

EDDY CURRENT EVALUATION OF TWO-LAYER AIRCRAFT STRUCTURES WITH CARBON FIBER REINFORCED POLYMER LAYERS ON ALUMINUM ALLOY SUBSTRATES

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ABSTRACT

Carbon fiber reinforced polymers (CFRPs) combine high load-carrying capacity with low specific weight, making them increasingly important for lightweight design in modern aerospace structures. Their use is expanding not only in primary components but also in repair patches for reinforcing aluminum alloy (AA) elements. However, suitable nondestructive evaluation (NDE) techniques for CFRP-AA assemblies remain limited. CFRPs are heterogeneous materials composed of carbon fibers and a polymer matrix, characterized by pronounced interfaces and anisotropic electrical conductivity due to fiber orientation. For evaluation purposes, CFRPs can be approximated as a homogeneous medium with an effective specific conductivity determined by composition and design. This study investigates the feasibility of measuring CFRP layer thickness on AA substrates using eddy current (EC) techniques. Conventional EC instruments designed for dielectric coatings are unsuitable due to the relatively high conductivity of CFRP. To address this, single-coil ferrite-core EC probes (8 mm diameter) were developed and operated at low frequencies in resonant mode. Experiments on specimens provided by the State Enterprise "ANTONOV" demonstrated that CFRP thicknesses up to 12 mm can be measured reliably. The results will contribute to the development of a dedicated EC instrument for CFRP thickness measurement. Moreover, the proposed technique is sensitive to delamination between CFRP and AA substrates or between CFRP layers, enabling potential application in in-service inspection and structural health monitoring. Such use requires initial baseline measurements at reference points for subsequent comparison during the service life of the structure.

Keywords

eddy current, carbon fiber reinforced polymer (CFRP), thickness determination, aluminum alloy, structural health monitoring, aerospace structures, operational frequency.

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1. INTRODUCTION

Over the past decades, various types of carbon-based composite materials have been developed for applications in civil and military aircraft, aerospace, and the automotive industry [1–4]. Among these, carbon fiber reinforced polymer (CFRP) composites offer numerous advantages, including high load-carrying capacity, corrosion resistance, and low specific weight. In many cases, multiple materials are used simultaneously in layered aerospace structures, with CFRP bonded to a metal substrate to improve load resistance [5].

In large-scale aircraft such as the Airbus A380, aluminum alloys (AA) account for approximately 60% of the structural weight, while CFRP constitutes about 25%. In the Boeing 787, the proportions are approximately 25% and 50%, respectively [6]. Bonded CFRP patches are also widely applied as a cost-effective method of reinforcing AA components during aircraft repair [7–9].

Despite these advantages, the safety and performance of CFRP-containing structures may be compromised by characteristic damage mechanisms such as delamination, impact damage, and fiber breakage. Delamination may occur within the CFRP layers themselves or at the CFRP–metal interface, resulting from mechanical loading or poor bonding quality. Such damage reduces load-carrying capacity and can ultimately lead to structural failure. Therefore, nondestructive evaluation (NDE) techniques are critical for ensuring the integrity, safety, and reliability of aerospace structures incorporating CFRP layers.

In this study, the state of the art in CFRP evaluation using the eddy current (EC) technique is analyzed, with particular emphasis on the ability to measure the thickness of CFRP layers covering AA components by means of eddy current nondestructive evaluation (EC NDE). The physical processes underlying the interaction of an EC probe with a two-layer structure of differing specific electrical conductivity (SEC) are examined to explain how CFRP thickness and delamination influence EC probe impedance—an important factor in selecting the optimal operating frequency. The proposed inspection technique is intended both for application during CFRP manufacturing and for in-service structural health monitoring of two-layer structures (AA covered by CFRP) to detect potential delamination.

2. NONDESTRUCTIVE EVALUATION OF CARBON FIBER REINFORCED POLYMER

– STATE OF THE ART

Various traditional NDE methods are currently used to test CFRP composites, including ultrasonic testing, infrared thermography, shearography, and the electromagnetic force vibration method [9–15]. In the latter approach [15], electromagnetic force is applied to the surface of CFRP material containing internal defects; the defects are identified because vibration intensity increases at their

locations. Among non-traditional NDE methods, the most promising results have been obtained using hybrid optical–acoustic techniques, in which the composite structure is excited by an ultrasonic wave and subsequently probed on the surface with an optical imaging system [16].

