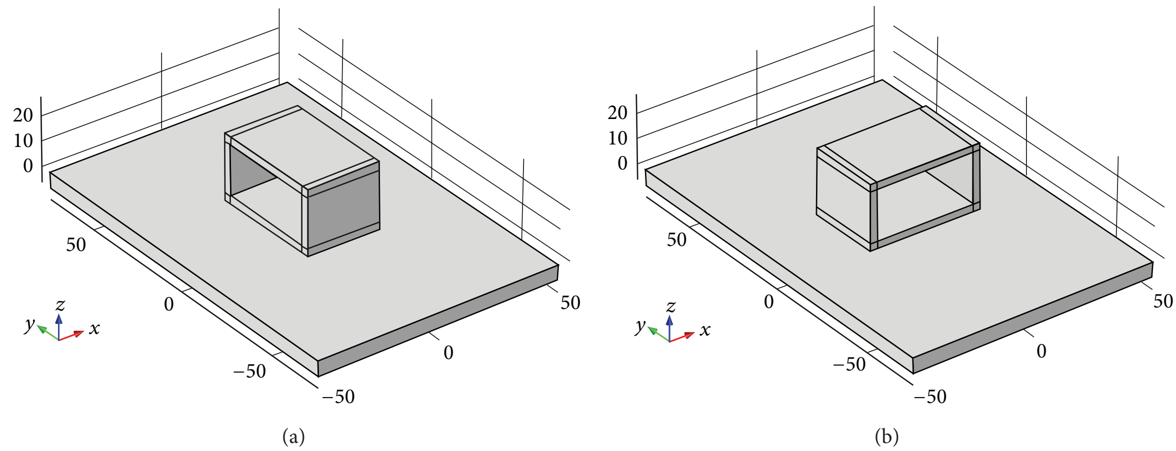

FIGURE 2: (a) Rectangular probe longitudinally placed. (b) Rectangular probe transversely placed.

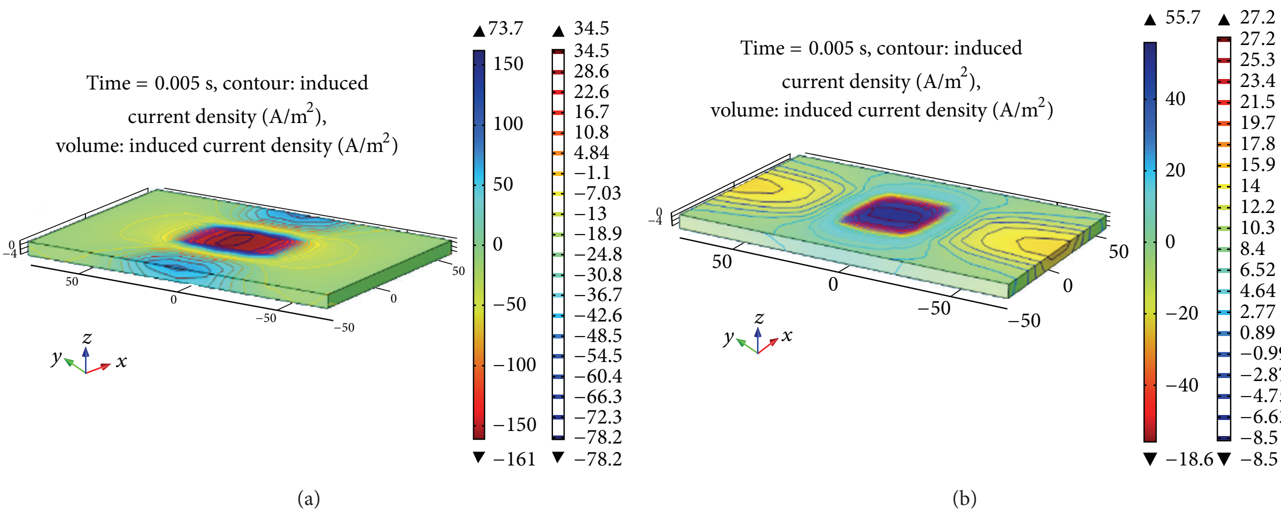

FIGURE 3: (a) Distribution of eddy current on the carbon fiber reinforced plate under rectangular probe longitudinally placed. (b) Distribution of eddy current on the carbon fiber reinforced plate under rectangular probe transversely placed.

