# Advanced Eddy Current Testing of Carbon Composites

Marie Rudolfova[1]
1 eddyczech, s.r.o., Czech Republic, marie.rudolfova@eddyczech.cz

**Abstract**

Carbon composites due to their specific properties find applications in various industries, especially in aerospace industry. Widely used carbon fibre reinforced polymers (CFRP) have already been applied even for the aircraft primary structures. The development of advanced diagnostic techniques that are able to easily detect and identify the degradation of the carbon fibre material is still a challenge for various NDT methods. This paper describes the possibility to apply eddy current (EC) for testing of carbon composite structures. Two types of eddy current probes were developed and tested with excellent results. The new conventional eddy current probes are able to reliably and easily detect surface and subsurface discontinuities such as delamination and thickness variation. The probe setting parameters are described for different types of carbon composites (type of matrix and reinforcement, layup). Precise settings are necessary for the successful eddy current testing. It was determined that reliable detection of a minimum surface defect size is Ø1.5 mm for specimens and that eddy currents are able to penetrate into a thickness up to approximately 4 mm depending on the type of carbon composite. Additionally, this paper describes the comparison of eddy current testing with ultrasonic phased array method (PAUT). Composite aircraft structures are very susceptible to impact damage usually detected using PAUT. Therefore, sensitivity and resolution analysis of impact damage detection was performed by means of these two methods. It was found out that the results are very similar to each other when standard pulse-echo technique of PAUT was used. This carbon composite eddy current testing could fully replace or complement other NDT methods such as visual or ultrasonic inspections. Also it could guarantee the product quality in production, aircraft maintenance and in the development of new aircraft structures.

**KEYWORDS**: Eddy current, Carbon, Composite, Inspection, Aircraft

## 1. Introduction

Any impact and/or fatigue loading causes damage in composite structure with complicated mechanical behaviour. Damage located inside the structure needs proper evaluation for next damage tolerance analysis of a structure and to determine its lifetime [1]. Any misinterpretation of damage size should result in additional costs or service

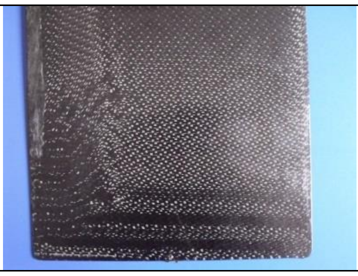
lifetime reduction. CFRP (carbon fibre reinforced plastic) composites have excellent mechanical properties such as high specific strength and stiffness and represent a huge potential for saving weight [2]. Currently, ultrasonic, ultrasonic phased array testing (PAUT) and bond testing are the primary methods used for the detection of delamination and dis-bonds. Some other methods, such as laser shearography give very good results, [3, 4] for damage size evaluation but are limited in application (for thick composites). In terms of their physical properties, especially anisotropy of electrical conductivity, carbon composites can be subjected to eddy current testing (ECT). The electrical properties of carbon composite materials depend on the type of carbon fibre and its volume fraction in the material. The electrical conductivity in the transverse direction is between 10 and 100 S/m, and in the longitudinal direction, it is between $5x10^3$ and $5x10^4$ S/m [1]. The electrical conductivity of the composite is determined by the conductivity of the individual fibres, the composition of the layers and the volume fraction of the fibres in the material [5]. Each application of EC testing has an optimal operating frequency range at which the desired eddy current depth of penetration can be achieved and the maximum detectability of discontinuities is ensured. Two frequency bands exist for eddy current inspection of aircraft metallic structures: low-frequency (Hz – kHz) and high-frequency testing (kHz – MHz) [5, 7, 8]. The low operating frequency is used for crack or corrosion subsurface detection in larger thicknesses of a metallic material, especially in a multi-layered structure, such as rivet joints (so called $2^{nd}$ layer). While the high operating frequency is used for surface crack or corrosion detection. To induce eddy currents in a carbon fibre, the magnetizing coil must be excited with a high frequency in units or tens of MHz.
This article describes design of eddy current probe, influence of operating frequency on the depth of penetration and defect/composite characteristics resolution.

