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Custom Eddy Current Probe Design and Automated Defect Mapping for Multistrand Carbon Fiber Cables

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Abstract- This paper describes the development of an eddy current-based non-destructive testing (NDT) method for the inspection of multistrand cables composed of carbon fibre reinforced polymer (CFRP) rods enclosed in a braided textile sheath. Conventional NDT methods, including ultrasonic testing, radiography and commercially available eddy current techniques, are often ineffective for these cables owing to their pronounced electrical anisotropy, cylindrical geometry and limited sensitivity to strand-level defects beneath protective covers. A customised eddy current system was developed, incorporating numerical optimisation of the probe geometry through finite element simulations prior to fabrication on flexible printed circuit boards. The inspection system, operated via both a collaborative robotic arm and a portable handheld device, achieved full circumferential coverage of the cable surface through sequential rotational scanning. Different defect morphologies, including crushed, severed and separated carbon fibre rods in both the first and second layers, were successfully detected through the braided textile sheath. A dedicated acquisition and processing software package was developed to enable automated data processing and defect mapping, including two-dimensional C-scan visualisation and three-dimensional surface reconstruction.

Keywords – IMEKO, TC10, Eddy current testing, CFRP cables, non-destructive testing, composite inspection, Industry, Innovation and Infrastructure.

I. INTRODUCTION

Multistrand carbon fibre cables, originally developed for high-performance applications, offer weight reductions of up to 70% compared to stainless steel whilst providing superior durability relative to synthetic fibre alternatives such as PBO® or aramid [1]. Their flexibility and toughness result from the bundled arrangement of multiple unidirectional composite rods that can move slightly relative to one another under loading. A braided textile jacket is applied around the cable to consolidate the multistrand structure and provide additional protection against abrasion and environmental exposure. However, this protective cover prevents direct access to the carbon rods, rendering both visual and ultrasonic inspections impractical without prior removal of the outer sheath. Eddy current methods, whilst potentially applicable in situ, are conventionally limited by lift-off effects and surface irregularities introduced by the textile cover [2].

Eddy current testing (ECT) with customised probes has demonstrated considerable potential for the evaluation of carbon fibre composites [3]. Successful high-speed and contactless ECT of unidirectional CFRP has been reported [4, 5], and comprehensive reviews of ECT applications confirm its adaptability to complex geometries [6, 7]. The electrical conductivity of CFRP materials is inherently anisotropic, with values along the fibre direction typically ranging from 10^3 to 10^4 S/m, whilst the transverse conductivity is one to two orders of magnitude lower [8]. This pronounced anisotropy produces highly directional eddy current patterns whose behaviour must be carefully considered in probe design. Furthermore, the cylindrical geometry of cable elements introduces additional challenges, including spatially varying lift-off and surface curvature effects that influence the current distribution and impedance response [4].

The present work focuses on the development and validation of a customised ECT system for multistrand carbon fibre cables, targeting defect detection through the braided textile sheath.

II. CABLE STRUCTURE AND DEFECT PREPARATION

The inspected cable, shown in Fig. 1, consists of more than 200 unidirectional carbon fibre rods of 1.8 mm diameter, arranged in a multistrand configuration within a cable of 32 mm overall diameter. The individual rods are visible at the cable cross-section (Fig. 1a), whilst the braided textile jacket that encloses the structure is shown in Fig. 1b.

a) b)

Fig. 1. Multistrand CFRP cable: (a) top view showing the individual carbon fibre rods; (b) braided textile jacket covering the cable structure.

To establish a comprehensive validation dataset, a range of artificial defects with different morphologies were introduced into the cable specimens. Following defect creation, the braided sheath was repositioned over the damaged area to replicate in-service inspection conditions. Three representative defect types are illustrated in Fig. 2: (a) five crushed rods without severing; (b) ten rods severed across both the first and second layers with a separation gap of 0 to 3 mm; (c) twelve rods comprising three severed and nine crushed elements across both layers. It should be noted that these represent only a subset of the defect configurations tested; additional morphologies and sizes were also successfully identified during the experimental campaign.