The eddy current (EC) method, based on electromagnetic induction, is a well-established NDE technique for assessing structural changes, detecting surface and subsurface defects (including corrosion damage), and measuring the thickness of metallic components [17–22]. The EC method offers several advantages, such as high reliability, efficiency, relatively simple testing procedures, and low inspection costs. Because CFRP has a measurable specific electrical conductivity (SEC), the EC technique can also be applied for its evaluation [23–28]. Although all carbon-based composites exhibit SEC values much lower than those of metals, they are sufficient to enable detection of material changes by EC methods [23–26]. It has been suggested [23] that EC inspection of CFRP is influenced not only by the conductivity of the fibers but also by the capacitive coupling between fibers due to the dielectric properties of the polymer matrix. In one study, rotating EC probes were used to estimate the anisotropy of SEC, requiring high operational frequencies above 7.5 MHz for textural analysis. Reported SEC values for carbon fiber one-layer material are approximately $\sigma = 5 \cdot 10^6$ S/m along the fibers and $\sigma = 1 \cdot 10^3$ S/m in the transverse direction [26]. However, generalized SEC depends on multiple factors and can range from $\sigma = 0.01 \cdot 10^4$ S/m to $\sigma = 3.6 \cdot 10^4$ S/m [24].

For EC inspection, sensitivity to material properties is determined by the product of SEC and operating frequency. Thus, compared to nonmagnetic metals, significantly higher frequencies are required for CFRP. For example, a single-coil pot-core EC probe with an outer diameter of 14 mm operated at 70–120 kHz was shown to improve sensitivity to damage in CFRP and provide greater penetration depth [27]. The applicability of EC methods to detect delamination at different depths in CFRP has also been investigated [28]. Results indicated that only delamination at shallow depths (up to 0.75 mm) could be detected in cross-ply specimens, while subsurface defects in unidirectional CFRP plates remained undetected.

In summary, detection of delamination in CFRP using EC methods is limited by the shallow depth of occurrence, as sufficiently high frequencies are required. Alternatively, larger EC probes can be used, but this reduces spatial resolution and localization. These limitations apply to EC NDE with one-sided access in the absence of a metal substrate.

The EC technique is also a well-established NDE method for measuring the thickness of dielectric coatings, with many instruments developed and successfully applied in industry [20]. In these cases, a metal substrate is present, and the distance to it is measured. At first glance, measuring the thickness of a CFRP layer covering AA components may seem similar to measuring dielectric coating thickness. However, conventional EC instruments designed for dielectric coatings are not suitable for determining CFRP layer thickness due to the relatively high electrical

conductivity of CFRP composites. Although the conductivity of CFRP is low compared to metals, it is still sufficiently high to affect the inspection process, particularly due to the skin effect at the applied operating frequencies. Currently, no commercial instruments are available for accurately measuring the thickness of CFRP layers on AA substrates, although the aviation and aerospace industries represent potential markets for such devices.

The concept behind measuring the CFRP layer on a metal substrate is to lower the operating frequency until the CFRP becomes effectively “transparent,” so that its electrical conductivity does not significantly influence the penetration depth of the eddy currents. For evaluating CFRP composites on a metal base, lower operating frequencies must therefore be used, in contrast to the higher frequencies typically applied when testing CFRP without a metal substrate. A similar approach has been employed in detecting fatigue cracks in AA aircraft structures reinforced with CFRP repair patches, where comparatively low operating frequencies were applied [21].

In general, CFRP composites can be classified as heterogeneous materials composed of at least two homogeneous components – carbon fibers and a polymer matrix – with pronounced interfaces and significantly different electrophysical properties. For EC applications, it is important to note that the polymer matrix is a good dielectric, whereas the carbon fibers exhibit relatively high SEC. The fibrous structure of CFRP also results in direction-dependent conductivity, i.e., at least uniaxial anisotropy of SEC, which can vary between layers depending on fiber orientation.