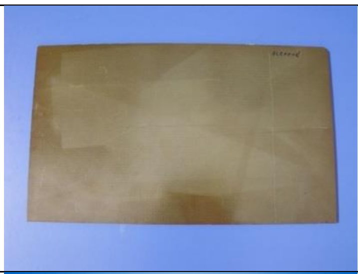
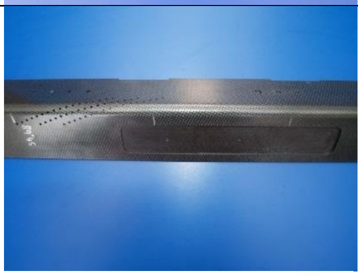
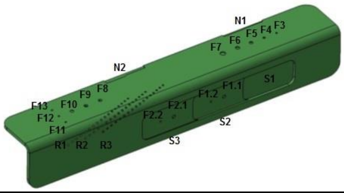
## 2. Eddy current testing of CFRP composite

### *2.1 Specimens for experimental measurements*

Several composite specimens (see Table 1) were used for the development of the eddy current probe that should be able to detect surface and subsurface discontinuities and structural defects, including delamination, missing bundles, fractures, fibre orientation failure, etc.

**Table 1. Specimens**

| Figure of specimen | Title / Specifications |
|---|---|
|  | Specimen No. 1 – carbon fibre fabric in epoxy resin – the specimen contains the natural structural defects such as waviness, fraying of texture and artificial flaws in the form of a Ø1.5 mm bore-hole and a notch of 10x1.2x0.5 mm (length x width x depth) with a specimen thickness of 2.3 mm. |

| | |
|---|---|
|  | Specimen No. 2 – unidirectional carbon fibre prepreg (epoxy matrix) – the specimen consists of 33 layers, ≈ thickness of 3.7 mm. Artificial flaws in the form of foil represent the delamination. The six inserts of foils are inserted between the 4th and 5th layer, the 8th and 9th layer, and the 12th and 13th layer. The sizes of the inserts range from 3x3 mm up to 22x22 mm |
|    | Specimen No. 3 – carbon fibre fabric reinforced PPS laminate – the specimen contains artificial flaws in the form of a flat bottom-hole (FBH), and steps and notches of various sizes. These artificial defects represented a loss of material or a change of thickness.<br>The smallest FBH diameter is 3 mm of the depth of 1 mm. The thickness variation is simulated by the steps of the thicknesses of 1.6 mm, 3.0 mm and 4.5 mm. |

The following parameters should be considered during the design and development of the high-frequency INDETEC EC probe [9, 10, 13]:

1. Type and dimension of the probe. A pencil probe of body diameter ≈ 12 mm and sensor diameter of ≈ 10 mm was selected.
2. Operating frequency interval f ≥ 1 MHz.
3. Coil with/without a core. A magnetic core was selected – increasing the self-inductance coil. A smaller coil dimension with less turns could allow for the use of a strong magnetic field with less loss [10, 11, 12].
4. Type of Winding. A winding was chosen so that the self-capacitance $C_0$ will minimized and a coil of good Q factor will be obtained [10, 11, 12].
5. Fill factor. Usually, a value of 70-90% fill-factor is used for reliable inspection. The value of 80% was selected for the lower mechanical wear on the probe and lower noise level.
6. Mode of coil configuration. Selected the driver/pick-up mode provides better sensitivity and more stable signal as independence of the device's electronics.

**Figure 1. Developed high-frequency INDETEC EC probe**

## *2.2 Experimental Results*

The following measurements were performed with the new high-frequency INDETEC EC probe and the functionality and applicability to CFRP composites were verified.
Selected operating frequency range 1 MHz – 12 MHz and horizontal/vertical amplification range 20 dB – 65 dB ensured detection of defects displayed in X-Y impedance plane (amplitude and phase analysis) and Y-t display (amplitude/time analysis).

