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Contribution to the Characterization of Carbon Fiber Reinforced Polymer (CFRP) Using High-Frequency Eddy Current "EddyCus®MPECS" Profiling Device

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Abstract. The rise of advanced materials science has led to widespread adoption of composite materials, particularly Carbon Fiber Reinforced Polymers (CFRP). CFRP combines the exceptional properties of carbon fibers (high-temperature resistance, low friction and corrosion resistance) with the benefits of a resin matrix (high specific strength, modulus, and fatigue resistance). This makes CFRP a versatile material for demanding applications in aerospace, military, automotive, sports equipment, and even medical fields. This paper explores the use of high-frequency eddy currents (EddyCus®) for non-destructive testing of CFRP. Unlike traditional methods limited to conductive materials, EddyCus® leverages frequencies up to 100 MHz to analyze changes in the probe's impedance. These changes, supported by Maxwell's equations and recent research, provide information on various material electromagnetic properties such as permeability, permitivity, and conductivity. The proposed approach involves scanning with the EddyCus® MPECS system four materials: copper (24% IACS), titanium (1.3% IACS), and two CFRP laminates samples with different thicknesses (0.22 and 0.44 millimeters) and fiber volume fractions between 60 to 80 percent. The system applies discrete frequencies in the MHz range, allowing us to analyze the material electromagnetic (EM) response as a function of frequency. For each scan, the MPECS software records the sensor voltage corresponding to each frequency point. This enables us to evaluate the variation of impedance and eddy current distribution within the material.

Keywords: Carbon Fiber Reinforced Polymer, Eddy current testing, High-frequency, Non-destructive Testing and characterization, Impedance variation, FEM simulation, EddyCus®MPECS.

1 Introduction

Carbon fibre reinforced plastic (CFRP) has been increasingly employed for structural materials in various industrial fields: aerospace, transport, energy, civil engineering and also on healthcare and sport; valued for their low density, high strength, fatigue resistance, and durability against heat and corrosion. Their structure multiple plies with varied fibre orientations or woven configurations enhances performance but introduces anisotropy and inhomogeneity [7][8]. Carbon fibres, embedded in an insulating polymer matrix, form conductive networks through occasional contact points, giving CFRPs directional electrical conductivity, as illustrated in Fig. 1 [9].

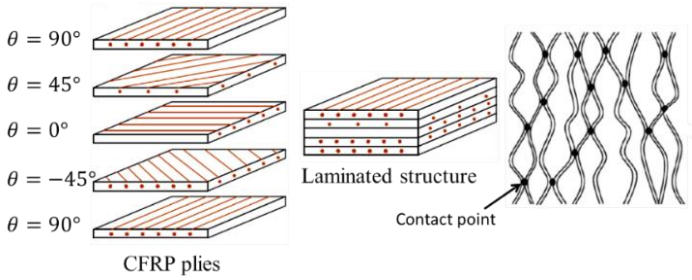

Fig. 1. Structure of a laminated CFRP with marked fiber contact areas.

Despite their excellent properties, these materials remain prone to damage from fatigue and impact, leading to mechanisms such as fiber breakage, delamination, or matrix cracking, the reason why CFRP should be continuously controlled and assessed during their lifetime [15]. This vulnerability highlights the importance of advanced non-destructive testing (NDT) methods, particularly eddy current testing (ECT), which provides a rapid, contactless, and real-time means of detecting conductivity variations caused by defects [10].

ECT is widely used for the inspection of electrical conductive materials in engineering field [1]. This method is based on electromagnetism theory. The ECT is based on the change in the electromagnetic quantities of the tested material to analyze its properties and defects. In general, ECT uses kHz range AC current to inspect high-electrical conductive materials, although, a few MHz AC current is used when low-electrical conductive materials, such as CFRP, are inspected [2]. ECT technology as one of the important means of composite defect detection, has also been a rapid development. An alternating current in the excitation coil generates a magnetic field that induces eddy currents in the nearby CFRP. These currents create a secondary magnetic field that opposes the primary one. Defects such as cracks disrupt this interaction, causing variations in the coil impedance, voltage, or current, which can be measured for material evaluation [3, 4, 6]. ECT uses electromagnetism to assess conductivity or permeability in materials. Higher frequencies (up to 100 MHz) allow this technique to probe less conductive materials, a capability offered by the "EddyCus®" system. Fig. 2 depicts the fundamental principles of ECT method [4].