materials, the electrical conductivity of each layer is different. The electrical conductivity of the fiber direction is the biggest, and the fiber direction of each layer is not the same. Changing the direction of the placement of coil will cause eddy current flow of different fiber layers. Therefore, testing coil placed with different angle has a great influence on the effect of carbon fiber defect detection. So choosing a suitable direction is particularly important.

Because the direction of the incision is Z-X direction, both longitudinal and transverse placement will be considered, as shown in Figure 2. The two models are calculated, respectively. The results are shown in Figure 3. The maximum value of eddy current density on the carbon fiber reinforced composite plate, respectively, is 73.7 A/m^2, 55.7 A/m^2. Obviously, the maximum value of eddy current density under longitudinal placement is bigger. Therefore, the direction of testing probe will be considered on the longitudinal directions.

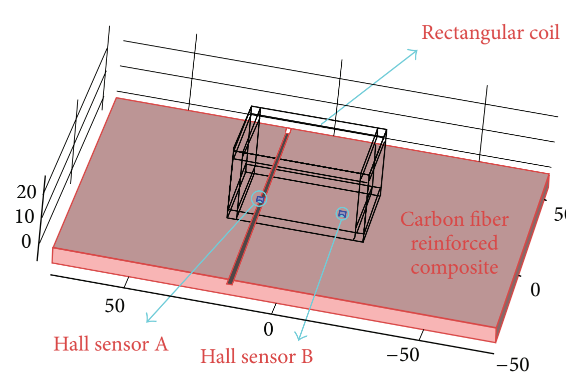

FIGURE 4: The structure of differential eddy current probe.

2.2.2. The Principle of Differential Eddy Current. Figure 4 shows the structure of differential eddy current testing probe,

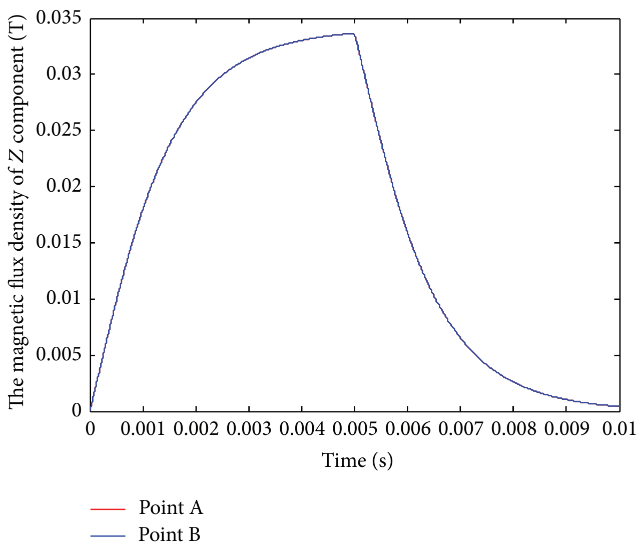

Figure 5: The magnetic flux density of Z component between points A and B.

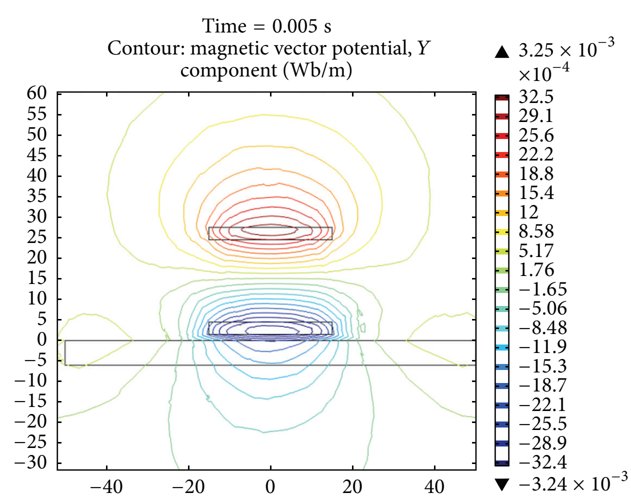

Figure 6: The distribution of magnetic induction line under horizontal longitudinal rectangular coil placed.