### *2.2.1 Specimen No. 1 - carbon fibre fabric in epoxy resin*

Carbon fibre fabric material is suitable for eddy current testing in terms of the signal-to-noise ratio (SNR) and the resolution of different types of defects as shown in Figure 2.

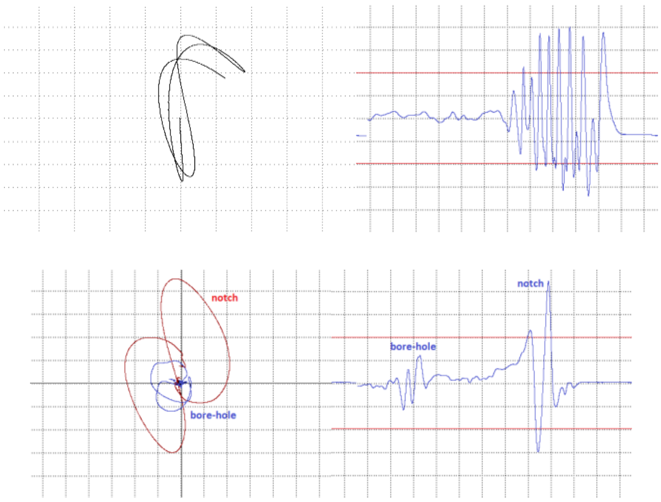



**Figure 2. EC signal of waviness displayed in impedance plane X-Y and in time base Y-t (up), EC signal of notch and a bore-hole displayed in impedance plane X-Y and in time base Y-t (down)**

### *2.2.2 Specimen No. 2 - unidirectional carbon fibre prepreg*

The common defect occurring in carbon composites is delamination. The eddy current response to structural noise is bigger than the EC response in the case of carbon fibre fabric (specimen No.1). The individual EC responses to inserts are shown in Figure 3. The increasing of the amplitude with the increasing of the insert sizes can be observed from the measured signals in the XY impedance plane. The phase difference between the lift-off and discontinuity is in the phase interval from 45° to 90°. Thus, the defect resolution required for reliable inspection is achieved.

*Structural noise* *Insert 3x3 mm* *Insert 8x8 mm* *Insert 22x22 mm*

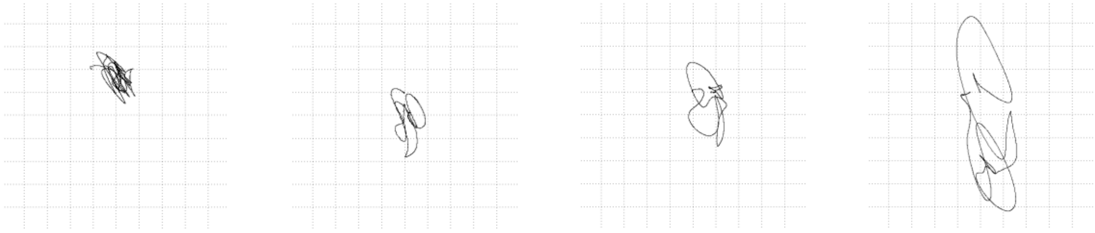
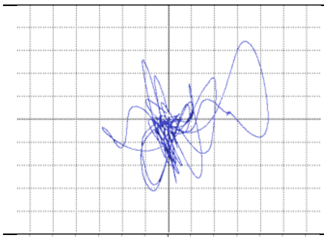
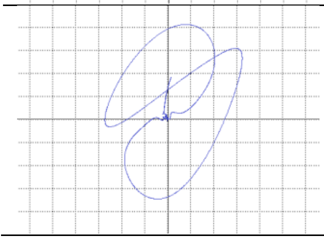


**Figure 3. EC responses to inserts of different sizes**

*2.2.3 Specimen No.3 - carbon fibre fabric reinforced PPS laminate*

The most significant results has been achieved for carbon fibre fabric reinforced PPS laminate. The eddy current responses of selected individual artificial defects are displayed in Table 2.