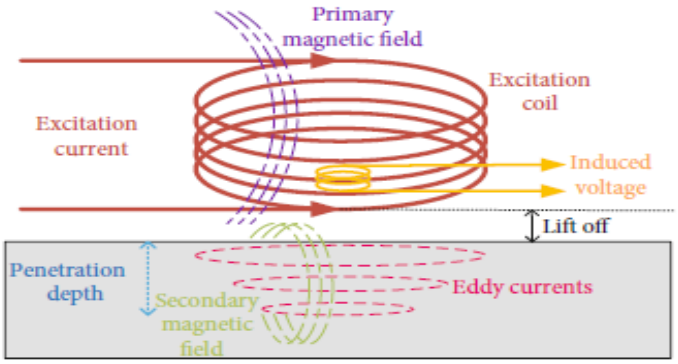

Fig. 2. Coil–specimen schematic for eddy current testing.

2 Theorical background

2.1 Anisotropy of CFRP

Because of their strong anisotropic behavior, CFRP structures must be designed and integrated into components in accordance with the applied load paths. This is necessary to maximize their exceptional specific stiffness and strength. Importantly, CFRP anisotropy is not limited to mechanical properties; it also affects electrical conductivity. The electrical response differs significantly between the fiber direction and the transverse direction. In contrast to isotropic metals, where eddy currents generated by a solenoid coil form circular distribution, EC in CFRP layers follow an elliptical pattern, as shown in Fig.3 from finite element (FE) simulations conducted in ANSYS. Additionally, the penetration of these currents through the laminate thickness is influenced by the stacking sequence and laminate architecture. The impact of these characteristics on the selection of an appropriate test frequency is further discussed in Section 2.3.

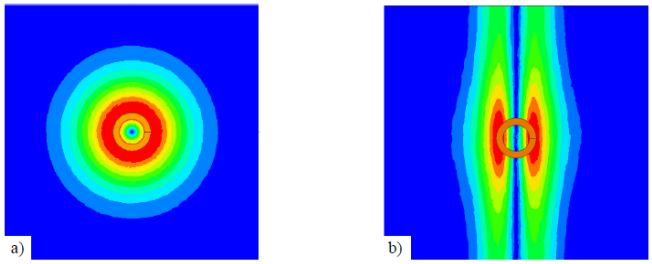

Fig. 3. Propagation of eddy currents in: a) isotropic material, b) anisotropic material (Unidirectional CFRP) when excited by a solenoid coil.

2.2 Electrical properties of CFRP

The electrical properties of single-layer, unidirectional CFRP materials depend on several factors and exhibit strong anisotropy (direction dependence) [3]:

Conductivity: The electromagnetic (EM) response of the composite is governed by its conductivity tensor. For unidirectional CFRP, the homogenised anisotropic conductivity tensor as a function of fibre orientation, θ_f, can be introduced as follows [16]:

$$[\sigma] = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} = \begin{bmatrix} \sigma_L cos^2(\theta_f) + \sigma_T sin^2(\theta_f) & \frac{\sigma_L - \sigma_T}{2}.sin(2\theta_f) & 0 \\ \frac{\sigma_L - \sigma_T}{2}.sin(2\theta_f) & \sigma_L sin^2(\theta_f) + \sigma_T cos^2(\theta_f) & 0 \\ 0 & 0 & \sigma_{td} \end{bmatrix} \quad (1)$$

where σ_L is the longitudinal conductivity, σ_T is the transverse conductivity and σ_{td} is the conductivity in the through-thickness direction. The longitudinal conductivity can reach values between 5×10^3 and 5×10^5S/m, while the lateral conductivity is significantly lower, ranging between 10 and 100S/m. These values can vary based on fiber type, orientation, stacking sequence, fiber volume content, density and compaction around the fibers. One of the main reasons for using eddy current testing on these weakly conductive materials is the use of test frequencies starting from 1 MHz. At these frequencies, in addition to line currents, displacement currents also develop at the fiber crossing points, as the matrix can act as a capacitor between closely spaced fibers, as illustrated in fig. 4 [12].

