Eddy Current Modeling in Composite Materials

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Abstract—The production of carbon fiber reinforced polymers, which are widely used both in civil and military applications, is an elaborate process un-free from faults and problems. Problems during the manufacturing, such as plies’ overlapping, can cause flaws in the resulting material, this way compromising its integrity. Compared with metallic materials, carbon epoxy composites show a number of advantages: Higher tensile strength, lower density and coefficient of thermal expansion, absence of fatigue state related phenomena, possible manufacturing of large layered structures. Within this framework, this work aims to propose a design of ferrite core probe for eddy current non destructive evaluation, in order to investigate the presence of defects in carbon fiber epoxy composite materials. The effect of the ferrite core is analyzed in order to focus magnetic flux density on the investigated specimen. Eddy currents generated by high speed ferrite core probe movement were investigated by using numerical simulation. Particularly, a Finite Element Approach has been exploited in order to characterize the transducer to specially emphasize the presence of defects in a multi-layer carbon fiber epoxy structure.

1. INTRODUCTION

Given their specific characteristic, the Carbon Fiber Reinforced Polymers Epoxy (CFRP/E) composites are used in different application, from airspace industry to civil applications. Nowadays, air companies exploit airplanes of their fleets as much as possible in order to amortize purchase and maintenance costs, in a sort of trade-o with the high safety requirements. Moreover, it is easy to understand how mechanic solicitations and atmospheric agents are responsible for a relatively rapid degradation of airplanes’ structures. Therefore, they must be produced in an almost perfect state, in order to not introduce other dangerous risk factors. But the manufacture process of CFRPs can induce a number of characteristic flaws, e.g., delaminations, inclusions, porosities. Therefore, it is absolutely necessary to carry out cheap tests of conformity and integrity. Thus, Non-Destructive Testings (NDTs) and in particular ferrite core Eddy Current (EC) probes are useful for our aims. In fact, it is possible to easily analyze even highly thick metallic as well as nonmetallic materials, with a good resolution and a remarkable operative versatility [1]. This technique, based on the investigation of magnetic flux of coils placed close to the specimen under analysis, is used to detect and characterize possible flaws or anomalies in workpieces. Typical testing configurations may consist of ferrite core coil probes, placed above a planar (or at least locally planar) conductive specimen and operating in the time-harmonic domain, at frequency depending on the problem (typically between a few [Hz] to a few [MHz]) [2]. The aim of ferrite core is to focus the magnetic fields into the specimen, in order to increase the probe sensitivity to the defect. For each application, the coil model as well as the operating frequencies are set according to the task. This work proposes an integrated approach starting from the design and implementation of a novel probe in order to optimize the sensor effect and the drop-in suppression, the operating parameters of the frequency and field strength. For our purposes, a Finite Element Analysis (FEA) code will be exploited for geometrical and physical modeling. Problems are so related to the possibility of classifying the flaw starting from the eddy current measurements. Various solutions are known in scientific literature to solve this kind of inverse problem [3]. In particular, an essential approach is due to advances of computational intelligence techniques. The paper is structured as follows. Section 2 briefly describes the electrical properties of carbon fiber. Section 3 presents the FEA approach. Subsequently, results about crack detection are shown. Finally, Section 4 draws up our conclusions.

2. CARBON FIBER ELECTRICAL PROPERTIES

In this section, a characterization of electromagnetic properties of CFRP materials is proposed. Knibbs and Morris [4] demonstrated that there is a linear relationship between the electrical resistivity and $\sin^2(\theta)$, where $\theta$ is the angle between the nominal lay of fibers with respect to the
Carbon fibers have an intrinsic electrical conductivity; therefore, one might expect that the composite material made from these fibers would be electrically conductive in the direction of the fibers. However, considerable transverse electrical conductivity is also observed. This transverse conductivity is a result of significant fiber-to-fiber contact. As might be expected, the longitudinal conductivity increases linearly with the fiber volume fraction. The transverse conductivity increases with the fiber volume fraction in a more complicated scaling relationship. The electrical anisotropy depends on the volume fraction of the material; hence, the longitudinal conductivity varies between $5 \times 10^3$ and $5 \times 10^4$ [S/m] while the transverse conductivity between 10 and 100 [S/m]. When the unidirectional layers are composed in a cross-ply forming a composite plate, there is the presence of a cross-ply [4], equal to 7633 [S/m]. Another peculiarity of these materials concerns the trend of the induced currents: They have an elliptical pattern caused by the anisotropy (see Figure 5).