**Table 2. EC responses to individual artificial defects**

| Eddy current response | Artificial defects |
|---|---|
|  | F7: FBH ø9.0 mm<br>Depth: 1.7 mm<br>distance from the probe: 3.9 mm |
|  | F8: FBH ø6 mm<br>depth 5.3 mm<br>distance from the probe: 0.3 mm |

*2.2.4 Resolution of discontinuities*

The correct NDE (Non-Destructive Evaluation) of the individual discontinuities among the basic requirements for reliable inspection. The eddy current response to different types of discontinuities, such as delamination, thickness changes, fracture, waviness, missing bundles, artificial notches and holes and metal fabric inserted into a laminate, were determined definitively. Some of these discontinuities are shown in Figure 4.

*Brass vs. bronze fabric* *Thickness change* *Delamination*

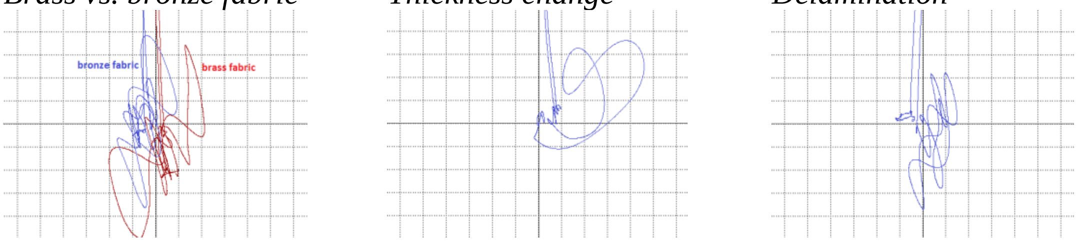
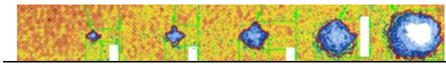
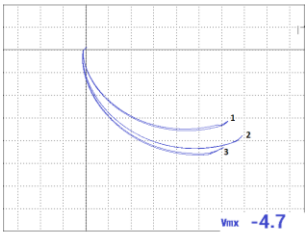
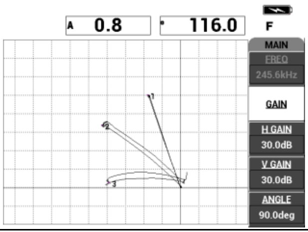



**Figure 4. EC signals for various types of discontinuities**

*2.2.5 Comparison with other NDT method/techniques*

The performance of the developed probe was compared with the most common testing method of composite structures. The results of comparison are described in Table 3.

**Table 3. CCECT vs. other NDT method/techniques**

| Image | NDT method/technique |
|---|---|
| CCECT  PAUT  | Impact measurement of carbon composite structure<br><br>CCECT (Carbon Composite Eddy Current Testing)<br>vs.<br>PAUT (Phased Array Ultrasonic Testing) |
| CCECT   Bond Testing   | Thickness measurement<br>1 - step of 1.2 mm THK<br>2 - step of 1.7 mm THK<br>3 - step of 2.4 mm THK<br><br>CCECT<br>vs.<br>Bond Testing - Resonance technique |

## 3. Conclusions

The eddy current probe was developed for CCECT (Carbon Composite Eddy Current Testing), especially for CFRP with a very good resolution of discontinuities during the near sub-surface inspection. The probe is able to detect surface and sub-surface defects up to a depth of 3.9 mm in production to guarantee product quality, in aircraft maintenance and in the development of new aircraft structures. This probe can fully replace or complement other NDT methods such as visual or ultrasonic inspections. It can be used for flat part inspections.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