Defect Detection of Carbon Fiber Composite by Eddy Current Sensor

X. Z. Zhang*, Y. P. Huang
Tsinghua University, Beijing, P. R. China.

* Corresponding author. Email: zhangxzh@tsinghua.edu.cn
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Abstract: Carbon fiber composite are used in various fields for its good properties, such as high strength-to-weight ratio and rigidity. In order to obtain high reliability of the composite, non-destructive detections are undertaken during fabrication and in application. An eddy current sensor was used to inspect defects in carbon fiber composite plates. The defects were drilled holes in various diameters through or not through the plates. Measurement data were analyzed to identify the positions and basic properties of the defects. Results has shown that less than 1 mm holes in diameter can be identified using a commercial 8 mm sensor for displacement measurement. Suggestions of further work were given.

Key words: Carbon fiber, composite material, defect, eddy current detection.

1. Introduction

Eddy current is one of the important non-destructive detection technologies [1], [2]. According to electromagnetic theory, eddy current in metal parts near a coil with alternating excitation will induced an additional field, which in turn affects the coil impedance. This phenomenon can be used to sense parameter changes of the metal part, including surface shape, conductivity, temperature etc. Carbon fiber belongs to semiconductor [3]. Its composites can also have eddy current effect, though the effect is less strong compared to situation of metal. Moreover, skin effect of the eddy current in this kind of composite extends thicker than metal. This makes it possible to detect a plate of a few millimeters. This is an advantage.

This laboratory has been using eddy current sensors for vibration measurement for many years. It is nature to extend this technology to the composite defect detection when carbon fiber composites show more advantages in higher strength and flexibility in construction.

The purpose of the work described in this paper is to evaluate the possibility of using eddy current technology in the defect detection of carbon fiber composites, and to given comments on improvements of the existing design of the sensors.

2. Principles of the Eddy Current Detection

In Fig. 1, a coil with alternating current (the frequency is normally at around 1 MHz) is placed near a plate of metal. According to the principle of eddy current, this will induce an eddy current in the plate, which tends to resist the change of electromagnetic field in the plate. The couple of the two fields make impedance of the coil changed. This change of impedance relates to physical properties and geometry of the coil and the plate. So, if there is any defect in the plate, it is possible to detect the defect by measuring the change of the impedance of the coil.

For high frequency current, there is 'skin effect'. The penetrating depth δ of the electromagnetic field is formulated as [1]

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

where f is the frequency (Hz) of the current through the coil, μ and σ the permittivity (H/m) and conductivity (S/m) of the plate respectively. From equation (1) we know, δ of semiconductor is quite larger than normal metal. This is shown in our experiment. It is because conductivity σ of carbon fiber is much smaller than that of metal. For a plate of carbon fiber composite, even we can suppose a same permittivity as in vacuum, its conductivity is anisotropy [4]. One reference gave σ as in equation (2), which is a tensor.

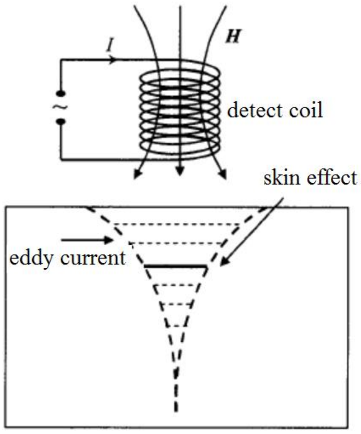

Fig. 1. Eddy current of metal near a coil.

$$[\sigma] = \begin{bmatrix} \sigma_l \cos^2\theta + \sigma_t \sin^2\theta & \frac{\sigma_l - \sigma_t}{2}\sin 2\theta & 0 \\ \frac{\sigma_l - \sigma_t}{2}\sin 2\theta & \sigma_l \sin^2\theta + \sigma_l \cos^2\theta & 0 \\ 0 & 0 & \sigma_{cp} \end{bmatrix} \tag{2}$$

where σ_l conductivity of carbon fiber composite in longitudinal direction, σ_t is in transverse direction, σ_{cp} is between layers; θ is the angle of fiber in Cartesian coordinates.

However, in the first step of research, we need not face such a complex equation. The composite plate we used is in woven pattern, where continuous carbon fibers are woven equally in x and y directions. For an approximation, isotropy assumption is made here.

3. Experiment

Test installations include an optic table (Zolix Instruments Co. Ltd), DC Voltage Supply (24V), an eddy current sensor (Rui Shi LtD, 9000XL,5/8mm), a digital voltage meter, and a 3D high precise manual positional coordinators (Zolix Instruments Co. Ltd).

