Analysis the Non-Destructive Testing of Carbon Fibre Reinforced Plastic (CFRP) using Eddy Current Technology.

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Abstract- This ***paper describes research on the use of eddy current techniques for non-destructive testing of carbon fibre reinforced plastic (CFRP). The research has involved bulk conductivity testing, fibre direction characterization and 3D FEM modeling of the CFPR and eddy current probes geometry. In the conductivity testing, how the sample thickness, fibre volume content and fibre conductivity affects the signal from the eddy current has been evaluated. Eddy current testing shows good directionality as CFRP is an anisotropic material, thus is very suitable to characterize the fibre orientation. Direction sensitive probes have been developed and tested to reveal information about the fibre direction and layer. Computer FEM software has been used to analyze the magnetic field inside the sample and probes. Specific probe geometries have been designed depending on the electrical properties of the composites and testing requirement. The experiment, simulation and analysis results show very good agreement. However, when the measuring frequency increases, noises and parasitic capacitance inevitably become significant and have a negative influence on the results. Improvements and further research are proposed which are believed to make eddy-current techniques a more feasible and efficient measurement method, will contribute to the development and maintenance of light weight CFRP composites***.

Keywords – CFRP, FEM.

I. INTRODUCTION

The limitation of non-destructive methods for the inspection of CFRP is a major problem involving many practical applications of the material, especially in the aircraft industry. The study of this project is directed towards non-destructive characterization of CFRP using eddy current methods. The relationship between the signal from different types of inductive probes and the microstructure of CFRP samples has been studied. The measurement of a bulk equivalent electrical conductivity of the material is based on the Deeds and Dodd’s analytic solution, which provides the fundamentals for prediction and detection of fibre fracture and material defects. Fibre direction characterization will also be performed on unidirectional and multidirectional CFRPs using a highly directional probe. Based on these, detection of CFRP defects can be realized. In addition, 3D finite element method (FEM) computer simulations have been developed to demonstrate the coupling of the probes and samples, and to support the experimental method. This project is aimed to build up a methodology of eddy current testing for characterization of CFRP and look forward to developing a set of testing systems. The main achievement of this paper was successfully developing and applying eddy current method to non-destructive characterization of CFRP material. The method was based on Dodd and Deeds theory of determining equivalent bulk conductivity using eddy current coils, as well as by virtue of CFRP material's electrical conductivity and anisotropy. An eddy current testing system consisting of all the devices and equipments, eddy current probes, and controlling computer was designed and put into use in the project. All operation including measurement configuration, probe setup, scanning control, signal processing and result analysis could be executed through the interface which was programmed in MATLAB environment. This system in cooperation with various probe designs was able to carry out bulk conductivity testing, fibre direction characterization and lift-off measurement. 3D FEM models of the CFRP samples, eddy current probes and measurement environment have been developed. The modeling results had a good agreement with measurement ones, which proved the theory and the performance of measurement system. The 3D models were also beneficial to simulate and predict the performance of more complicated samples and measurement conditions. What is more, this eddy current method has also been applied to the non-destructive characterization of hybrid aluminium/CFRP material and the material's properties could be obtained.

II. Proposed Algorithm

2.1 Requirement For Testing

During the process of manufacturing, it is possible that defects and flaws of various natures and sizes can be introduced into the materials and components which may result in the malfunction or failure of the final product. On the other hand, during service, the industrial component may suffer quality decrease and risk of failure due to the presence of other imperfections such as fatigue and impact cracks. These defects and flaws may even result in further accidents and individual injury. Therefore, for the purpose of high product quality and less cost, at the manufacturing stage, it becomes necessary to find proper and reliable examination to detect mis-assembled.

A defect, explained by EEC (European Economic Community) [8], indicates the group of imperfections which can make the component defective or unserviceable, while the word 'flaw' represents any imperfection which is classified to be non-rejectable. Hence, according the definitions, it is incorrect to call an imperfection as an acceptable defect. Although there is no uniform standard by which to distinguish both, common sense and the evaluation method can be helpful [9]. In applications relating to quality-control or fitness-for-purpose in which the evaluation is carried out to decide rejectable component or product, these two terms make a considerable difference and cannot be interchanged.