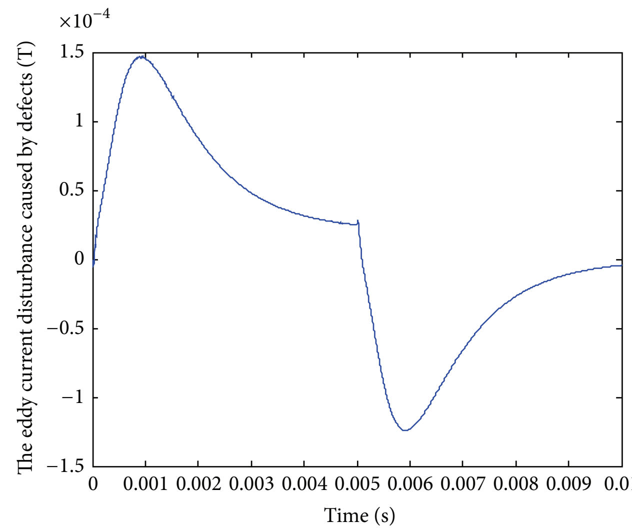

Figure 7: The eddy current disturbance caused by defects.

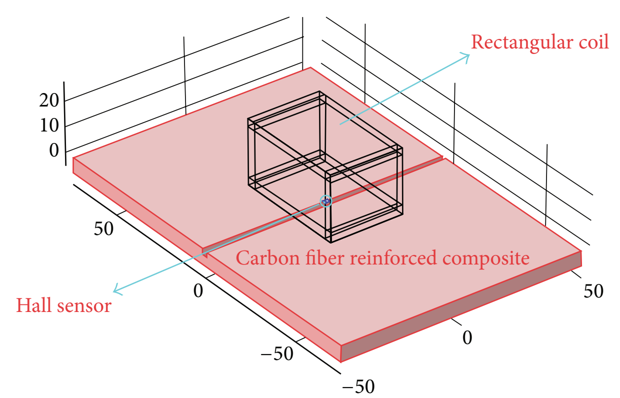

Figure 8: The structure of direct measurement eddy current probe.

the distance of A, B is 30 mm, and the distribution of the two points is symmetrical. When point A does not exist incision, the model is calculated and the magnetic flux density of Z component is extracted. The result is shown in Figure 5. It can be easily seen that the magnetic flux density curve of Z component between two points is a coincidence. Figure 6 shows the distribution of magnetic induction line on the Z-X cross section under rectangular coil longitudinally placed. It indicates that the distribution of magnetic induction line is a center of symmetry. When A point exist incision, the model is also calculated and the magnetic flux density of Z component is extracted. The magnetic flux density of Z component of the two points is subtracted as shown in Figure 7. Combining the above analysis, the curve of Figure 7 represents disturbance of eddy current caused by defects.

2.2.3. The Analysis of the Defect Detection Sensitivity of Differential Probe. In order to analyze the defect detection sensitivity of differential probe, defect detection sensitivity was compared by simulation under two measurement methods of differential and direct measurement.

In the direct detection model, Figure 8 shows the structure of direct measurement eddy current testing probe. The incision is located in the center of the bottom of the coil; the magnetic field signal extraction point is located in the center of the bottom of the coil. Defect simulation is carried out under the two ways and the magnetic flux density of every incision is extracted. The results of detection are shown in Figure 9.