3. FEA APPROACH

In this section of the paper, we want to show how simulate the behavior of a ferrite cored EC in order to detect delamination defects in CFRP materials. The simulations exploit the Finite Element Method (FEM) and require geometrical and physical definition of the same coil, its ferrite core and the CFRP plate. The exciting current, i.e., $I_{\text{eff}}$, and the frequency, i.e., $f_{\text{exc}}$, have been chosen according to the skin-effect phenomenon. For our purpose, we verified the distortion of EC’s flux lines (A/m$^2$) caused by the presence of defect and the magnetic field’s density (T) while the probe moves right over the surface defect. In our FEAs we use the $A - \psi$ formulation [5]. In a general subdomain $\Omega$, the magnetic potential $A$ is obtained by:

$$-\nabla \cdot (j\omega \sigma - \omega^2 \epsilon_0 \epsilon_r) A - \sigma v \times (\nabla \times A) + (\sigma + \omega \epsilon_0 \epsilon_r) \nabla V - J^e = 0$$

(1)

$$j\omega \sigma - \omega^2 \epsilon_0 \epsilon_r) A + \nabla (\mu_0^{-1} \mu_r^{-1} \nabla \times A) - \sigma v \times (\nabla \times A) + (\sigma + \omega \epsilon_0 \epsilon_r) \nabla V = J^e$$

(2)

where $\sigma$ is the conductivity; $\omega$ is the angular pulsation; $\mu_0$ and $\mu_r$ are the void’s magnetic constant and the material’s permeability respectively; $\epsilon_0$ and $\epsilon_r$ are the void’s and the material’s dielectric constants, respectively; $v$ is the instantaneous velocity of the object derived from the expression of the Lorentz force and $J^e$ is the external current density on exciting coil. $v$ has been varied, and set to 5, 10 and 15 m/s. In order to set point-by-point $J^e$, we used the direction cosine trigonometric

![Figure 1: Relation between the principal axes, reference axes, and fiber orientation.](image)

Table 1: Coil and E-shaped ferrite-cored dimensions.

<table>
<thead>
<tr>
<th>Coil (mm)</th>
<th>E-shaped core (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External diameter: 6</td>
<td>F: 4</td>
</tr>
<tr>
<td>Internal diameter: 4</td>
<td>E: 8</td>
</tr>
<tr>
<td>Height: 2</td>
<td>A: 11</td>
</tr>
<tr>
<td>Number of turns: 18</td>
<td>B: 5.25</td>
</tr>
<tr>
<td>Lift-off: 0.005</td>
<td>D: 3.5</td>
</tr>
<tr>
<td></td>
<td>D': 1.5</td>
</tr>
<tr>
<td></td>
<td>H: 2</td>
</tr>
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The ferrite core probe has been modeled according Figure 2 and Table 1. In our FEA code, we set the boundary conditions as follows. Magnetic insulation ($\mathbf{n} \times \mathbf{A} = 0$ derived from $\mathbf{B} \cdot \mathbf{n} = 0$), for fictitious subdomain (representation of an infinite volume) [8]. Regarding boundaries of plate, the continuity is insured by $\mathbf{n} \times (\mathbf{H}_1 - \mathbf{H}_2) = 0$ [8]. Our studies have been based on a discrete domain [9] having number of elements equal to 17287. Mesh has been generated with tetrahedral elements and a geometric dimension of 0.5 (mm) for the CFRP plate, the exciting coil and its ferrite core. The composite plate $[90^\circ, 0^\circ, 90^\circ]$ with dimensions $7 \text{ cm} \times 4 \text{ cm} \times 3 \text{ mm}$ has been modeled with three parallelepipeds representing three different layers. The conductivity of the CFRP plate is given by the following expression:

$$\begin{bmatrix} \sigma \end{bmatrix} = [R]^{-1} \cdot [\sigma'] \cdot [R]$$

(3)

where $[R]$ is a rotation matrix which relates the components in the primed coordinate system to the unprimed coordinate system (see Figure 1). Respectively, $[R]$ and $[\sigma']$ are equal to:

$$[R] = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(4)

$$[\sigma'] = \begin{bmatrix} \sigma_l & 0 & 0 \\ 0 & \sigma_l & 0 \\ 0 & 0 & \sigma_{\text{cross}} \end{bmatrix}$$

(5)

where $\sigma_l$ is the conductivity along the fibers, $\sigma_t$ is the conductivity transverse to the fiber and $\sigma_{\text{cross}}$ is the conductivity with overlapping of unidirectional layers [7]. These reference axes, along which the conductivity matrix is diagonal, are called the principal axes. When the fibers are oriented at some arbitrary angle $\theta$ (as shown in Figure 1) with respect to the $x$-axis, the conductivity matrix
Figure 4: $XY$ plane: Eddy current distribution for various fiber orientations. (a) Fiber orientation: 0 Degrees, (b) fiber orientation: 90 Degrees.

Figure 5: Elliptical pattern for induced currents.

Figure 6: Variation of magnetic flux with respect on linear scanning direction with variation of the dimension of the crack.

is no longer diagonal and there is cross coupling of the components. Figure 4 illustrates the eddy currents distribution for various fiber orientation. During our computer simulations, frequency $f_{exc}$, current $I_{exc}$ and the size of the defect have been varied. Figure 6 depicts results of the analysis for different size of defect in CFRP, with a $f_{exc} = 1$ [MHz] and a $I_{exc} = 100$ [mA]. Figure 6 shows results of numerical simulations for a cylindrical defect’s with a basis’ diameter from 0.1 [mm] to 1 [mm]. It is possible to note a clear magnetic field’s variation for $x = 0$ [mm]. Figure 6 shows that an increasing of defect’s dimension corresponds to an increasing of magnitude of magnetic flux density, from $1.2 \cdot 10^{-3}$ [T] to $3.5 \cdot 10^{-3}$ [T]. We expect such kind of increment also in real applications, but other experimental conditions (e.g., absence of perfect geometry) may affect the increment itself. Figure 7 describes how the magnetic field in high-speed case is asymmetric. In
general, the magnetic field strength decreases when the probe speed is increased. Therefore, eddy currents due to probe movement not only distort the probe of magnetic field but also decrease the intensity of the magnetic field during the inspection.

4. CONCLUSION

In this paper, an implementation of high speed ferrite cored EC probe for detection of defect in composite materials is presented. Based on numerical simulations carried out with a FEM based approach, eddy currents and magnetic flux’s density variations during the inspection have been investigated. For the implementation of ferrite core EC probe, a time-harmonic FEA code with 3-D geometries has been studied to evaluate the progressive increase of the investigation size of the defect for the variation of magnetic flux density (in modulus). The proposed method provides a good overall accuracy in detecting defect’s presence, as our simulations demonstrate. At the same time, the procedure should be validate for defect with different shape of for different ferrite core probe profiles. The presented results can be considered as preliminary results; further work suggests the possibility to focus on the development of the proposed high speed inspection system, which involves: Probe design and optimization based on 3-D numerical simulations; feature extraction from FEA signals; defect characterization using signal processing techniques and Artificial Neural Networks for inversion algorithms at high speed measurements. The authors are actually engaged in this direction.

REFERENCES