Testing can be found in many places in everyday life and industry, and examples include:

- Aircraft skins are subject to corrosion and stress corrosion cracking.
- Food and medical products require high standard inspection before they are bought by the consumers.Underground pipelines need regular checking to detect cracks.
- Drink machines check the inserted coins for the total amount.
- Airports use security gate to detect threat objects carried by passengers.
- Pipes in industrial plants may be subject to erosion and corrosion from the products they carry.
- Concrete structures may be weakened if the inner reinforcing steel is corroded.
- Doctors use medical devices to image patients' organ.
- The wire ropes in suspension bridges are subject to weather, vibration, and high loads, so testing for broken wires and other damage is important.

2.2 Structure and Electrical Properties Of CFRP

Carbon fibres are made in the form of bundles, called strands or tows containing, usually, 10^4 discrete filaments, which are typically 7 to 15 µm in diameter. Carbon fibre composites are made with carbon fibres embedded in a polymer, commonly epoxy. These stiff and strong fibres carry the loads to which the component or structure is submitted. The matrix has low stiffness and low strength and it contributes to the shape of the component. The plastic matrix is used to transfer loads to the fibres and between them as it's another important task.In a CFRP composite, a single layer has a thickness of about 0.05 to 0.2 mm, and consequently, in order to obtain usable engineering mechanics components, some layers are stacked one by one to form a lamina.A lamina with fibres in only one direction is called a unidirectional lamina. Alternatively, a few laminae with fibres in different directions are used to form a laminate. The directions of the fibre in each part of the mechanical component need to be chosen by the designer to offer the component required properties and minimum cost.

Table 1: Conductivity of Material.

Material	Conductivity(10^4 s/m)	Direction of measurement
Copper	5900	n/a
Aluminum	3500	n/a
Iron	1000	n/a
Graphite	13	n/a
Carbon	3	n/a
Carbon fibre	4-17	n/a
Unidirectional CFRP	0.9-1.5 0.01-0.2	Parallel Perpendicular

From the above Table 1, it can be seen that the conductivity of unidirectional CFRP composites is lower than that of metals by a factor of about 1000, while the conductivity in cross fibre direction is further lower by up to more than 100 times. Under ideal condition, if do not take coupling capacitance between fibres into account, in CFRP, the current can only flow through individual carbon fibers, as the fibers are surrounded by insulating polymer. However, because of the presence of inter-fiber contact points, the current may flow from fibre to fibre. So, the total electrical impedance of a piece of CFRP material is an assemblage of the impedance of all fibers and their structure. Due to its internal structure, for unidirectional CFRP laminates, the electrical properties are anisotropic, which means that along fiber direction (0^0 direction), the conductivity of the composite is calculated by total single-fiber conductivity and fiber-volume fraction, while the conductivity is relatively small perpendicular to fibers (90^0 direction). The current switch between fibres depends on the existence and number of inter-fiber contact points. Some resistance values of CFRP material are shown in Table 1.

2.3 *Defects in CFRP*

A particular component has various physical and mechanical properties and also there have different damage mechanism, as is the case for CFRP. Some of the defects which may change the material properties and adversely influence the performance of the component. These include planar flaws running parallel to the surface (delamination, ceramic debonding), perpendicular flaws (cracks of the matrix or of the patches) and volume imperfections (pores, voids, inclusions). Their existence can have a great impact on the performance of the material, it can be seen that some defects are similar and sometimes it is not easy to tell one from another. As the effects of different defects are various and a corresponding method is needed to deal with each one, it is very important to distinguish one type of defect from others.