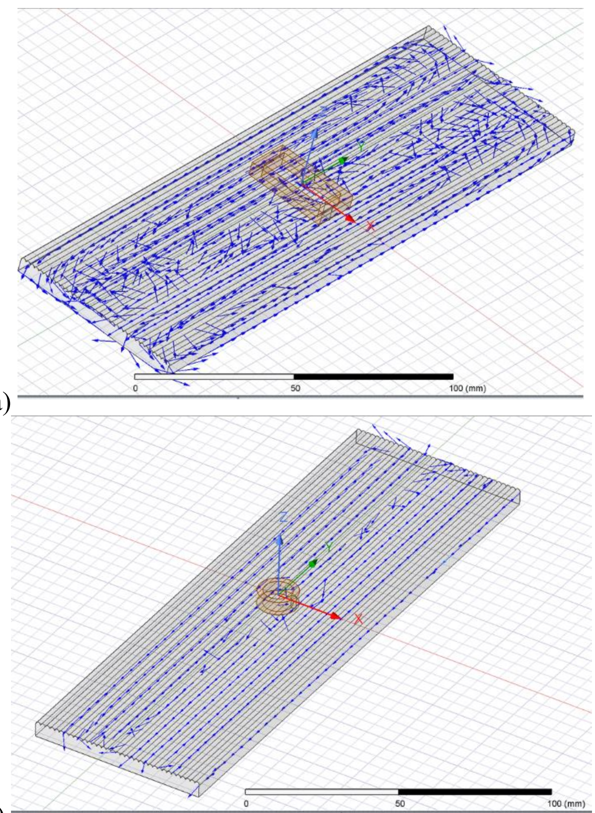
a) b) c)

Fig. 2. Representative artificial defects introduced in the CFRP cable: (a) five crushed rods; (b) ten severed rods in the first and second layers with 0–3 mm gap; (c) twelve rods (three severed and nine crushed) across both layers.

III. PROBE DESIGN AND NUMERICAL OPTIMISATION

Prior to the fabrication of the final probe on flexible printed circuit board (PCB) substrates, a numerical study based on the finite element method was conducted to evaluate the influence of different coil geometries on the eddy current distribution within the CFRP rods. The electromagnetic model incorporated the anisotropic conductivity of unidirectional pultruded elements, with values consistent with those reported in the literature, and simulated the interaction between various coil configurations and a locally flattened representation of the cable surface.

The comparison of two representative simulation results, presented in Fig. 3, demonstrates that the excitation coil geometry and the number of turns significantly influence the orientation and intensity of the induced currents relative to the fibre direction. The objective of this optimisation phase was to identify the configuration that maximises sensitivity to localised rod discontinuities while maintaining adequate spatial resolution. Based on these results, the most promising geometries were selected and fabricated using flexible PCB technology, enabling conformance to the cylindrical surface of the cable.



(a)

(b)

Fig. 3. (a) Eddy current distribution induced by a rectangular probe with 50 turns; (b) eddy current distribution induced by a cylindrical probe with 100 turns.

IV. RESULTS AND DISCUSSION

The customised eddy current system employed a differential reflection probe configuration. Longitudinal scanning was performed by a collaborative robotic arm, whilst a dedicated rotational fixture provided circumferential indexing in 3° increments after each sweep, yielding a total of 120 passes for complete 360° coverage. The excitation frequency was set at 5.1 MHz, and data were acquired at a sampling rate of 800 samples per second along each longitudinal pass. A portable handheld version of the system was also developed for on-site inspection scenarios.

A dedicated acquisition and processing software package was developed to enable automated data collection and real-time defect mapping. The software assembles the individual longitudinal scans into a two-dimensional C-scan representation of the complete cable surface, in which the signal amplitude is mapped as a function of circumferential position and longitudinal distance. This planarized visualisation enables rapid identification of defect locations and their spatial extent. The inspection results corresponding to the three defect types described above are presented in Fig. 4, which shows the complete C-scan map of the cable surface together with the A-scan signal profiles from the passes that most clearly identified defects (a), (b) and (c), in order of appearance.

