PROCESS MONITORING FOR RESINS, CARBON FIBER FABRICS, PREFORMS AND CONSOLIDATED CFRPS BY HF RADIO WAVE TECHNIQUES

H. Heuer\textsuperscript{1a, b}, M. Schulze\textsuperscript{a}, M. Pooch\textsuperscript{a} S. Gäbler\textsuperscript{a, c}

\textsuperscript{a} Fraunhofer Institute for Ceramic Technology and Systems, Material Diagnostic, Dresden
\textsuperscript{b} TU Dresden Chair Sensor Systems for Non-Destructive Testing, Dresden
\textsuperscript{c} Leibniz Institute of Polymer Research Dresden, Germany

Keywords: CFRP, carbon fibre, non-destructive testing, high frequency eddy current, imaging impedance spectroscopy

Abstract
Eddy current testing is well established for non-destructive testing of electrical conductive materials [1]. The development of radio frequency (RF) eddy current technology with frequency ranges up to 100 MHz made it possible to extend the classical fields of application even towards less conductive materials like CFRP [2][3]. It turns out that RF eddy current technology on CFRP generates a growing number of valuable information for comprehensive material diagnostic. Both permittivity and conductivity of CFRP influence the complex impedance measured with RF eddy current devices. The electrical conductivity contains information about fiber texture like orientations, gaps or undulations in a multilayered material. The permittivity characterization influenced by dielectric properties allows the determination of local curing defects on CFRP e.g. hot spots, thermal impacts or polymer degradation. An explanation for that effect is seen in the measurement frequency range and the capacitive structure of the carbon rovings. Using radio wave frequencies for testing, the effect of displacement currents cannot be neglected anymore. The capacitive structures formed by the carbon rovings is supposed to further strengthen the dielectric influences on eddy current measurement signal [3]. This report gives an overview of several realized applications and should be understood as a general introduction of CFRP testing by HF Radio Wave techniques.

1. Introduction

Along the value chain of carbon fibre reinforced plastic (CFRP) different nondestructive testing (NDT) methods such as ultrasonic, thermography, x-rays or optical methods are successfully applied [5]. However, looking in more detail at the process chain, there is a gap where standard NDT methods cannot be used. For automated mass production facilities based on infusion processes (e.g. RTM – Resin Transfer Molding), it is important to acquire quality parameters prior to the resin infiltration step. This opens up the possibility of in-time process recalibration, for rework or repair of the fiber preform, if necessary. With knowledge of the incoming material characteristic at the textile- or preform stage, the following process steps can be adjusted in-time to reduce final part rejects resulting from defects in the pre-stage material. If problems like missing or misaligned fibre bundles, waves or insertions are detected in time, the further processing can be stopped and readjusted resulting in less material waste. In addition, subsequent process steps can be controlled by utilizing the information on the incoming product quality e.g. gaps between fiber bundles which will influence the infiltration behavior. The current trend in aerospace industries is to evolve to more large primary aircraft structures in CFRP with high levels of function integration, resulting in more expensive parts and increasing the need for first-time-right products to avoid complex repairs. A critical defect originated in the lay-up phase, is Foreign Object Debris (FOD) introduced in the manual process steps. FOD prevention campaigns cannot reduce the occurrence to zero and therefore an inspection stage before subpart consolidation and -final cure can be economically interesting. This leads to an increasing demand for NDT methods that can be applied inline to dry multilayered carbon textiles as well as wet and consolidated materials. The application of ultrasound, thermography or sheargraphie

\textsuperscript{1} Corresponding Author: Prof. Henning Heuer, Fraunhofer IKTS-MD, Maria-Reiche Str. 2, 01109 Dresden, Germany henning.heuer@ikts.fraunhofer.de, T:+49 351 88815 630, F: +49 351 88815 509
requires solid state material for mechanical or thermal wave propagation or for deformation analyses respectively. Due to this limitation these standard NDT techniques cannot be applied to dry or wet pre stage components.