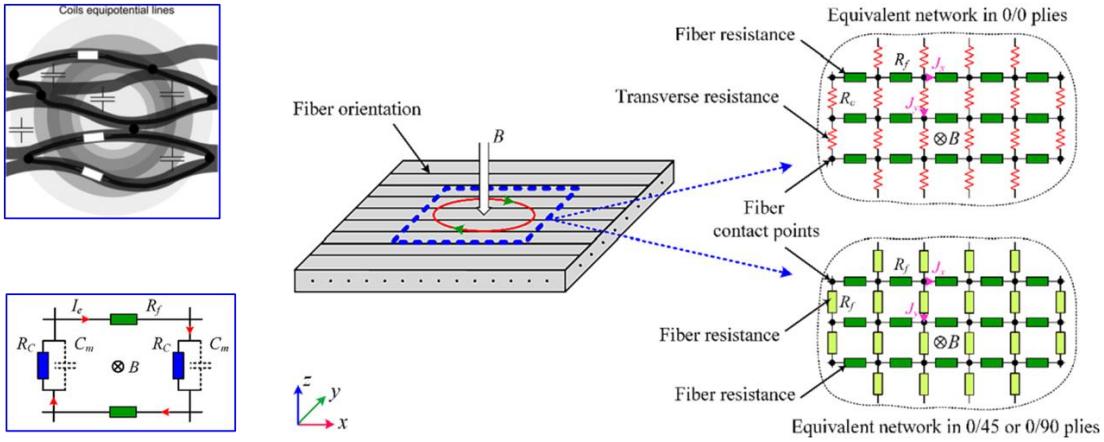

Fig. 4. Sketch of the electric and dielectric behaviour and the equivalent networks of resistance elements in CFRP.

Permittivity: this property, crucial for radio frequency (RF) testing, influences both the measurement signal and eddy currents. In dry carbon, the permittivity is mainly determined by the fiber coating and surrounding air. When CFRP is formed, the air is replaced by a polymer resin, causing the permittivity to depend on the resin type and processing quality. The effects of displacement currents and their influence on the measurement signals must be examined and understood in detail to enable reliable testing. On the other hand, this opens up a new field of application for eddy current testing. Until now, eddy current testing was limited only to components that were weakly or well-

conducting
electrically.

If permittivity differences can be measured at very high frequencies with optimized sensors, defects can be detected in almost non-conducting materials such as plastics [13].

Fig. 4 illustrates the main electrical effects of an alternating magnetic field on CFRP. Three key parameters influence these effects:

a. Fiber Volume Ratio: this ratio directly affects the average electrical conductivity due to the varying number of conductive fibers within a specific volume. This value is essential for setting appropriate measurement parameters like frequency and penetration depth.

b. Electrical Connections between Fiber Bundles: the structure (woven, crimped, etc.), interface chemistry, and consolidation density (achieved through pressing) all impact the electrical contact between neighbouring fiber bundles. Even identical materials can exhibit different eddy current propagation due to variations in internal electrical connections. The horizontal electrical connection (in-plane, parallel to the surface) directly influences the contrast in the RF image. The vertical connection (through the depth) affects the interlaminar interfaces and, consequently, the penetration depth.

***c. Capacitive Effect and Displacement Current*:** besides the electrical connections, the dielectric properties of the matrix material also influence the complex signal impedance.

2.3 High-Frequency EddyCus Testing in the frequency range of Radio Waves

The EddyCus® Multi Parameters Eddy Current Scanner (MPECS) system (Fig. 5, (a)) uses eddy currents to assess the conductivity of carbon fiber materials for quality control [5]. These materials, despite low conductivity, allow eddy currents to be induced in the fibers. The system's high-resolution sensors can scan with four frequencies, enabling detection and separation of defects across multiple layers. By processing the scanned images as shown in the fig. 5 (b) and (c), the image-based eddy current test of an aluminum plate with two horizontal grooves and a multiaxial carbon fiber fabric, respectively. The system can identify various flaws like missing fibers, misaligned threads, and inconsistencies within the material.

