Conductivity Inversion of Unidirectional CFRP Laminates Using Eddy Current Testing

SHEN Wei, *JI Hongli**, *QIU Jinhao*, *XU Xiaojuan*

College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P.R.China

(Received 8 July 2020; revised 12 September 2020; accepted 13 September 2020)

Abstract: Due to the electrical anisotropy of carbon fiber reinforced polymer (CFRP), this paper presents a method to inverse the anisotropic conductivity of unidirectional CFRP laminate using eddy current testing (ECT). The relationship between the conductivity and probe signal of ECT is studied by means of numerical simulation. Finally, the accuracy of inversion result is improved by optimizing the initial conductivity by use of experimental data.

Key words: carbon fiber reinforced polymer (CFRP); eddy current testing (ECT); conductivity inversion; forward model

CLC number: TP274 **Document code:** A **Article ID:** 1005-1120(2020)S-0035-06

0 Introduction

As a perfect combination of carbon fiber and resin, carbon fiber reinforced polymer (CFRP) has excellent properties such as high strength, light weight, high temperature and high pressure resistance[1-2]. Due to these excellent properties, CFRPs have been widely used in aerospace, military and civil industries[3-4]. Unlike isotropic materials, CFRP is heterogeneous multiphase material, whose electrical conductivity is mainly determined by carbon fibers. Therefore, the conductivity of CFRPs depends on the distribution of carbon fibers and the formation of fiber conduction paths, thus the overall performance is anisotropy[5].

Knowing the conductivity of CFRPs, as well as the other electromagnetic properties, is of great importance for various applications. However, these properties are not known in advance, and need to be determined by either contact or non-contact method. The contact measurement is mainly based on the probe method, which uses the impedance analyzer to measure the resistance between the two stages, and the conductivity can be calculated[6]. Although this method has higher accuracy, the whole process is cumbersome. Non-contact methods, based on resonant circuits and the physics of the eddy current, have been proposed to determine the whole conductivity of CFRP[7], but the anisotropy has been weakly treated.

In this paper, unidirectional CFRP laminate is taken as an example to study the electrical anisotropy of this new materials using eddy current testing (ECT) method[8]. Firstly, the forward model is constructed by ANSYS software to calculate the eddy current field, and then, the influence of electrical anisotropy of unidirectional CFRP laminate on the output signal is studied. Then, the ECT system and experimental method adopted in this paper is briefly introduced. Finally, the initial value of the conductivity is estimated based on the experimental data and brought into the model for calculation. Based on the comparison between the theoretical results and the experimental ones, the initial value is corrected. According to the iterative algorithm, the anisotropic conductivity is finally obtained by minimizing the error between the calculated simulation results and the measured ECT signal.

---

*Corresponding author, E-mail address: jihongli@nuaa.edu.cn.

How to cite this article: SHEN Wei, JI Hongli, QIU Jinhao, et al. Conductivity inversion of unidirectional CFRP laminates using eddy current testing[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2020, 37(S): 35-40.

http://dx.doi.org/10.16356/j.1005-1120.2020.S.005

1 Principle of Conductivity Inversion

1.1 Construction of the forward model

Conductivity inversion is a typical inverse problem, which requires a fast and accurate solution from the positive problem. In general, two ways can be used to build the ECT forward model: the integral method using theoretical formula and the analysis method using experimental signal. For integral method, it needs to divide the entire eddy current field and calculate each field by "Maxwell" equations. Then, linking the fields together according to boundary conditions. Although the way has high precision, the derivation is complicated. The analysis method needs to preprocess the detected signals, and then constructs the mapping relationship by neural network or fuzzy inference, which requires a large amount of data to maintain the robustness.

To this end, this paper uses ANSYS software with built-in integral formula to construct the forward model. The whole model can be regarded as an electromagnetic field solving domain. The solution domain contains the exciting source, the conductor region and the air region, as shown in Fig.1. The different regions are connected by boundary conditions.

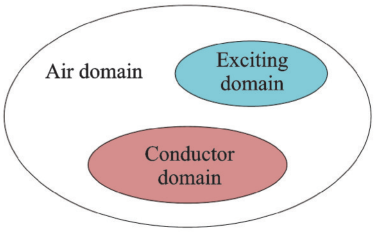


Fig.1 Electromagnetic field solving domain

The corresponding three-dimensional eddy current field model used in this paper is shown in Fig.2.