Samples of carbon fiber composite plates are made by Chang Sheng Fiber Products. The dimensions are 100mm×100mm with thickness of 2mm. Holes of diameters 1mm, 2mm, 3mm are drilled through on each sample respectively. Other two samples with 3 mm in thickness have holes not through, where one has a hole of 1 mm in depth, another has a hole of 2 mm in depth. Diameter of the not-through holes is 2 mm.

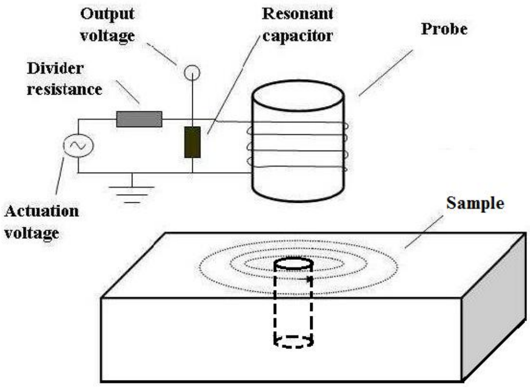

Fig. 2. Diagram of test installation.

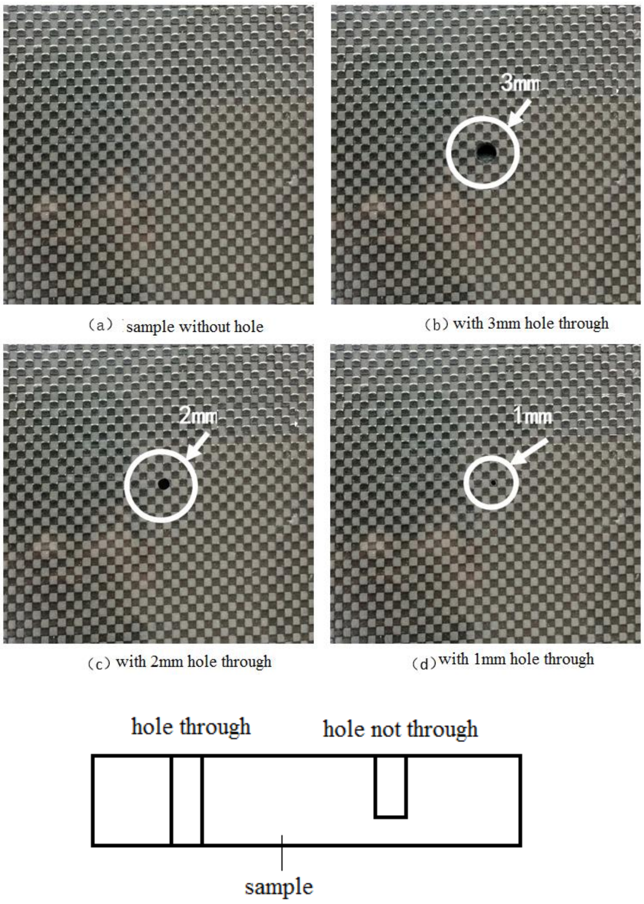

Fig. 3. Samples: Above (a) sample without hole (as comparison in test), (b) sample with hole through of 3mm in diameter, (c) sample with hoe through of 2mm in diameter, (d) sample with hole through od 1 mm in diameter. Bellow: diagraph to show hole through and hole not through.

Measurement was performed around the holes of samples, which was a 20mm×20mm region. With a step of positional coordinators being less than 2mm, each sample needs more than 121 test points. Voltages of each test point were measured 3 times. These 3 data were averaged. Matlab was used to process the measured data and plot the contour maps. For those samples with holes through, these maps are shown in Fig. 4 (a)-(d). Figure 4(a) is the sample without any hole. There is some variation of measured voltage in this plate. The value of the variation is within 0.3V. This variation very possibly comes from the uneven pattern of the carbon fiber. However, the sensor did not sensitive enough to this pattern, so we simply took this variation as measurement uncertainty. Fig. 4(b)-(d) are the samples with holes through the plates, with diameters of 3mm, 2mm and 1mm respectively.

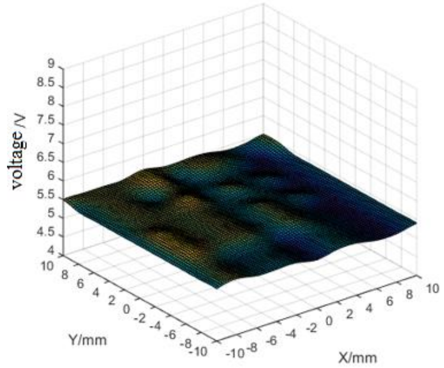

Fig. 4(a) Voltage contour of sample (thickness =2mm) without hole.