To analyze such heterogeneous anisotropic structures, the concept of an *effective medium* has been proposed. In this approach, CFRP is conditionally treated as a homogeneous material with an effective SEC that depends on the quantitative composition of its components. This effective SEC is expected to be significantly higher than that of the polymer matrix, yet lower than that of the carbon fibers. The effective medium concept has been applied in various contexts. For example, it was used to determine copper content in ores, where heterogeneity arises from the low SEC of diorite (host rock) and the much higher SEC of chalcopyrite (copper pyrite) [29]. It has also been used to analyze the influence of SEC anisotropy on the signal of EC probes with circular windings [30]. Similarly, an effective medium approach—expressed through the term “effective coercive force”—was applied to study the magnetic hysteresis loop parameters of layered objects consisting of materials with different magnetic characteristics [31].

The thickness of a CFRP layer can be measured using absolute-type EC probes, including the simple single-coil probe operated in resonance mode. This design is advantageous due to its simplicity and is therefore widely used in many EC instruments. For example, several instruments of the Wirotest family, based on the amplitude–frequency mode, were developed at the Warsaw Institute of Precision Mechanics and successfully applied in numerous industrial contexts [32,33].

Previous investigations of absolute-type EC probes in resonance mode at low operating frequencies demonstrated the feasibility of determining CFRP layer

thickness on metal substrates, including non-magnetic aluminum alloys and ferromagnetic steels [34]. These studies also described general approaches to minimizing the influence of interfering factors when applying the eddy current resonance method. However, there was no analysis of the physical processes that explain how CFRP thickness and delamination affect probe impedance, and the operating frequency range was restricted. Furthermore, the amplitude dependences of the resonant circuit output signals were presented in absolute values, which limits the comparability of the results obtained.

3. PRELIMINARY CONSIDERATIONS FOR EDDY CURRENT INSPECTION OF TWO-LAYER AIRCRAFT JOINTS CONSISTING OF CFRP AND ALUMINUM ALLOY

To prepare for the subsequent analysis, several inspection scenarios for two-layer joints composed of an upper CFRP layer (1) and an AA substrate (2) using an EC probe (3) are reviewed (Fig. 1). In the first case (Fig. 1a), the EC probe is placed directly on the CFRP surface without lift-off ($h_c = 0$), and no delamination is present between the layers ($d = 0$). In the second case (Fig. 1b), a finite lift-off distance exists between the probe and the CFRP surface ($h_c > 0$), but delamination is absent ($d = 0$). In the third case (Fig. 1c), there is no lift-off ($h_c = 0$), while some delamination is present between the AA substrate and the CFRP layer ($d > 0$).

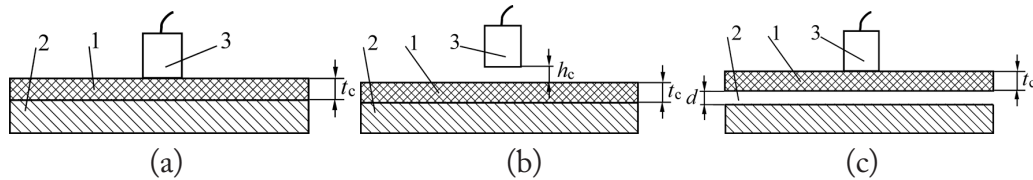


Fig. 1. Two-layer structure consisting of AA (1) and CFRP (2) with EC probe (3): (a) without lift-off; (b) with lift-off h_c ; (c) with delamination d between the AA substrate and the CFRP layer.

Let us consider the changes in the impedance of a single-coil EC probe, associated with changes in the thickness of the CFRP layer placed on non-magnetic AA. Fig. 2 schematically shows a hodograph that displays changes in the EC probe impedance in the complex plane as a function of the SEC σ of the non-magnetic materials. Here, the point “0” corresponds to the EC probe impedance when it is located in the “air” (at a distance from conductive objects that is sufficient to eliminate their influence), while points “C” and “A” correspond to the impedance values when the EC probe is placed on the surfaces of sufficiently thick specimens of CFRP and AA, respectively. Accordingly, the inductance of the single-coil EC probe, plotted along the vertical axis, is denoted as ωL_0 for point “0”, ωL_C for point “C”, and ωL_A for point “A”. In practice, points “0” and “A” are located very close to each other

(especially at low operating frequencies), since CFRP exhibits much lower SEC than any metal. In Fig. 2, the distance between points “0” and “A” has been deliberately exaggerated for clarity.