In Fig.2, the fibers direction parallels to the x-axis of the cartesian coordinate system. To analyze the sensitivity, a probe angle θ, which is between the line connecting the transmitter-receiver (T-R) probe and the fiber direction, is defined. The parameters of each model are tabulated in Table 1, in which the lift_off refers to the distance from the bottom of the ECT probe to the surface of the sample.

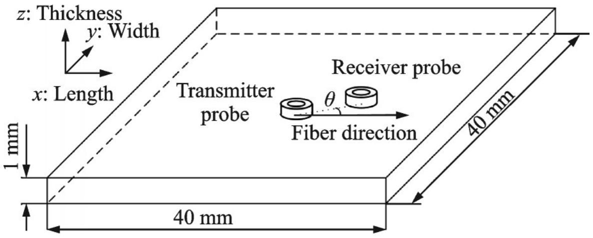


Fig.2 Three-dimensional eddy current field model

Table 1 Parameters of each model

Model		Parameter/mm
Probe	Inner diameter	1.2
	Outer diameter	3.2
	Height	0.8
	Lift_off	0.5
CFRP	Length and width	40
	Thickness	1
Air	Length and width	80
	Thickness	20

1.2 Validation of the forward problem

Assuming the fibers direction of unidirectional CFRP laminate parallels to the x-axis of the cartesian coordinate system firstly, then the conductivity of the laminate can be represented by a diagonal matrix[10].

$$\sigma=\begin{bmatrix}\sigma_x & 0 & 0\\ 0 & \sigma_y & 0\\ 0 & 0 & \sigma_z\end{bmatrix} \tag{1}$$

where σ_x and σ_y denote the conductivity in the directions along and transverse to the fibers, respectively; σ_z denotes the conductivity in the thickness direction. Thus, the conductivity inversion becomes a multi-parameter optimization problem. To improve the accuracy of the inversion, this paper involves two parts: the influence of conductivity in the three directions on output signal and the probe angle θ, which is the most sensitive to the change of each conductivity. Since the sample is centrally symmetric, the probe angle θ used in this paper is 0°, 30°, 45°, 60°, and 90°, respectively. At the above several angles, the probe voltages on different frequencies of different conductivities are simulated separately. The obtained results in the case of $\theta = 0°$ are selected to analyze the relationship between the probe voltage and the frequency, which is shown in Fig.3.

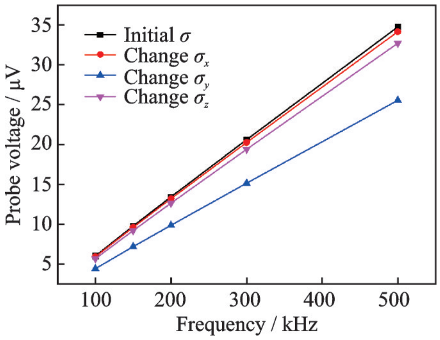


Fig.3 Relationship between voltage and frequency in the case of $\theta = 0°$

In Fig.3, the initial conductivity $\boldsymbol{\sigma}$ means $(\sigma_x, \sigma_y, \sigma_z) = (30\,000, 4.8, 1.2)$ S/m. Then conductivity in the three directions are reduced by one-third respectively which mean the conductivity after the change are: $(20\,000, 4.8, 1.2)$ S/m, $(30\,000, 3.2, 1.2)$ S/m and $(30\,000, 4.8, 0.8)$ S/m. As can be seen from Fig. 3, a linear relationship between the voltage signal and the frequency is obtained, and can be fitted by the relationship of

$$V = a \times f + b \tag{2}$$

where V represents probe voltage and f excitation frequency. The coefficient a under different conductivities are shown in Table 2.

Table 2 Coefficient *a* of fitting curves

Conductivity / (S•m^{-1})	Coefficient
Initial σ	7.17
Change σ_x	7.04
Change σ_y	5.27
Change σ_z	6.75

It can be seen from Table 2 that there is a certain relationship between the coefficient and the conductivity. Also, even the conductivity in the three directions are all reduced by one-third, and the value of the coefficient varies differently, indicating that different conductivity parameters have different influences on the probe voltage. According to the change of the coefficient, it's clearly that transverse conductivity σ_y has the greatest influence on the probe voltage.

