Determination of Indication Depths at High Frequency Eddy Current Testing of CFRP

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Abstract. Nowadays, consumption and production of the carbon fiber reinforced polymer (CFRP) increase very fast, therefore a demand for the relatively simple and fast methods of quality control increases as well. Thanks to the sensitivity, ease of application and fast speed of utilization, High Frequency Eddy Current (HF EC) method is increasingly used for quality control of CFRP. One of the most important and complicated existing tasks for the method is the determination of the real depth of the indication or defect e.g. for carbon fiber ply determination.

In order to address this task experimental and numerical study has been made. The last was based on the concept of the coils combination with different operating frequencies, which provides different penetration depth into CFRP and, in the result, the possibility to quantify it. First experiments in this direction showed encouraging results, where half-transmission 2-coils sensors with different operating frequencies and penetration depth were used for the depth determination of copper elements embedded in laminated cross-ply CFRP specimen. The finite element modeling was done, compared with experiment and results are discussed in the paper.

Introduction

Every year usage of advanced composite materials increases dramatically, among them CFRP and glass fiber reinforced polymer (GFRP) are holding the dominant place [1]. This effect could be explained by their outstanding thermo-mechanical properties, superior corrosion resistance, high strength-to-weight ratio and rigidity which are required in aerospace (aircrafts, spacecrafts, micro air vehicles (MAVs)), automotive and wind industry, civil engineering (e.g. retrofitting, concrete reinforcement), sports goods and other consumer and technical applications [2].

Anisotropic materials like CFRP and GFRP consist of components, which have various physical and mechanical properties (e.g. conductive carbon yarn and dielectric epoxy matrix) and exhibit different damage mechanisms, which can occur during manufacture or in service. For evaluation of the defect’s harmfulness, as well as the necessity to change or repair the part, an information about its type, location, size and depth is essential [3]. For example, one of the known defects is out-of-plane waviness (or undulations), which doesn’t lead to a strong difference in inhomogeneity in comparison to the whole structure. This
exacerbate a task to detect them, whilst the amplitude of the wave and its depth plays significant role in the judgment about the textile part validity [4].

The textile production of CFRP is focused on the development of various types and structures of the textile, and on the study of the innovative fiber orientations as well as binding [5]. For the assurance of woven structures’ quality it is needed to define an orientation of fibers on different depth.

For these and other important tasks, an appropriate method has to be found. Conventional non-destructive methods for CFRP composites include IR thermography, X-ray tomography and a variety of ultrasonic (US) techniques. Thermography methods are portable and economic and could cover large components in a single image. The main challenge is, to determine the specimens’ information precisely from the measured data, which requires many complex algorithms [6], [7]. X-ray tomography, e.g. micro-CT, is very precise and easily locates three-dimensional defects regardless of CFRP composite type [8], [9]. However, X-ray tomography scanners are very expensive and cumbersome, 3-D X-ray imaging is very time-consuming and the size of the sample is very limited, all these make X-ray unsuitable for most field applications, particularly aerospace or automotive devices. Conventional US pulse-echo techniques usually require couplants or full immersion of the sample for optimal energy transfer, which can affect overall scanning speed and greatly limit the number of applications where these techniques can be used. [10], [11]. More advanced optical methods, such as digital image correlation (DIC) and optical coherence tomography (OCT) are sometimes used, but they are usually limited to surface inspection or measurements on semi-transparent composites [12].

In recent years Eddy Current (EC) testing [13, 15, 16] becomes more widespread for CFRP investigation thank to the relatively low costs of its inspection and utilization and high operational speed. In comparison to other, EC method doesn’t require additional coupling (as US), mechanical loading (as DIC) and doesn’t extremely limit the inspected area (as X-ray). EC spectroscopy is used for investigation of electric properties of conductive materials. The induced primary electromagnetic field (EMF) affects conductive material, where under its influence eddy and displacement currents occur, which induce a secondary magnetic field (MF), directed opposing to the primary field and resisting its propagation. The resisting MF is dependent of the material’s conductivity, where the higher the last one, the higher the opposing field. Resulting difference between generated and induced voltage (resulting induced voltage) is measured and analyzed.

Using the current EC testing systems, a depth determination is only possible to a very limited extent with use of 2D Fourier transformation. Current research is concerned with the variation of physical parameters of the EM coils, such as the measurement frequency and the diameter for receiving a new approach of the depth determination using the new HF EC method.