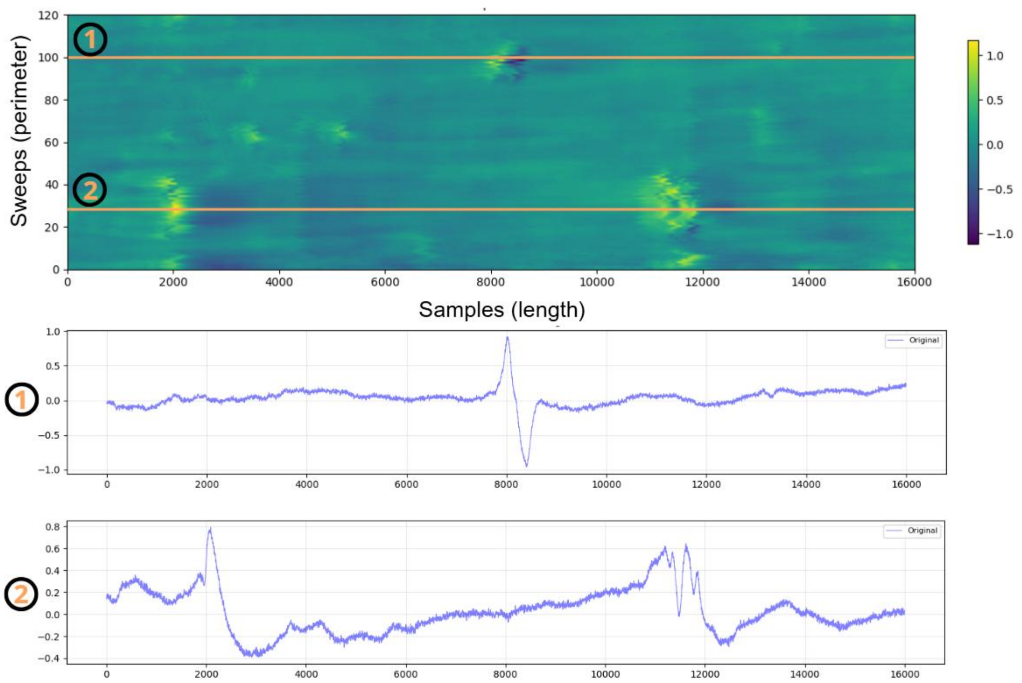


Fig. 4. Inspection results: planarized C-scan map of the cable surface with A-scan profiles corresponding to the longitudinal passes that best identified defects (a), (b) and (c).

Furthermore, the acquired data can be reconstructed into a three-dimensional surface representation that preserves the cylindrical geometry of the cable, providing an intuitive visualisation of defect locations relative to the cable structure, as shown in Fig. 5.

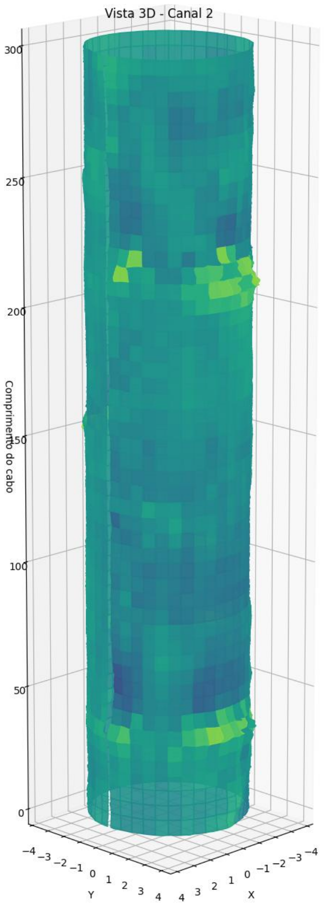


Fig. 5. Three-dimensional reconstruction of the eddy current inspection data mapped onto the cylindrical cable geometry.

V. CONCLUSIONS

The developed eddy current inspection method demonstrated high effectiveness in detecting defects within multistrand carbon fibre cables, even through the external braided textile sheath. The numerical optimisation of the probe geometry proved essential for selecting the most suitable coil configurations prior to fabrication. The customised system achieved sufficient sensitivity and effective inspection depth to identify crushed, severed and separated carbon fibre rods in both the first and second layers. The dedicated acquisition software enabled automated data processing, two-dimensional C-scan mapping and three-dimensional visualisation of the inspection results. Experimental validation confirmed a clear correlation between the detected indications and the actual physical defects, demonstrating the viability of customised eddy current testing for the non-destructive evaluation of multistrand CFRP cables, with strong potential for structural and marine applications.

VI. ACKNOWLEDGMENTS

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