The thicknesses of the AA and CFRP specimens at points “A” and “C” are sufficiently large and exceed the true depth of eddy current penetration into these materials. This depth can be approximated as 3δ , i.e., three times the standard penetration depth δ [21,35,36]. For non-magnetic materials such as CFRP and AA, the standard penetration depth δ is derived from the approximation of plane electromagnetic wave propagation in the material and depends on operating frequency and SEC, according to the formula $\delta = \sqrt{2/\omega\sigma\mu_0}$, where: $\omega = 2\pi f$ is the circular frequency; f the operating frequency; σ the SEC of the inspected non-magnetic material and $\mu_0 = 4\pi \cdot 10^{-7} \text{ H/m}$ is the magnetic permeability of vacuum, respectively. But it must be borne in mind that the real depth of penetration of eddy currents (and related depth of inspection) depends not only on the operating frequency and SEC, but also on the size of the EC probe, the lift-off (clearance) between the EC probe and the inspected surface, and the noise level [21, 36].

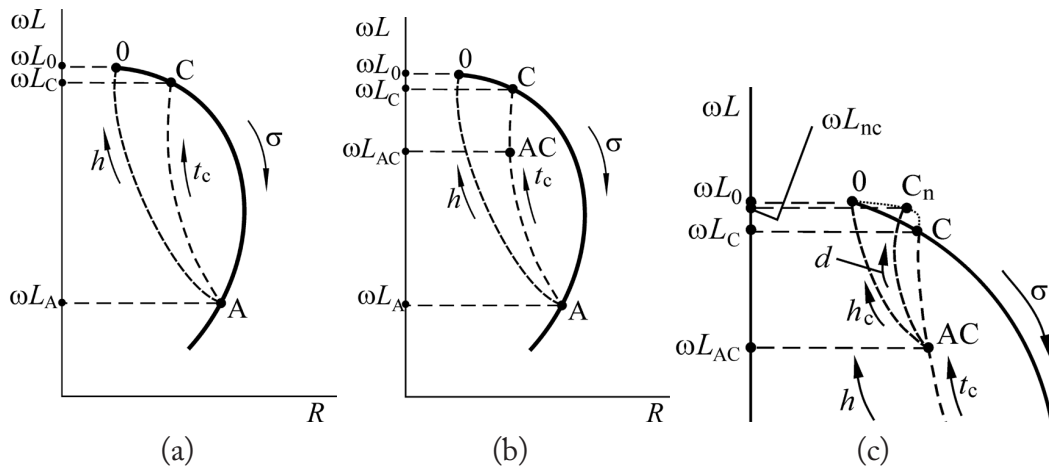


Fig. 2. Characteristic changes in the EC probe impedance in the complex plane: (a,b) as a function of the thickness t_c of the CFRP layer on AA substrate and the lift-off h influence for non-magnetic materials; (c) as a function of delamination d .

The dashed line from point “A” to point “0” (Fig. 2) illustrates the effect of changes in lift-off height h (or the dielectric coating thickness) between the AA specimen surface and the EC probe on the impedance. Another dashed line, from point “A” to point “C,” represents the effect on the EC probe impedance due to changes in the CFRP layer thickness t_c between the AA surface and the EC probe (Fig. 1b). This impedance is measured when the EC probe is located on two-layer joints composed of the upper CFRP layer and the AA substrate. The hodograph of the influence of the CFRP thickness t_c reaches point “C” when this thickness corresponds to the true penetration depth of eddy currents in CFRP at the selected operating

frequency, at which point the AA substrate no longer affects the EC probe impedance. This value is estimated as $3\delta_c$, i.e., three times the standard penetration depth for CFRP [34,35], and corresponds to the upper limit of the CFRP layer thickness measurement range on the AA substrate using the EC technique [21].

At point “C,” the AA substrate no longer affects the impedance, but along the entire curve from point “A” to point “C,” the impedance is influenced by both the CFRP layer and the AA substrate. It is reasonable to assume that the sensitivity of this effect decreases exponentially as the CFRP layer thickness increases, following the attenuation law of electromagnetic fields in an electrically conductive medium. For a CFRP layer with a defined nominal thickness t_c^n , the corresponding point “AC” lies on the dashed line t_c between points “A” and “C” (Fig. 2b). At this point, the impedance of the EC probe is influenced by both the CFRP layer with nominal thickness t_c^n and the AA substrate. The related inductance of the EC probe at this point is characterized by the values ωL_{AC} (Fig. 2b). For simplicity, we assume that the AA substrate thickness remains constant and does not significantly affect the EC probe impedance, although the starting point of the line t_c would shift as the AA substrate thickness decreases.