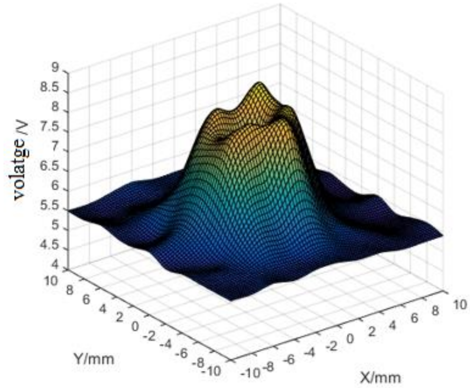

Fig. 4(b) Voltage contour of 3mm hole (through) in diameter.

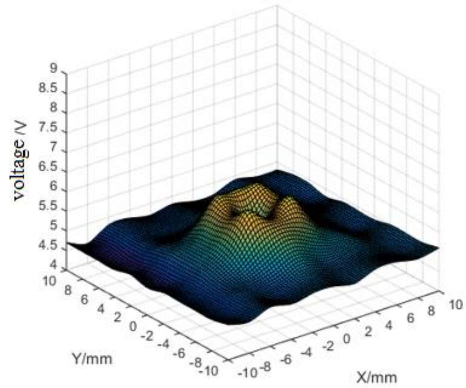

Fig. 4(c) Voltage contour of 2 mm hole (through) in diameter.

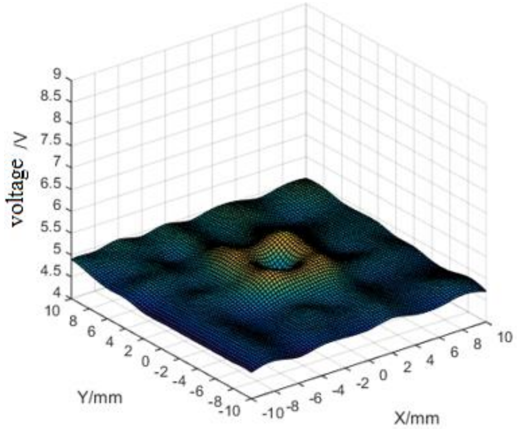

Fig. 4(d) Voltage contour of 1 mm hole (through) in diameter.

Compared Fig. 4(b)-(d) with Fig. 4(a), it is found that samples with holes could be identified clearly, because of the hill shape voltage contour maps. These hills showed different heights for the holes of different diameters. If they were compared each other, it was easy to see which map was for larger holes, and which was for smaller. However, it was hard to obtain the diameter of the hole from only one map itself.

Further test was done to the samples with holes not through the plates. In the test, eddy current sensor was place to the back size of the holes' opening. This meant there was a thickness of plate facing the coil which was without hole. This situation is more a practical issue, as very often we cannot see defects with eyes. They occur underneath. It is found that for these two samples, holes (diameter of 2 mm, depths of 1 mm and 2 mm respectively) can also be identified even they are not through the plates. See Fig. 5(a) and (b) for the contour maps. However, it is also difficult to judge how deep the defect is from the surface. Form the contour maps, Fig. 5(a) has little difference to Fig. 5(b). But maximum values show the case of 2 mm in depth (i.e. 1 mm from the surface) is 8.9V, while the case of 1 mm in depth (i.e. 2 mm from the surface) is 7.9V.

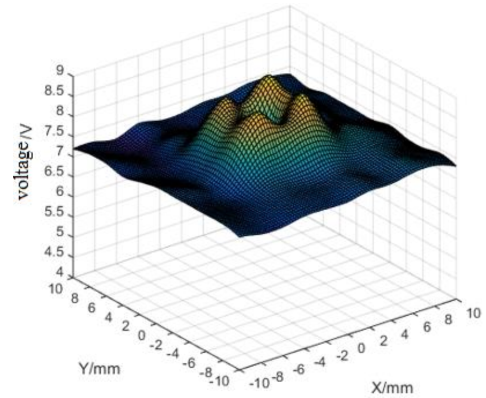

Fig. 5(a) Voltage contour of not through hole (2mm in depth, 2mm in diameter).