Table 1 Questions to be answered by NDT along the CFRP value chain.

<table>
<thead>
<tr>
<th>Process Step</th>
<th>Question to be answered by NDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Carbon Rowing</td>
<td>Number of Filaments? Type of Filaments, Cuts or Damage?</td>
</tr>
<tr>
<td>2 Fabric</td>
<td>Number of layers and its orientation? Misalignments / Waves /Gaps? Insertions?</td>
</tr>
<tr>
<td>3 Preform</td>
<td>Right stack pre assembly? Waves or misalignments after draping</td>
</tr>
<tr>
<td>4 Component</td>
<td>Dry spots, Curing process successful? Delamination?</td>
</tr>
<tr>
<td>5 Product Life Cycle</td>
<td>Degradation of Fibres? Degradation of Polymer? Re-Qualification or Recycling?</td>
</tr>
</tbody>
</table>

An ideal NDT method should be applicable along the whole CFRP value chain, from the fibre bundle over the fabric/prepreg and preform stage up to components and its life time. This paper provides an overview about a radio frequency technique that was emerged by an extension of state of the art eddy current techniques. Typical tasks of radio frequency techniques are the determination of fibre bundle orientation, misalignments, gap size distribution, local fibre areal weight / thickness and waviness. By measuring dielectric properties curing effects, hotspots, dry spots and polymer degradation can be analyzed, too. The RF technique shows a high potential to be used as an integrated inspection technique along the whole value chain and product life time by imaging the electrical and capacitive properties of CFRP nondestructively (Table 1).

2. Radio Frequency Inspection

Eddy current (EC) technology is a well-established nondestructive method for the characterization of surfaces or materials by analyzing conductivity and permeability variations. A primary magnetic field is generated when an alternating current is applied to an induction coil. Eddy currents are generated in a conductive specimen when the coil is placed near that specimen (Figure 1).
The eddy current within the specimen generates a secondary magnetic field opposed to the primary field. If the material properties are changed e.g. due to a deviation of current paths resulting from cracks or insertion in the sample, the secondary field also changes and causes a complex impedance shift in the pick-up coil. The measured values from the pick-up coil are evaluated on the complex impedance plane. An important parameter is the frequency of the excited alternating current. Due to the skin effect, the depth of excitation in the specimen decreases with increasing frequency. The point where the eddy current density has decreased to $1/e$, or approximately 37% of the surface density, is called the standard depth of penetration $\delta$[1]. The excitation depth into a material is affected by the frequency of the excitation current $\omega = 2\pi f$, the electrical conductivity $\sigma$, and magnetic permeability $\mu$ of the sample as given by:

$$\delta = \sqrt{\frac{2}{\omega \sigma \mu}}$$  \hspace{1cm} (1)

This skin depth effect is the most important limitation for frequency selection during inspection. E.g. due to the good conductivity of Aluminum a frequency in the kHz range or lower has to be used to generate an acceptable probing volume for conventional crack detection in Aluminum structures. But beside the penetration problem frequency has a second important effect. By the use of higher frequencies, the penetration depth will be lost but increasing signal strength can be obtained.

The density of the eddy current is influenced by the frequency itself. The modified Faraday’s law for a coil or wire explains the relation between magnetic flux and time domain, namely:

$$V = -N \cdot \frac{d\phi}{dt}$$  \hspace{1cm} (2)

where $V$ is the induced voltage or signal strength respectively, $N$ is number of turns, and $d\phi/dt$ is the rate of change of magnetic flux in Webers per seconds. Equation (2) simply states that the induced voltage is proportional to the rate of change of the magnetic flux. In other words, since a frequency is an inverse of time, when the frequency of the flux increases the pick-up signal, which can equally be regarded as induced voltage ($V$), also increases. Higher frequencies therefore represent a good option through which the sensitivity of the Eddy-Current method can be increased for low conductive materials such as Carbon materials due to the extended tradeoff between penetration depths and signal amplitude. Depending on conductivity and permeability of the material under test, an optimal frequency within the electromagnetic spectrum exists, exhibiting a suitable ration between penetration depth (equals to probing volume) and signal strength [6].