In the differential detection model, the signal is processed according to the previous section which introduced the principle of differential eddy current detection. It mainly includes the subtraction of the magnetic flux density of two points and the extraction of the peak value of the signal of eddy current disturbance caused by defects. In the direct measurement detection model, the method of signal processing is that the signal of defect subtracts the signal of

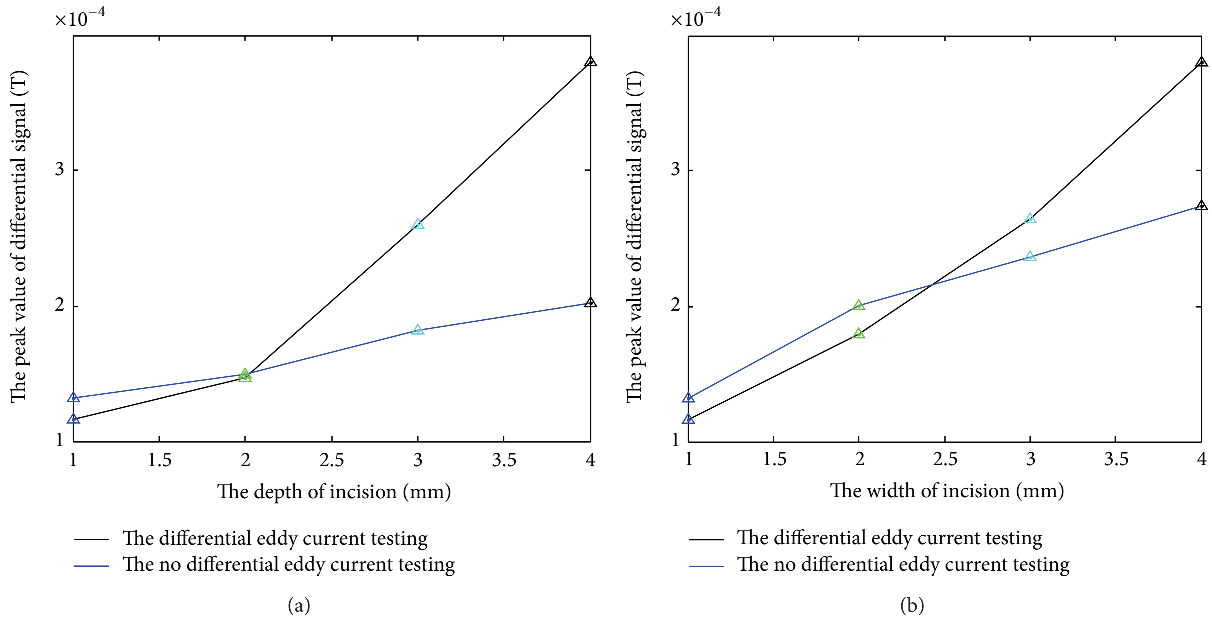

Figure 9: (a) Relationship between the differential signal peak and defect depth. (b) Relationship between the differential signal peak and defect width.