To find the most sensitive probe angle for conductivity changes in three directions, a parameter α is defined to represent the rate of change.

$$\alpha = \frac{\left| a_c - a_i \right|}{a_i} \tag{3}$$

where a_c represents the coefficient a obtained in a changed conductivity under a certain direction, and a_i the coefficient a obtained in the initial conductivity under the same certain direction. The rate of change α at different probe angles can be calculated by using Eq.(3), and the corresponding results are shown in Fig.4.

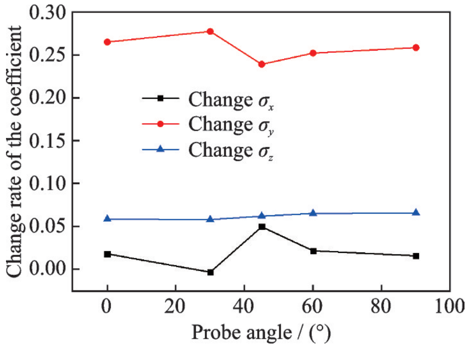
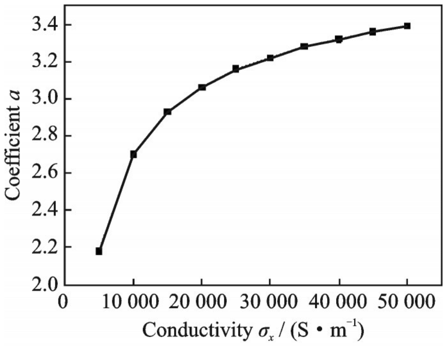


Fig.4 Relationship between the coefficient a and the probe angle

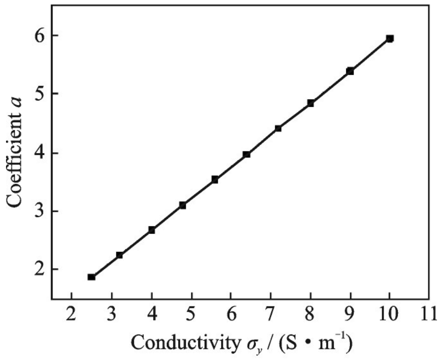
As shown in Fig.4, for the conductivity in different directions, the largest value of α was obtained at different angle θ. Since a higher α means a higher sensitivity, it's clearly that the most accurate probe angle for σ_x, σ_y and σ_z are 45°, 30° and 90°, respectively.

To construct the relationship between the conductivity and the probe signal, the change trend of the coefficient with the conductivity at the corresponding probe angle is analyzed. It should be noted that when the coefficient is studied as a function of a certain conductivity, the other two conductivities remain unchanged. The obtained results are shown in Fig.5.

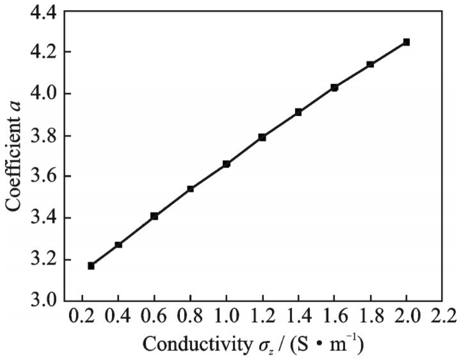
As plotted in Fig.5, it is clear that the change trend of the coefficient a with conductivity in the three directions and the initial value of conductivity could be estimated according to the experimental data.



(a) Probe angle = 45°



(b) Probe angle = 30°



(c) Probe angle = 90°

Fig.5 Relationship between the coefficient a and conductivity

2 Experiment Setup

The ECT system for CFRP scanning and imaging developed by our lab is presented in Fig.6. It consists of a signal generator, a T-R probe, a lock-in amplifier, a DAQ card and a PC processing.