3. Electrical properties of CFRP and measurement setup
Unidirectional single layered carbon fiber material has a conductivity up to \( \sigma = 5 \times 10^6 \text{ S/m} \) in longitudinal and \( \sigma = 1 \times 10^3 \text{ S/m} \) in the lateral direction. Through variation of fibre type, fibre orientation, stacking sequence, fibre / volume content, fibre density and compaction around the carbon rovings, these values differ. In addition to the conductivity of the CFRP also its permittivity is important for Eddy-Current testing. It generates a displacement current in the material, which influences the measurement signal as well as the eddy current [9][10]. In a dry carbon material, the permittivity is dominated by the fiber coating and the surrounding air. In a CFRP the air is substituted by a polymer resin, so that the permittivity is depending on type and processing quality of the resin [9]. Figure 2 shows the main electrical effects of applying an alternating magnetic field to strongly anisotropic CFRP material that are influenced by three main parameters.

![Figure 2 Electric and dielectric behavior of carbon matrix composites](image)

Fiber/Volume Ratio: The Fiber/Volume ratio determines the amount of conductive carbon fibres in a volume section and defines the average electrical conductivity of the material, which needs to take into account for general measurement parameterization (frequency, penetration depth).

Electrical connection between fiber bundles: Depending on the structure (woven, crimped, non-crimped etc.) chemical and structural conditions of the interfaces of filaments and the consolidation density due to mechanical pressing, the electrical contact between neighboring bundles can vary. Identical materials can provide different degrees of Eddy-Current propagation due to the quality of internal electrical connections during consolidation. This effect identifies differences in handling or mechanical processing of the material.

Capacitive effect and displacement current: In addition to the electrical connection of fiber bundles, the dielectric properties of the matrix material also influence the complex signal impedance.

This three parameters can be analyzed by RF EC instruments. Medium Frequency Eddy-Current (MF EC) inspection instruments are available in many configurations by different commercial suppliers. Typically, the instruments are designed for manual handling of a single coil sensor or array probe with wheel tracker. The frequency range and parameterization of such standard devices is optimized for conventional NDE task such as crack detection or material identification for metallic specimens. Also, mechanical manipulators like X-Y-Z axe scanners or robot based manipulators are in commercial use to scan an EC probe over a 3 dimensional surface (e.g. rotor blades). For low conductive carbon based materials, the frequency range needs be extended to the HF range up to 50 MHz, and in some special cases up to 80 MHz is required. This frequency range was usually observed only in laboratory based equipment [10]. Initiated by the increasing demand for HF Eddy-Current measurements, instruments operating in the range of 100 kHz up to 100 MHz were developed. The results shown in the following chapters where acquired with EddyCus® instruments. Combined with a precision X-Y-Z manipulator with minimum 25 µm step width, high resolution HF EC images can be acquired. The sensors glide non-contact or lightly contacted over the surface. The used system can capture a maximum surface area of 300 mm by 300 mm with a maximum speed of 300 mm/sec.
at a sampling rate of 3,000 samples per second. In addition, the EddyCus® software provides a frequency sweep mode between 100 kHz – 100 MHz with 256 steps or a sequential multi-frequency data acquisition with up to four frequencies. The instrument allows the acquisition of complex HF EC signals in amplitude and phase shift in the complex impedance plane and as a time plot by C-Scan [4].

**Figure 3** EddyCus® systems 

a) Linear Axis system for flat and slightly curved structures and 

b) Robot based system 3d structures

To perform Eddy-Current measurements in a frequency range above 1 MHz mechanical vibrations (lift off variations) and electromagnetic disturbance needs to be controlled precisely. Also, electrical conductive dust in carbon contaminated environments can deteriorate the measurement results. To solve this practical problem a robust setup needs to be used that is shielded against dust and has an EMS safe architecture (Figure 3).