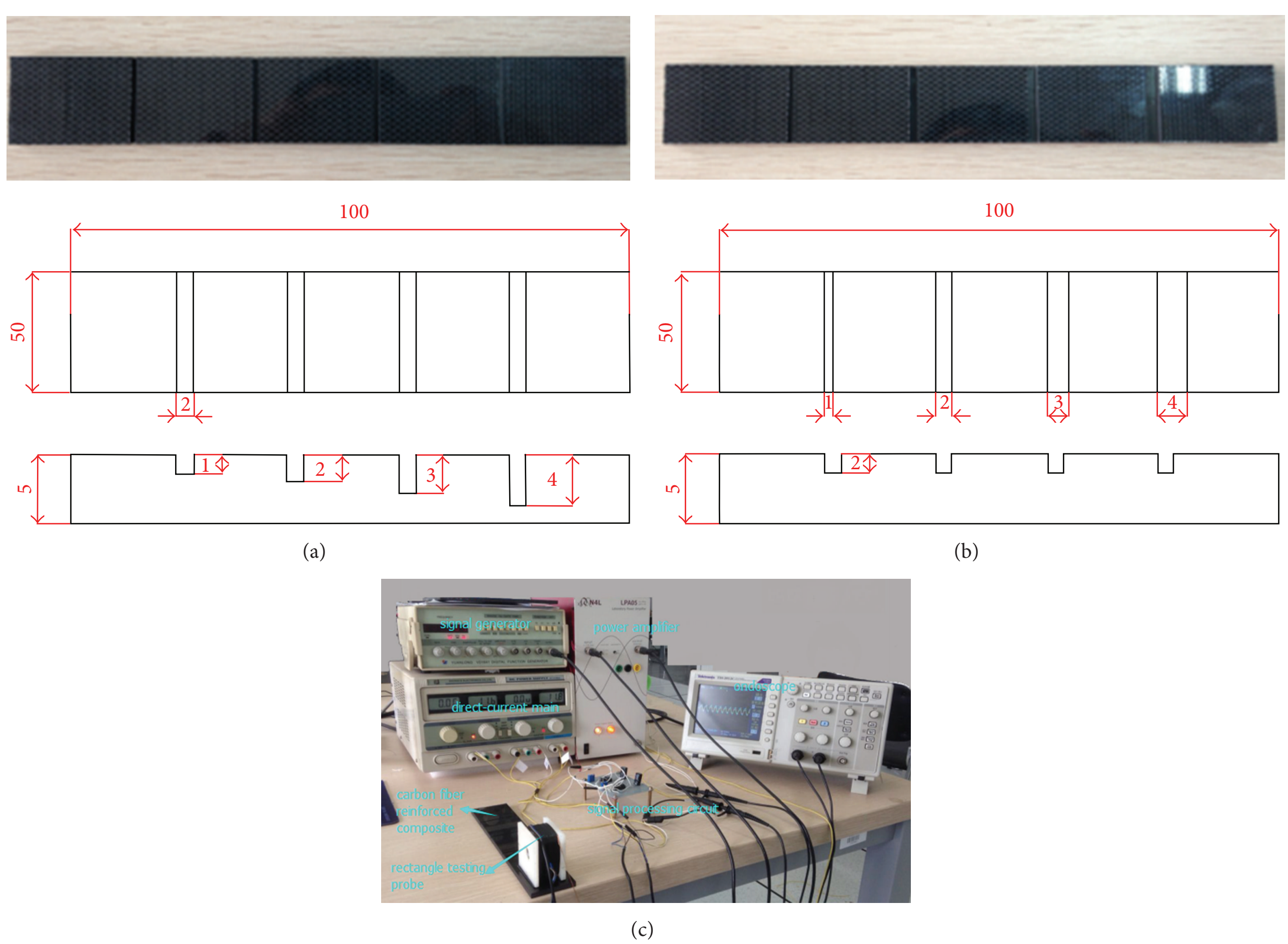

Figure 10: (a) Testing sample of notch depth. (b) Testing sample of notch width. (c) Experimental facility.