2.4. Probe for Planar Defects

Planar cracks and delamination’s which are orientated in the same direction as the eddy currents are more difficult to find with conventional probes which are more sensitive to vertical defects, because planar defects are virtually no diversion of eddy current generated by those probes and have little or no effect on the impedance of the probes. Gap probe consists of a ferrite yoke through which a magnetic flux is excited by means of a pair encircling coils. When the lower end of the yoke is in contact with the material surface, the latter completes the magnetic circuit and eddy currents flowing in planes perpendicular to that surface appear. This probe has advantage of close electromagnetic coupling with the object under test.

2.5Defect Detection by Eddy Current Testing

Massive effort has been made in studying advanced NDT techniques capable of detecting defects in CFRP composites including ultrasound and X-ray. In industry especially aerospace, some traditional methods such as visual inspection, coin tapping, and ultrasonic pulse echo and low-energy radiography are already in use. More recently, late technologies like ultrasonic phased array scanning, electrical potential technique, near-field microwave, lamb waving sensing and electrical resistance change method are catching more and more attention from research labs and industry. However, CFPR composites heterogeneous and anisotropic composition makes their structures too complicated to inspect by conventional non-destructive testing methods.

An application of eddy current testing which has rapidly grown in importance is the detection and sizing of surface and subsurface defects in materials. With recent improvements in design of electrical equipment and probes, the method is both more reliable and accurate. Eddy current flaw detection can test objects of almost any shape and size with help of development of more recent techniques such as multi-frequency testing. As discussed previously, when the structural property of conductive material is modified because of the presence of a flaw, a change in eddy current phase and amplitude will occur which is being monitored and can be observed by measurement equipment and then the defect characteristics could be analyzed. It has recently been demonstrated that eddy currents methods could be used for the inspection of composite materials. Previous work on the use of eddy current techniques for composites testing have shown that fibre damage with or without matrix cracking can be detected, and variations in fibre volume fraction is also successfully revealed.

Using eddy current testing, low energy impact damage (0.5J) in CFRP materials can be detected with better sensitivity than other popular NDT technique such as radiography, ultrasonic, and infrared thermography.

To detect the flaw in CFRP, one simple way is to scan the inspected object using a single-coil probe of appreciate design and keep the lift-off constant. Then look into the output signals to check if there has any abrupt change due to sharp discontinuities in structure. When a defect or any kind of discontinuity occurs in the object in which eddy current is induced, the paths of the currents are diverted and changes in impedance of the coil take place in a way in accordance the nature of the defect. It is already proved that the parallel defects such as planar cracks and delamination’s which are in the same direction as the eddy currents is difficult to detect, so care should be taken in directing the axis of the coil or use other type of probe. Effort has been made to predict the relation between changes and defect’s size and shape using analytic methods and realistic results have been obtained by the following modeling techniques:

- Theoretically by the use of numerical methods;
- Mechanically by introducing artificial defects;
- Coupled mechanical and electrical models.

One of the most important issues in eddy current testing is how to generate eddy currents in the inspected object and received them back, which is largely dependent on the design and setup of the eddy current probe. The configuration of the probes could be a single coil with air core, or a pair of coils with several turns which are wound on formers of specific material and used as transmitter and receiver respectively. For certain application, there may have wide range of choice for the coil number, former material, former shape and the probe size. This section will give a further discussion on some designs of eddy current probes for detecting different defects in CFRP.

IV.CONCLUSION

In the last several decades, NDT techniques have been increasingly developed and intensively applied in industry. However, more advanced and reliable NDT methods are still urgently required to meet the demand in rapidly growing industries such as aerospace, automobile and medical device. Among the popular and comparatively mature NDT methods, eddy current testing owns advantages over others in such as cost, development period and efficiency and eddy current instrument can realize in-service and non-contact testing. Eddy current testing is expected to help provide a more complete picture of the structural integrity and properties of the objects being tested. To improve the performance of CFRP, it is necessary to take inspection on the materials both during the manufacturing process and service time. Considering the cost and efficiency, non-destructive characterization is proved as a very useful tool to make sure CFRP component working properly without failure

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