In eddy current testing, the standard penetration depth δ is defined as the length at which the eddy current density has decreased to about 37% of its value at the surface of metals. By the High-Frequency Eddy Current (HFEC) based Impedance the penetration depth is derived as follows [17,18]:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \sqrt{\frac{1}{\pi f\mu\sigma}} \qquad (2)$$

Where the angular frequency ω=2πf, μ is the permeability and σ is the electrical conductivity of the CFRP sample. The test frequency f can be varied to achieve the desired penetration depth. For example, voids in castings can be detected up to an adjustable depth or sheets can only be examined for surface cracks. In CFRP laminates, the standard penetration depth can usually only be estimated based on experience or by performing a series of complex tests [11].

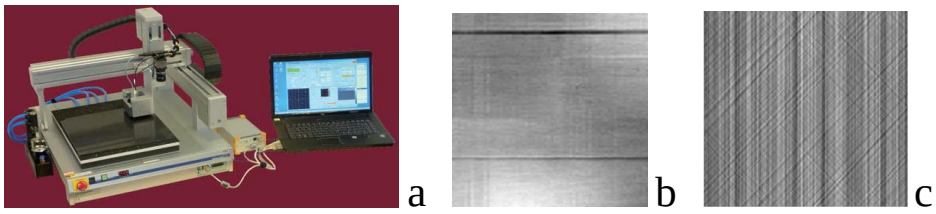

Fig. 5. Fig. 5. a) EddyCus® MPECS system device. Eddy-current scan of b) an aluminum plate with horizontal grooves, and c) triaxial CFRP laminate (90°/45°/−45°).

The induced voltage is:

$$U_{ind} = -\frac{d\phi}{dt} \qquad (3)$$

where $d\phi/dt$ is the rate of change of magnetic flux.

Equation (2) states, that increasing the frequency causes decreasing of the penetration depth and equation (3) shows that increasing of the frequency increases the signal of the amplitude. This means that the lower the conductivity or thickness of the specimen, the higher the frequencies needed for higher sensitivity [5]. Fig. 6 illustrates, that High-Frequency Eddy Current based on the EddyCus system operates in frequency range between 100 kHz to 100MHz.

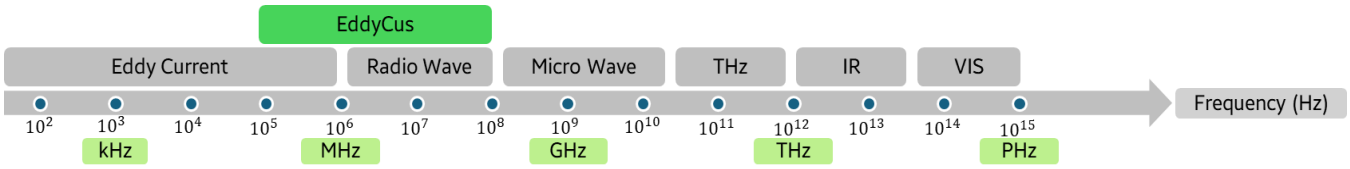

Fig. 6. High-Frequency Eddy Current based testing system diagram.

3 Experiment, Results and Discussion

The experimental principle involves scanning using the EddyCus MPECS system. A circular Transmitter- Receiver (T-R) coil sensor operating is employed to scan the material under testing (MUT), with sensor dimensions provided in Table 1. A ferrite core is used for the T-R coils. The lift-off distance is 0.1mm. In our profiling configuration, the sensor remains stationary, where, before each measurement, the probe was calibrated in air to define a stable reference level and prevent any distortion of the excitation signal, ensuring that the measured impedance reflects only the material contribution, while a frequency sweep (255 discrete frequency values in the MHz range) is applied to the MUT. These frequencies are represented along the abscissa axis of the plots (0-254, with each point corresponding to a specific frequency). The objective is to analyze the electromagnetic response of each sample, considering their dimensions and fiber volume content. For each scan, the MPECS software records the ECT sensor voltage values. Profiling mode was performed on four different material samples: copper, titanium, and two CFRP specimens of varying thicknesses (0.2 mm and 0.4 mm) with fiber volume fractions estimated between 60% to 80%.

Table 1. Eddy current testing probe parameters

Component	Parameter	Value / mm
Transmitter Coil	Outer diameter	1.65
	Inner diameter	2.15
	Height	0.6
	no. of turns	30
Receiver Coil	Outer diameter	1.65
	Inner diameter	2.05
	Height	0.72
	no. of turns	45
Ferrite Core	Diameter	3.3
	Height	5

The Fig. 7 shows the sensor response across the frequency range for all tested materials. The resonance frequency of the sensor is approximately 7.1 MHz. The results indicate that copper and titanium, being highly conductive, exhibit significantly higher impedance values compared to CFRP, which is characterized by low conductivity. Nevertheless, the use of a high-frequency differential eddy current sensor enables the visualization and characterization of the conductivity behavior in CFRP materials.