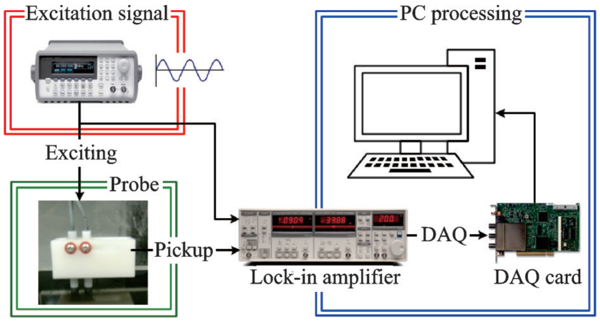


Fig.6 ECT system

The detection principle of the whole system can be concluded as: The signal generator produces a sinusoidal harmonic signal that is fed into the transmitter probe and the lock-in amplifier. The signal entering the transmitter probe will generate an electromagnetic field, so that the corresponding eddy current is induced in the CFRP specimen, and the signal of corresponding information in the specimen can be obtained by the receiving coil and then imported into the lock-in amplifier. The imported signal is demodulated and noise-processed by the phase sensitive detector and the filtered in lock-in amplifier, which allows extracting a weak useful signal buried in background noise. The experiment results are collected by the data acquisition card and stored in PC.

The tested unidirectional CFRP laminate is shown in Fig.7. The plate is made up of 8 layers of unidirectional prepreg, and the thickness of each prepreg is about 0.125 mm.

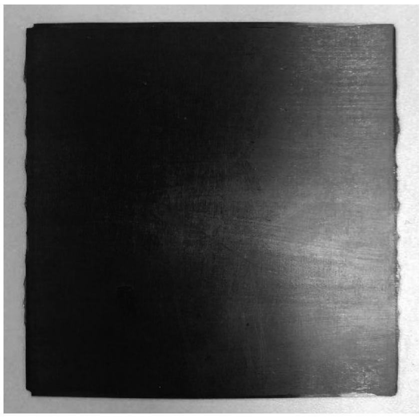


Fig.7 Unidirectional CFRP laminate

3 Results and Analysis

In the experimental process, the output signal of the pickup coil is obtained by single point acquisition instead of continuous scanning. To correspond with the simulation results, the probe voltages at different frequencies are measured during experiment process, and the coefficients are obtained by the linear relationship fitting. In addition, for improving the sensitivity of conductivity inversion in the three directions, the T-R probe and the fibers direction are at the angle of 30°, 45° and 90°, respectively. Experimental results are shown in Table 3.

Table 3 Experimental results

f /kHz	Probe voltage V/μV		
	30°	45°	90°
100	3.27	2.8	2.24
150	3.73	2.62	2.79
200	4.68	3.36	3.47
250	6.28	5.8	5.9
300	7.82	6.86	7.59
a	2.33	2.26	2.762

In Table 3, the coefficient a is fitted by using Eq.(2). According to the coefficients in Table 3, together with the curve trend in Fig.5, the conductivity of the unidirectional CFRP plate in the three directions can be estimated. Substituting the estimated value into the simulation model, the obtained results is shown in Table 4.

Table 4 Calculation results of initial conductivity

Conductivity/ $(\mathrm{S \cdot m^{-1}})$	Probe angle/(°)	Coefficient a	
		Simulation	Experiment
σ_x=3.5	30	2.191 3	2.33
σ_y=15 000	45	2.162 6	2.26
σ_z=0.7	90	2.621 1	2.762

The conductivity parameters are revised by comparing the coefficient between the simulation and experiment at different angles. Increase the value of conductivity if the coefficient of simulation is less than that of experiment, otherwise decrease it if larger. Repeating the above iterative process until the difference between the calculated and experimental values satisfies the convergence goal of 0.01. The final result is shown in Table 5.

According to Table 5, the conductivity of the unidirectional CFRP laminate obtained in the final inversion is (15 034, 3.78, 0.66) S/m.