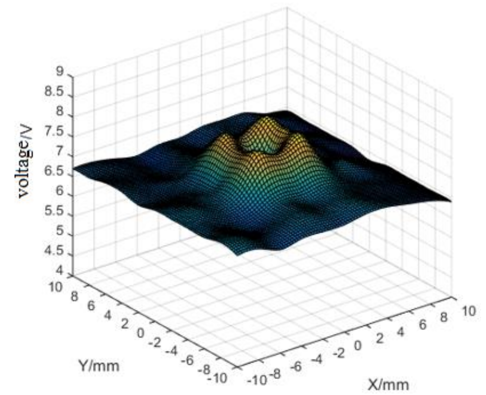

Fig. 5(b) Voltage contour of not through hole (1mm in depth, 2mm in diameter).

4. Discussions

In Fig. 4(a), the variation of the sensor's out-put voltage is around 0.3V for plate without any hole, compared with a base out-put of about 5V on average. As carbon fiber in the plate has patterns, and as the sensor is very sensitive to distance change (within a few micrometer), this variation has to be considered as measurement uncertainty. In other word, any defect causes voltage change of less than 0.3V will not be able to identify in the experiment.

For samples with holes through, minimum peak-valley difference of voltage around the holes is 0.8V (in the case of 1mm dimeter hole). We tried to use all the data with various diameters of holes to extrapolate the minimum defect to identify, or the resolution for the sensor:

$$U = 1.25d - 0.5667, \quad R^2 = 0.9745 \tag{3}$$

From equation (3) and with 0.3V of the variation plate we tested, it is predicted that the smallest hole the sensor is able to defect is about 0.7mm in diameter. It seems reasonable, for hole of 1 mm in diameter can be identified clearly (see Fig. 4(d) for its contour map).

The next thing is to reduce the minimum diameter of holes we can detect, by decreasing the diameter of the detect coil. Now with coil diameter of 8mm, the resolution is about 1/10 of the coil diameter. If we use smaller coils, can we still obtain 1/10 resolution of the coil diameter? This will be done in further work. However, because of carbon fiber pattern in composite plate, smaller coil may cause large fluctuation when the sensor is traveling through the normal plate. This makes it harder to identify smaller defect. Other design of the coil may improve the resolution [5]-[7].

Another interesting issue is how deep a defect can be found if it is underneath. In another paper [8], we studied the relation of the current frequency in the coil to penetrating depth in the 'skin effect'. It is found that reducing the frequency from 2.5MHz to 0.8MHz, the penetrating depth in carbon fiber composite plate increased to about 2 times, which reached to more than 3mm. This does not happen in metals, where high conductivity makes the penetrating depth being less than 0.1mm for those frequencies. The dependence of penetrating depth on coil frequency in carbon fiber composite is an advantage for eddy current detecting.

5. Conclusion

We try to use eddy current sensor to detect the defect in carbon fiber composite plate. The sensor is originally used for displacement measurement for metal part. Experiments on composite plate samples with holes of various diameters (through or not through) show the possibility of the method. Holes as small as less than 1mm in diameter can be detected with the sensor of 8mm in diameter. Also, the eddy current is able to penetrate 2 mm under plate surface to detect a hole of 2 mm in diameter. Resolution limit of the existing design is discussed. Further work will be on more experiment using various diameters of coils and searching for new design of the sensor.

References

[1] Wu, J. S., *et al*. (2014). *Eddy Current Technology and Its Applications*, Zhong Nan University Press.

[2] Du, F., *et al.* (2015). State of art and prospect of eddy current testing for carbon fiber reinforced resin matrix composites. *Chinese Science and Technology, 6*, 77-78.

[3] Shackelford, J. F. (1990). *Introduction to Materials science for Engineers*, MacMillan Publisher Company.

[4] Xie, D. X., *et al.* (2008). *FE Analysis for 3D Eddy Current Field*, Mechanical Industry Press.

[5] Grimberg, R., Savin, A., & Rotundu, C. R. (2001). Eddy current microscopy applied to graphite-epoxy composite. *Sensors and Actuators, A: Physical, 1-2(91)*, 73-75.

[6] Schulze, M. H., *et al*. (2010). High-resolution eddy current sensor system for quality assessment of carbon fiber materials. *Microsystem Technologies, 5(16)*, 791-797.

[7] Koichi, M., *et al*. (2016). Detection of in-plane and out-of-plane fiber waviness in unidirectional carbon fiber reinforced composites using eddy current testing. *Composites Part B: Engineering, 86,* 84-94.

[8] Jiang, L., & Zhang, X. Z. (2013). Preliminary experiment of CFRP displacement direct measurement with eddy current sensor. *Applied Mechanics and Materials, 241-244,* 3-8.

X Z Zhang is working at Tsinghua University in the field of engineering physics. His research interests include rotating machine vibration and fluid flow measurement. He is the author of book "Electromagnetic Induction Flow Measurement" and is on editor board of "Flow Measurement and Instrumentation".