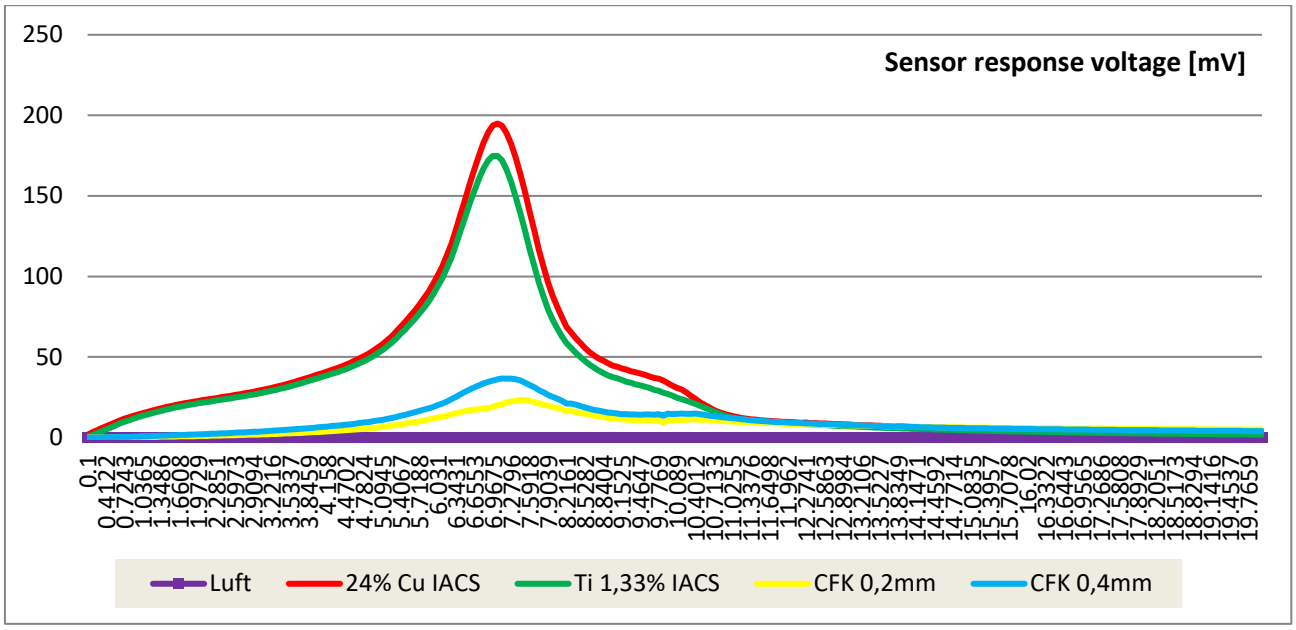

Fig. 7. ECT sensor voltage [mV] as a function of frequency [MHz].

The following figures summarize the experimental results obtained with the EddyCus MPECS system, showing both the impedance magnitude |Z| versus frequency and the corresponding polar diagrams for the MUT. In the |Z|-frequency plots showed in Fig.8, copper and titanium exhibit the highest impedance values at low frequencies, due to strong inductive coupling with their highly conductive surfaces. As the frequency increases, the response is influenced by the skin effect and by the interaction between inductive and capacitive elements within the probe sample system. Around 8 to 11 MHz, a sharp drop appears, corresponding to a resonance or coupling effect, after which the impedance stabilizes beyond 12 MHz. The thicker CFRP sample shows a slightly higher coupling, consistent with its larger fiber volume fraction and higher effective conductivity.