4. Experimental Results

4.1 Inspection of Texture and Waviness

As shown in [10][11] the HF Eddy Current technique can be applied to dry, wet and consolidated carbon based materials. One major task of HF EC is the characterization of waves inside carbon fibre preforms or consolidated materials. The image of Figure 4 shows in-plane and out-of plane waves perpendicular to each other. The In-plane wave can be seen directly due to the typical not straightforward orientation of the fibre bundle. An out out-of-plane wave shows a modulation of the signal amplitude.

**Figure 4** HF EC Images of CFRP plates with in-plane and out-off-plane waves. (Size 150 x150 mm x 5mm). a) indication of wave position, b) raw data image

Due to local changing of fiber volume content the signal amplitude changes depending on the out-

---

2 [http://www.youtube.com/watch?v=wNng6ClM1CM](http://www.youtube.com/watch?v=wNng6ClM1CM)
of-plane wave position. In Figure 4 the out-of-plane waves are indicated by black contrast change compared to the typical undulation of in-plane waves. Due to this different contrast mechanism it follows that in-plane waves and out of plane waves require a different algorithm for evaluation. For industrial application of HF EC Imaging techniques, the textural information like roving orientation, gap sizes or waviness needs to be extracted by image processing. Especially for multi axial materials, a two dimensional fast Fourier transformation (2D-FFT) shows high potential for automated fiber texture analyses [11]. In textured materials the image frequency is correlated with the periodic structure (e.g. CFRP wave). In relation to the texture of CFRP fabrics, the image frequency correlates with gap size and fiber bundle size whereas the rotation of the image frequency maxima represents a layer orientation. The Figure 5 a) shows a HF EC Image of a 3 axial non-crimp fabric with two horizontal layers on the back side. The corresponding 2D-FFT of Figure 5b shows the 3 characteristic lines indicating the 45°, 0° and -45° layer.

![Image of Figure 5](image1.png)

*Figure 5 Analyzing the image frequencies of a 5 layer CFRP (30 x30 cm) with two horizontal layers that differ by 2°. a) shows the raw HF EC, b) corresponding 2D FFT (rotated by 90°), The green line indicated the misaligned horizontal layer.*

By selecting one orientation and performing an inverse 2D-FFT the textural image of one individual layer can be reconstructed. The Figure 6 shows such a reconstruction of one layer of Figure 4 with significant In-Plane waves in-plane undulations[11].

![Image of Figure 6](image2.png)

*Figure 6 Analysis In-Plane waviness of Sample in Figure 4 by Filtering in the Fourier Space and following inverse FFT.*

4.2 Characterization of defects according to their depth

The modulation of the signal amplitude as a function of the depth of an out-of-plane wave can be explained by formula (1) and (2). The eddy current density decays exponentially with increasing depth. For an isotropy material with good conductivity, the current density can be calculated by:
\[ J(d) = J_s e^{-d\delta} \]  

(3)

Where \( J_s \) is the Current density at the surface, \( d \) is the depth of object and \( \delta \) the penetration depth shown in (2). But due to the strong anisotropy of CFRPs, this relation can be used only as rough estimation. To validate the in-depth resolution for a specific CFRP material, a reference sample with insertions in different depth has to be used. Figure 7 shows a HF EC Image of CFRP plate with 14th layers with a fiber volume content of 67\%. During the laydown process, pieces of copper foil where inserted between different layers. The shape of the copper foil was used to identify the insertion depth by reference after curing.

![Figure 7 HF EC Image of CFRP with inserted Copper foils in different depths.](image)

With increasing depth the signal amplitude and the phase angle where the maximum amplitude occurs is changing. In the following diagram Fig. 8, the signal amplitude over the number of CFRP layers covering the copper foil is shown. An exponential decay of amplitude such as expected by formula (3) was found. In this special case the copper insertion was seen until the 12th layer. The phase angle where the amplitude reaches a maximum shows a linear dependency on depth.