Methodology

HF EC tomography is based on the principle of conventional Eddy Current (EC) inspection, but operates on frequencies up to 100MHz, whereas EC works on kHz range. As well as EC introscopy, HF EC is non-invasive, relatively cheap and easily applicable for investigation of the conductivity distribution of the mechanical parts, which have various curvature and size.

Due to high operating frequencies HF EC is more sensitive to small deviations in conductivity in the material and allows evaluation of not only conductive, but dielectric properties as well. The last could be explained by the Equation 1 which shows that total currents in the material caused by the magnetic field circulation \( \mathbf{rot} \mathbf{H} \) are the sum of the electric current density \( \mathbf{j} \) and displacement current \( i \omega \varepsilon \mathbf{E}_0 \), which occur in dielectric
component ($\varepsilon$) and has the bigger influence beginning from the certain frequency $\omega$. Presence of displacement currents is the main specific feature of the HF EC method, which differentiates it from the conventional EC spectroscopy.

$$\text{rot}\vec{H} = \frac{\partial (\varepsilon \vec{E})}{\partial t} + \vec{j} = \vec{j} + i\omega \varepsilon \vec{E}_0.$$  \hspace{1cm} (1)

As CFRP is a composite structure, which consists of the inhomogeneously conductive textile and dielectric epoxy matrix, for its inspection, a HF EC method should be taken, which is sensitive to all of the components of the material. In the paper two approaches are suggested for depth determination using the HF EC method, based on the physical principle of the attenuation of the EMF in a material.

The exponential decay of currents in thickness is basic and understandable principle of EMF behavior penetrating into conductive materials (Eq.3, Figure 1(a)). Despite the inhomogeneity, EMF in CFRP in general has the same character, as in other conductive materials, where the higher the frequency of EMF the smaller the penetration depth. The layer, where the field’s concentration reaches its maximum and which depth corresponds to the value, where fields decay exponentially is known as skin layer (Eq.2).

$$\delta = \frac{1}{\sigma f \pi},$$ \hspace{1cm} (2)

$$J = J_s e^{-(1+j)d/\delta},$$ \hspace{1cm} (3)

where $f$- EMF frequency (Hz), $\sigma$- conductivity of the material [S], $J_s$ is the current value at the surface [A], $d$-depth [m].

The first concept intends the EC image data processing using threshold for currents density on depth. From the Eq. 2 and Eq. 3 is obvious, that starting from some frequency $f$ electromagnetic field fully penetrates the CFRP specimen. Here EMF decreases exponentially, as well as resulting currents. When investigated structure lays deeply, the EMF at that level is not strong enough to excite high density of Eddy Currents in the structure, therefore the resulting signal which corresponds to the structure’s location also decreases with depth. This aspect was used in previous work for depth quantification, where for textile CFRP a voltage value threshold was set, which corresponds to the different attenuation on certain depth [14]. The deeper the defect layer was - the lower the threshold.

![Fig. 1. a) Eddy Current distribution into conductive material; b) Schematic concept of sensors combination for depth differentiation](image-url)
The results are presented on the Figure 2. This approach could help differentiate a depth of clearly visible defects knowing the attenuation character of EMF for certain frequency for the specified material. For cases of out-of-plane waviness or CFRP plies on depth separation such approach is not appropriate. Therefore, other concept was suggested.

The second concept is based on the combination of different coils that provide different operating frequencies, depending on their parameters (diameter, amount of windings, etc.), where excitation EMF penetrates studied material on different depth. The more sensors are used – the higher depth resolution could be achieved (Figure 3). Measurement results, received in the form of images of conductivities in CFRP on different depth are combined, allowing to evaluate material’s layers separately and to clearly identify defects on different depths.

To prove a concept, experiments were conducted using EddyCus MPECS® device and cylindrical multilayer coils with different diameters and operating frequencies (Table 1), obtained results were compared with simulation data in ANSYS Mechanical.

Results

In order to check the validity of our concept we performed experimental study of defects’ on depth in CFRP quantification by using coils with various parameters on specially fabricated specimen. The tested specimen was 16 cross-ply CFRP with stacking sequence [45/-45] with sizes of 160x75x4.5 mm length, width and high respectively, schematic representation and photo of the specimen are shown on Figure 4 (a), (b) [17]. Square copper foil elements 15x15mm were placed as conductive contrast markers with the step 1.33mm on depth from each other: 0, 1.33, 2.66 and 4 mm. In our experiment, the scanning area was 130x30 mm of the CFRP plate marked with dash-dotted contour on Figure 4 (b).