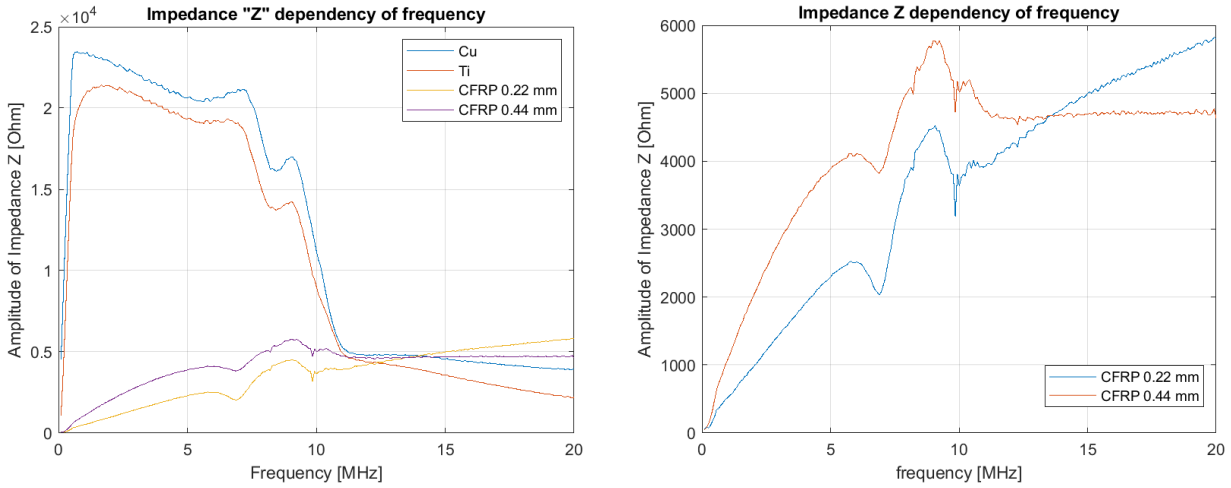

Fig.8. |Z|–frequency plots of all the MUT (left) and for the to CFRP (right).

To better interpret these responses, the polar diagrams given by Fig.9. display the evolution of the real and imaginary components of impedance as frequency increases. Copper and titanium form large, nearly circular loops, characteristic of strong eddy-current generation. In contrast, the CFRP samples show smaller, asymmetric loops closer to the origin, evidence of their lower conductivity and anisotropic nature. The thicker CFRP sample exhibits a slightly larger loop, confirming stronger electromagnetic interaction.

The irregularities observed along the CFRP trajectories indicate transitions where capacitive and inductive effects balance, revealing the coexistence of conduction and polarization mechanisms within the composite. Altogether, these results bridge the experimental measurements with the physical interpretation of anisotropic conduction, highlighting how fiber orientation, thickness, and coupling phenomena shape the complex impedance response of CFRP materials.

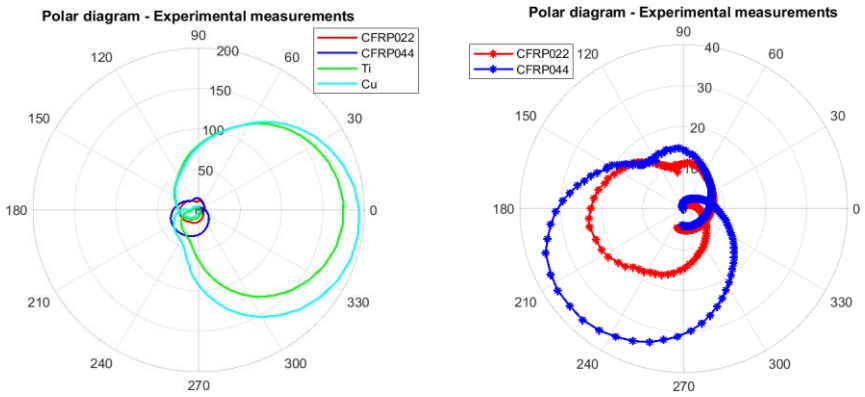

Fig.9. Polar diagram of signals from MUT.

Conclusion

In eddy current testing of carbon fiber reinforced polymer (CFRP) composites, the voltage response measured by the sensor of EddyCus is strongly influenced by the excitation frequency. As the frequency varies, the skin depth of the induced current changes, modifying the distribution of the magnetic field within the materials. These variations alter the electromagnetic coupling between the sensor and the Copper, Titanium and CFRP surfaces, resulting in measurable changes in the sensor's output voltage. Furthermore, local variations in the electrical conductivity or permittivity of the CFRP can perturb the eddy current distribution, leading to additional modifications in the detected voltage signal.

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