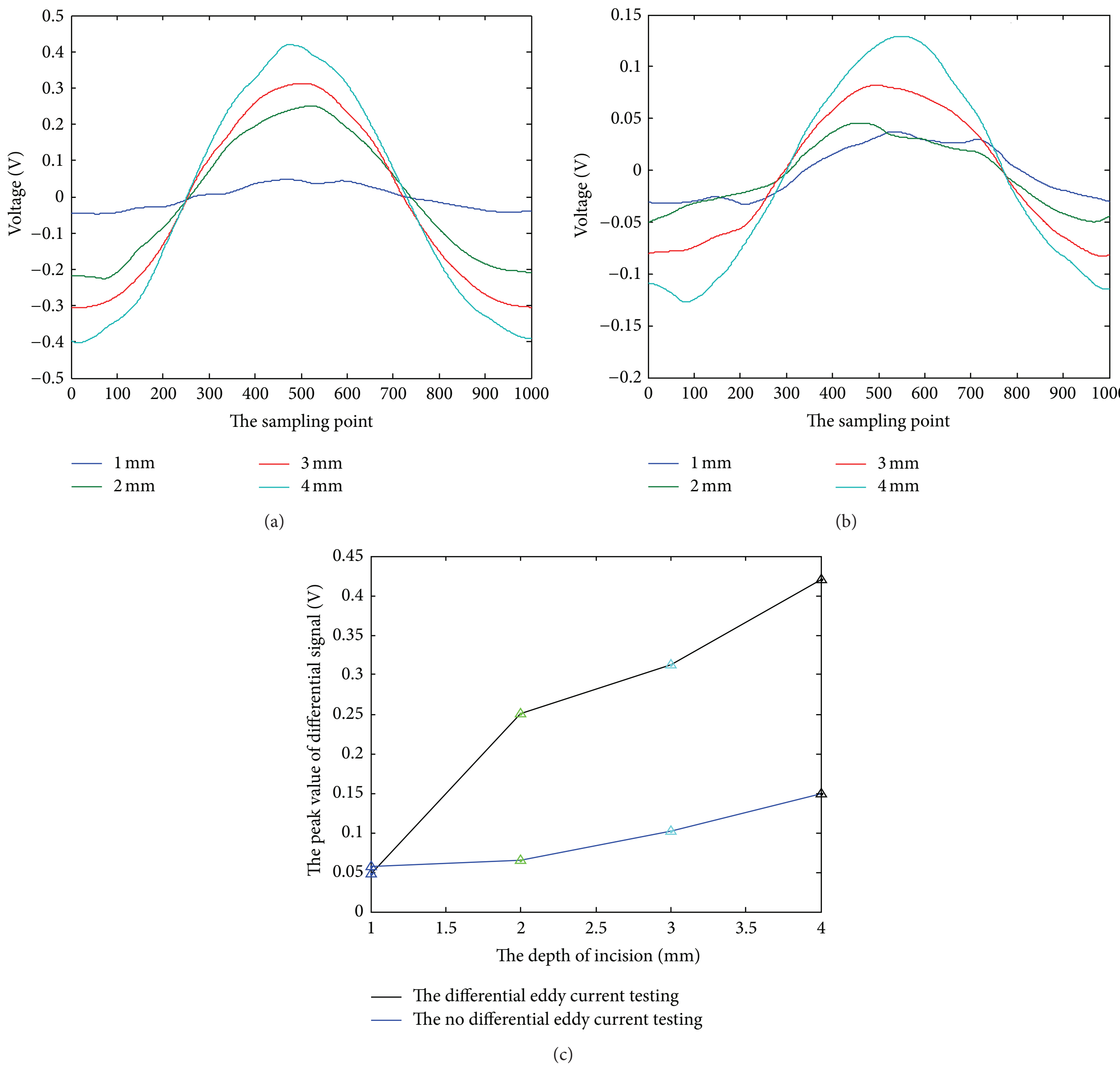

FIGURE 11: (a) The signal of differential eddy current testing probe. (b) The signal of defects differential signal by using direct measurement eddy current testing probe. (c) Relationship between the differential signal peak and defect depth.

no defect and extracts the peak value of differential signal. Details of the signal processing method are in [20]. The signal processing result is shown in Figure 9. It shows that the defect detection sensitivity under differential detection mode is higher than the direct measurement mode.

3. The Experimental Study

3.1. Experiment Device. Experiment device is mainly composed of the pulsed signal generator module, rectangular probe with hall sensor, power amplification module, signal conditioning circuit, data acquisition module, and specimen. The module of pulse signal generation uses YUANLONG VD1641 function generator, which has an optional arbitrary waveform generation capability. The type of Hall sensor uses SS95A226. The differential eddy current testing probe is composed of rectangular coil and two hall sensors. The distance between the two hall sensors is 30 mm as shown in Figure 4. The eddy current testing probe of direct measurement is composed of rectangular coil and one hall sensor, as shown in Figure 8. Power amplifier module is LPA05B, which is developed by the Newton Newtons4th by Science and Technology Company Ltd. Signal conditioning circuit mainly includes the filter circuit and the signal amplifying circuit. Amplifying circuit chooses instrument