A list of used sensors is presented in Table 1, where each separate coil is cylindrical multilayer coil with ferrite core and shield with different diameter and resonant frequency. In experiment seven 2-coils combinations were used (half-transmission representation), where №1 is a pick-up coil with wide pass band used in every combination and №2-8 – various driver coils which differ by the resonant frequency, diameter and amount of windings. The placing of the pick-up coil for all experiments corresponds to the x-axis (0° angle Figure 4 (a)), where the currents distribution is close to the maximum. Operating
frequency for each coil was chosen near $F_{res}$ on frequency, where the coils pair is most sensitive, i.e. the system has the biggest signal difference between air and CFRP.

Scanning results are presented on Figure 5 for each driver coil listed on Table 1. The underlined number on Figure is an operating frequency value for each used coil. First line is an Imaginary part of the resulting EC signal for each coil which corresponds to the currents occurred on the reactive components in the material. The Real part presented on the second line on the Figure 5 corresponds to the conductive currents.

![Schematic representation of the CFRP specimen and experimental set-up;](image)

**Fig. 4.** a) Schematic representation of the CFRP specimen and experimental set-up; b) Photo of the specimen with dash-lined scanned area

<table>
<thead>
<tr>
<th>№</th>
<th>Type</th>
<th>$F_{res}$, MHz</th>
<th>$F_{act}$, MHz</th>
<th>Diam., mm</th>
<th>$w$</th>
<th>$d_{wire}$, mm</th>
<th>$R$, Ohm</th>
<th>$L$, uH</th>
</tr>
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<tbody>
<tr>
<td>1.</td>
<td>Pick-up</td>
<td>8</td>
<td>-</td>
<td>2,4</td>
<td>50</td>
<td>0.06</td>
<td>1,367</td>
<td>14,24</td>
</tr>
<tr>
<td>2.</td>
<td>Driver</td>
<td>31.45</td>
<td>28.65</td>
<td>2,4</td>
<td>15</td>
<td>0.125</td>
<td>0.103</td>
<td>1.18</td>
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<tr>
<td>3.</td>
<td>Driver</td>
<td>24.1</td>
<td>7.1</td>
<td>3,3</td>
<td>20</td>
<td>0.1</td>
<td>0.26</td>
<td>2.36</td>
</tr>
<tr>
<td>4.</td>
<td>Driver</td>
<td>16.1</td>
<td>6.6</td>
<td>7</td>
<td>20</td>
<td>0.25</td>
<td>0.1</td>
<td>4.85</td>
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<tr>
<td>5.</td>
<td>Driver</td>
<td>13.6</td>
<td>5.9</td>
<td>2.4</td>
<td>30</td>
<td>0.08</td>
<td>0.45</td>
<td>5.68</td>
</tr>
<tr>
<td>6.</td>
<td>Driver</td>
<td>8</td>
<td>2.05</td>
<td>2.4</td>
<td>50</td>
<td>0.06</td>
<td>1,239</td>
<td>15.69</td>
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<tr>
<td>7.</td>
<td>Driver</td>
<td>3.45</td>
<td>0.55</td>
<td>7</td>
<td>80</td>
<td>0.1</td>
<td>2.136</td>
<td>77.1</td>
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<tr>
<td>8.</td>
<td>Driver</td>
<td>2.4</td>
<td>0.45</td>
<td>9</td>
<td>100</td>
<td>0.1</td>
<td>3,214</td>
<td>172.2</td>
</tr>
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</table>

Table 1. List of the cylindrical coils used in the experiment

To understand behavior of the EMF in the CFRP on different frequencies, to prove experimental results, and to check the ability to predict which coils need to be created to penetrate a certain depth into the CFRP material, simulations were done and compared with experiment.

An electromagnetic field distribution in CFRP material and its dependence on the parameters of driver coils is investigated using finite-element modeling (FEM). A modelled specimen was designed as a sixteen-ply [-45/45]s CFRP, 60 x 60 x 4mm, length, width and thickness respectively. Voltage applied to the driver coil was 250 mV, longitude conductivity – 28.4 kS/m, transverse and through thickness conductivity – 4 S/m. Other parameters as coil resistance, diameter, amount of windings and resonant frequency were varied for each coil and listed in Table 1. The driver coil was placed directly above the center of the specimen with lift off 1 mm. For comparison, in Table 2 are presented an EC distribution character in accordance to the operating frequency of the coils. Here are showed Real and Imaginary parts of resulting currents (electric currents and Eddy Currents) in CFRP plate, with top and crosset cut view for coil №2 on frequency 28.65 MHz and coil №6 on frequency 2.05 MHz. As it could be seen from the images, the higher the frequency, the smaller the depth and radius of the currents distribution, moreover, it is seeing, that currents propagates along the fiber and directed 45° and -45°, and overlapped on the axis.
For analysis of the currents’ distribution in thickness, certain specimen volume under the pick-up coil was chosen. This procedure was done for each driver coil on operating frequencies used in experiment.