![Phase Angle and Signal Amplitude over Depth of Defect](image)
4.3 Characterization of Infiltration and Curing

As explained in chapter 2, not only the conductive carbon fibres but also the permittivity of the matrix material influences the eddy current measurement signal. This effect can be used for quality control of processes, where the complex permittivity of the composite changes [9]. So, potential applications could range from cure monitoring (e.g. resin flow front detection, determining the degree of polymerization) to the testing of consolidated CFRP with focus on infiltration or curing defects. A typical infiltration defect is the occurrence of unimpregnated dry spots [12]. That means that there is not enough resin reaching a certain area of the CFRP part. Consequently, matrix material is lacking locally. Which result in a deviation of local permittivity and local conductivity, especially at the contact points between roving’s. Consequently, this defect can be identified using eddy current, even when it occurs within the non-visible layers (Figure 9).

In addition to the ‘dry spots’ also ‘hot spots’ within a CFRP component can be identified using eddy current technology (Figure 10). Those defects can occur when component structure doesn’t allow an appropriate heat distribution, while dissipating the thermal energy that is generated during the curing reaction. If the temperature of the spot stays below the glass transition temperature of the resin (at that specific state of cure) the curing process gets faster. If temperature climbs above that temperature, thermal damage of the matrix material is the consequence [13].
Even in complex CFRP structures the ‘hot spot’ within the matrix can be well separated from fiber related effects. The change of the complex Eddy Current signal due to conductivity variations (e.g. varying number of layers) has a different direction compared to the change resulting from permittivity variations (Figure 11). The differentiation towards edge and lift-off effects is more challenging and requires further research work to be conducted.

![Figure 11 Eddy Current Data of 10x10 cm CFRP sample with a 'hot spot' displayed in the complex plane](image)

5. Conclusion

In the decision matrix of NDT methods for CFRPs, the HF EC method can provide unique information when compared to other NDE methods. CFRPs exhibit an electrical conductivity enabling the use of electromagnetic testing techniques. In recent years, high resolution eddy current imaging technology has been substantially developed further. HF EC Imaging is a potential technology for inspection of raw carbon fiber fabrics, infiltrated wet prepregs and consolidated CFRPs. HFEC based methods are interesting due to the simplicity of machinery integration, allowing HF EC sensors to be directly integrated into the process chain without affecting the material properties and quality. Textural analyses and fault testing can be performed with an image quality up to 500 µm resolution. Analyzing the quality of semi-finished products such as reinforcement fabrics very early in the value chain can help to increase the yield of the production process and the safety of the final product. The initial trials of FOD detection of a Ω stiffener in the prepeg stage proved to be successful up to 4 CFRP fabric layers deep in this configuration. This opens up the potential of two inspection intervals per stiffener in serial production. Small scale trials with manually operated probes are required to validate shop floor use and quantify real life inspection speeds. The potential to inspect terminating layers offers the possibility to integrate HF EC technique into a fully automated system for research on the production of airplane parts e.g. frames in the fuselage, produced in a RTM process at the DLR in Stade, Germany. The characterization of permittivity changes allows at the characterization of the curing process. In a long term vision the possibility of a non-destructive characterization of CFRPs textural properties may open the way for more accurate structural design and more consequent light weight design. Experiments currently conducted have to show if HF EC can be used to monitor CFRP ageing by observing deviation of dielectrical properties of the polymer matrix due to matrix degradation.
Literature

[8] International Telecommunication Union, Nomenclature of the frequency and wavelength Bands used in telecommunications, itu-t recommendation B.15

This conference publication is an excerpt of the open access publication of:

Heuer et al; “Review on quality assurance along the CFRP value chain – Non-destructive testing of fabrics, preforms and CFRP by HF radio wave techniques” Composites Part B: Engineering, Volume 77, August 2015, Pages 494–501,

Online access http://www.sciencedirect.com/science/article/pii/S1359836815001419