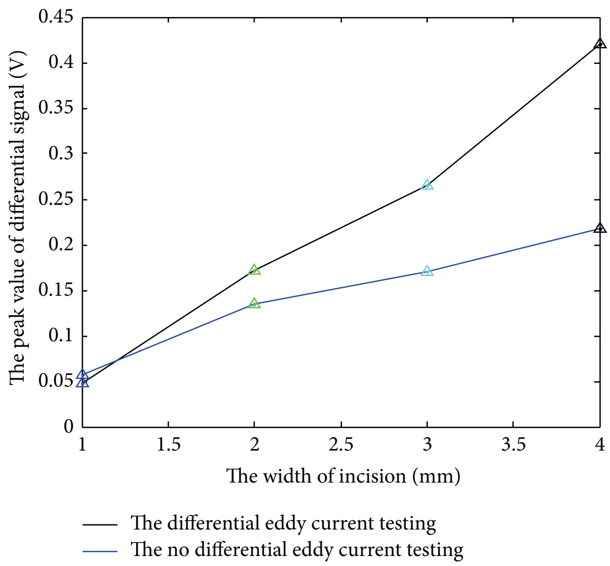

Figure 12: Relationship between the differential signal peak and defect width.

amplifier INA111 produced by Analog Devices Company as the core chip. The data acquisition card called DAQ2010 is used as experiment data acquisition module and the data is collected by the corresponding data collection toolbox in Matlab. Testing specimen mainly includes two carbon fiber reinforced composite plates engraved with different depth and width, as shown in Figures 10(a) and 10(b). The thickness of the testing specimen is 5 mm. The thickness of each fiber layers is approximately 0.25 mm. There are totally 20 carbon fiber layers. The direction of fiber of each layer is +90 degrees or −90 degrees. It is obtained by being suppressed at high temperature. Experimental apparatus is shown in Figure 10(c).

3.2. Notch Depth Experiment. When defects are detected by using direct measurement eddy current probe, hall sensor was placed above defects. Different depth of the incision is detected by the two kinds of eddy current testing probes and the detection signals were extracted. The acquisition signals are smoothed by digital signal processor, averaged to a cycle, subtracted, and so on. Details of the signal processing method are in [20]. The signal processing results are shown in Figure 11.

When defects are detected by using differential eddy current probe, one hall sensor was placed in the carbon fiber reinforced composite plate without defect; the other is placed above defect. The outputs of the two hall sensors are received by positive and negative input port of amplifier, so it achieved to magnify the difference of the magnetic field. Details of the signal processing method are in [20]. The signal processing results are shown in Figure 11.

The results show that the defect detection sensitivity under differential eddy current testing probe is higher than the direct measurement, which is consistent with the simulation results.

In view of the carbon fiber reinforced composite plate surface defects of different depth, the simulation and experimental results show that the differential pulse eddy current testing probe has good sensitivity of depth in defect detection.

3.3. Notch Width Experiment. The method of width detection is similar to depth. Different width of the incision is detected by using the two kinds of eddy current testing probes and the detection signals are extracted. The acquisition signals are smoothed by digital signal processor, averaged to a cycle, subtracted, and so on. Details of the signal processing method are in [20]. The signal processing result is shown in Figure 12. It shows that the defect detection sensitivity by using differential eddy current testing probe is higher than the direct measurement, which is consistent with the simulation results.

In view of the carbon fiber reinforced composite board surface defects of different depth, the simulation and experimental results show that the differential pulse eddy current testing probe has good sensitivity of width in defect detection.

4. Conclusion

Aiming at detecting carbon fiber reinforced composite material, differential and direct measurement of the pulsed eddy current flaw detection of finite element simulation model were established. Being combined with the simulation and experiment results, the conclusions can be concluded as follows.

(1) For surface crack defects of a carbon fiber reinforced composites, the induced eddy current density of rectangular probe longitudinally placed is larger. The fiber direction approximately is the longitudinal. So the direction of rectangle testing probe is placed longitudinally.

(2) The peak value of differential signal is increased with the enhancement of the depth or width of incision.

(3) In view of the surface crack defects of a carbon fiber reinforced composites, rectangular differential pulsed eddy current testing probe has good surface defect detection sensitivity.

According to the research results of rectangular differential probe, the nondestructive testing of carbon fiber reinforced composite has achieved further development. In future work, further investigations on natural cracks will be undertaken in the future. In addition, subsurface defects like delamination and impact damages rather than surface defects (notches) will be carried out and the relationship between delamination sizes and location will be investigated.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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