Table 2. Current distribution in \([45/45]\) CFRP for two coils with different resonant frequencies

<table>
<thead>
<tr>
<th>Coil</th>
<th>Fres, MHz</th>
<th>Fact, MHz</th>
<th>Real Top</th>
<th>Imag Top</th>
<th>Real part, crosscut</th>
<th>Imag part, crosscut</th>
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</thead>
<tbody>
<tr>
<td>№2</td>
<td>31.45</td>
<td>28.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>№6</td>
<td>8</td>
<td>2.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dependencies of the normalized current density over the depth for each driver coil are presented on Figure 6. Graphs a, b, c and d show coils’ curves for one, two, three and four detected layers respectively. The threshold of the highest current density, which correspond to the skin layer thickness, is shown with dash-dotted line. Simulated skin layer thickness value is compared with the experimental effective penetration depth and discussed in the paper.
Results of the depth determination using different coils combinations are presented. The simulation and experimental results shown on Figure 5 and Figure 6 are analyzed and compared.

Estimating the penetration depth from experiment and skin layer value for driver coils from modeling, from Figure 6(a) it could be seen that for coils №2 with Fact = 28.65 MHz and №3, Fact = 7.1 MHz, modeled penetration depth is big enough to detect 2 Cu elements, but EC images for these two coils from Figure 5 shows that only the first Cu element is detected for Imaginary and Real parts. For coils №5 Fact = 5.9 MHz and №4 Fact = 6.6 MHz simulations showed a possibility to detect 2 Cu elements on depth 0 and 1.33 mm, but the signal penetration depth is close enough to locate the Cu element on depth 2.66 mm. Experimental images confirm modeling results and presents only the first 2 Cu elements. Experimental results for coil №6 Fact = 2.05 MHz conform to the modeling results which declare the possibility to detect 3 Cu elements. For low frequency coils №7 Fact = 0.55 MHz and №8 Fact = 0.45 MHz the experimental EC scan showed the full penetration into the specimen and detection of 4 Cu elements, compared to modeling, where 3 Cu elements are distinguishable.

It is evident from the experiment that the contrast of the Cu elements is decreasing with depth, what correlates with the modelled curves’ character. The highest image resolution was obtained with the smallest driver coils (with diameter 2.4, 3.3 mm), as well as insignificant influence of edge effects in resulting image compared to the coils with 7 and 9 mm diameter.

As it was presented, not all modeled values correspond to the experiment. That could be explained by several imprecisions. The CFRP conductivity set for modeling was the average for such type of CFRP, but not measured exactly in studied specimen. Also, mistake of the interpolation for scattered currents value which correspond to its inhomogeneous
distribution in dependency of the fiber orientations, could play significant role. Cu elements embedded into the specimen could act as an effective electromagnetic conductor, therefore penetration depth differs with the model, where it was estimated in the poor CFRP. However, in authors’ opinion, the energy conversion and transmission in CFRP in 2 coils’ system have the most impact. Here half-transmission coils have the form of transformer where driver and pick-up coils differ by the parameters (e.g. amount of windings) and are connected partially through the CFRP, where each coils’ pair has different distance in-between. All the coils parameters as well as distance in-between and properties of medium are influencing the energy transmission and have to be studied. Also, the pick-up coil plays a role of a pass band filter and could exclude the informative signal corresponded to the certain depth, therefore driver and pick-up coils system has to be spectrally adjusted.

Conclusions

In the paper was discussed the novel concept of HF EC application for depth of CFRP differentiation. It was suggested to use diverse EM coils with different resonant frequency for receiving various penetration depth following the equation of EMF in material attenuation. Validity of the method was checked experimentally and compared with the model. It was shown that the approach works and among experimental coils four could be chosen to divide a depth on 4 regions with depth resolution 1.33mm. Modeling results in the rate of 50% couldn’t correlate with experiment, which could be explained by inaccuracies of the CFRP model. As results showed, this work would be a great basis for the next development of the method and its successful implementation in industry.

References

[17] Specimen was produced and provided by ITM TU Dresden.