Table 5 Final results of conductivity inversion

Conductivity/ $(\mathrm{S \cdot m^{-1}})$	Probe angle/(°)	Coefficient a	
		Simulation	Experiment
σ_x=3.78	30	2.327 5	2.33
σ_y=15 034	45	2.267 5	2.26
σ_z=0.66	90	2.766 3	2.762

4 Conclusions

The eddy current method is used to study the conductivity inversion of unidirectional CFRP laminate. Firstly, the three-dimensional eddy current electromagnetic model of unidirectional CFRP composites is constructed by using ANSYS software, and the influence of the electrical conductivity of this material in the longitudinal, transverse and thickness directions on the output signal of the probe is studied. Secondly, the relationship between the conductivity and the output signal is constructed, and the initial values of conductivity in the three directions are estimated based on experimental data obtained by the eddy current testing. The initial value of the conductivity is revised according to the comparison between the theoretical calculation results and the experimental ones. Finally, through the continuous correction of the conductivity, the error between the theoretical and experimental results is within 0.01, and the final inversion result is obtained. Compared with the previous inversion method, the proposed method in this paper does not require a large amount of experimental data, while has high operability and fast speed.

References

[1] HUANG X. Fabrication and properties of carbon fibers[J]. Materials, 2009, 2(4): 2369-2403.

[2] LIU Yaodong, KUMAR Satish. Recent progress in fabrication, structure, and properties of carbon fibers [J]. Polymer Reviews, 2012, 52(3): 234-258.

[3] ROBERTS T. Rapid growth forecast for carbon fibre market[J]. Reinforced Plastics, 2007, 51: 10-13.

[4] MANGALGIRI P D. Composite materials for aerospace applications[J]. Bulletin of Materials Science, 1999, 22(3): 657-664.

[5] MENANA H, FELIACHI M. Electromagnetic characterization of the CFRPs anisotropic conductivity: Modeling and measurements[J]. The European Physical Journal Applied Physics, 2011, 53(2): 21101.

[6] TODOROKI A. Electrical resistance change of unidirectional CFRP due to applied load[J]. JSME International Journal, 2004, 47(3): 357-364.

[7] KOYAMA K, HOSHIKAWA H, KOJIMA G. Eddy current nondestructive testing for carbon fiber-rein-

forced composites[J]. Journal of Press Vessel Technol , 2013,135(4): 041501.

[8] AULD B A, MOULDER J. Review of advances in quantitative eddy current nondestructive evaluation [J]. Journal of Nondestructive Evaluation, 1999, 18 (1): 3-36.

[9] PARK J B, HWANG T K, KIM H G, et al. Experimental and numerical study of the electrical anisotropy in unidirectional carbon-fiber-reinforced polymer composites[J]. Smart Materials and Structures, 2007, 16 (1): 57-66.

[10] PRATAP S B, WELDON W F. Eddy currents in anisotropic composites applied to pulsed machinery [J]. IEEE Transactions on Magnetics, 1996, 32(2): 437-444.

Acknowledgements This work was supported by the research fund of State Key Laboratory of Mechanics and Control of Mechanical Structures (Nanjing University of Aeronautics and astronautics) (No.MCMS-I-0518K01&MCMS-I-0519G02) , a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD), and the Natural Science Funding (No. 51875277).

Authors Mr. **SHEN Wei** is a postgraduate of State Key Laboratory of Mechanics and Control of Mechanical Structure, Nanjing University of Aeronautics & Astronautics, Nanjing, China. His research focuses on eddy current testing. Prof. **JI Hongli** is a professor of State Key Laboratory of Mechanics and Control of Mechanical Structure, Nanjing University of Aeronautics & Astronautics, Nanjing, China. Her research focuses on semi-active control, smart materials and structures.

Author contributions Mr. **SHEN Wei** carried out the most of the work in the paper, including the simulation and experiment, also the writing of the manuscript. Prof. **JI Hongli** and Prof. **QIU Jinhao** provided the overall idea of the paper. Ms. **XU Xiaojuan** summarized the existing researches. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: WANG Jing)

基于涡流检测的碳纤维复合材料层合板的电导率反演

沈 威，季宏丽，裘进浩，徐笑娟

（南京航空航天大学航空学院，南京 210016，中国）

摘要：由于碳纤维增强复合材料（Carbon fiber reinforced polymer, CFRP）的电各向异性，提出了一种利用涡流检测（Eddy current testing, ECT）来反演单向CFRP层合板电导率的方法。通过数值仿真研究了电导率与ECT探头信号之间的关系。最后，通过实验数据不断对电导率进行优化迭代，提高了反演结果的精度。

关键词：碳纤维增强复合材料；涡流检测；电导率反演；正向模型