Now let us consider the changes in EC probe impedance when a delamination d (Fig. 1c) occurs at the boundary between the CFRP layer of nominal thickness t_c^n and the AA substrate. Such delamination may develop during service due to poor adhesion, bonding defects, or the action of complex operational loadings and corresponding deformations. The corresponding changes in EC probe impedance are schematically shown in Fig. 2c, which presents only the upper part of the complex impedance plane for clarity.

Before delamination occurs, the EC probe impedance corresponds to point “AC” on the curve between points “A” and “C,” representing a CFRP layer of nominal thickness t_c^n directly bonded to the AA substrate without separation. In Fig. 2c, the dashed line between points “C” and “0” characterizes the effect of decreasing CFRP thickness when the EC probe impedance is influenced only by the CFRP layer, with the AA substrate no longer contributing because it is effectively too distant. Point “Cn,” located between “C” and “0,” corresponds to the EC probe impedance under the influence of a CFRP layer of nominal thickness t_c^n .

The dashed line from point “AC” to point “0” (Fig. 2c) represents the influence on the EC probe impedance associated with variations in lift-off (clearance) h_c between the EC probe and the surface of a two-layer specimen consisting of an AA substrate and a CFRP layer of nominal thickness t_c^n (Fig. 1b). Another dashed line, from point “AC” to point “Cn,” characterizes the influence on the EC probe impedance related to the spread of delamination d in a CFRP layer of nominal thickness t_c^n (Fig. 1c).

In summary, the inductive (reactive) component of the EC probe impedance increases continuously with increasing CFRP layer thickness in the absence of delamination, from ωL_A to ωL_C , producing an unambiguous dependence.

The occurrence of delamination d (Figs. 1c and 2c) leads to a further increase in the inductive component, up to the value ωL_{Cn} . However, none of these values exceed the inductive component of the sensor impedance in “air,” which corresponds to ωL_0 . This demonstrates the fundamental feasibility of monitoring delamination during service life: the presence of delamination d increases the inductive component of the EC probe impedance above the value ωL_{AC} , which characterizes a CFRP layer of nominal thickness t_c^n tightly bonded to the AA substrate.

4. EXPERIMENTAL PROCEDURE, INVESTIGATED EDDY CURRENT PROBES AND SPECIMENS

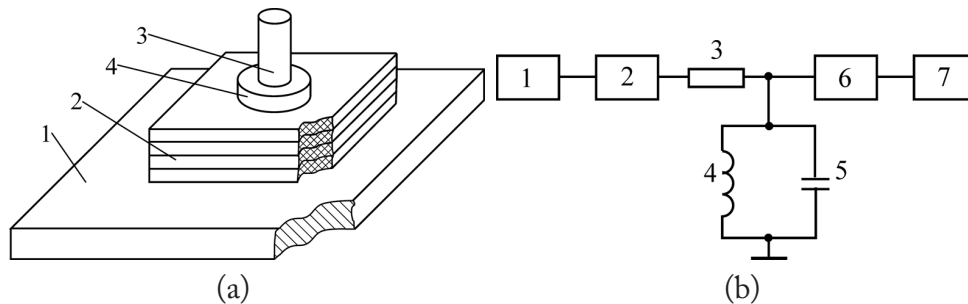


Fig. 3. (a) Flat AA specimen (1) with stacked CFRP plates (2) and ferrite core (3) with EC probe winding (4). (b) Scheme of the parallel resonant circuit with EC probe: 1 – driving generator; 2 – power amplifier; 3 – resistor; 4 – inductance of EC probe winding; 5 – capacitance of resonant circuit; 6 – band-pass filter; 7 – voltage indicator.

Two single-coil EC probes were developed and manufactured for this study: one with a 300-turn coil and the other with a 600-turn coil. Both probes used coils wound with 0.09 mm diameter wire. The coils were mounted at the end of ferrite cores with a diameter of 8 mm and a length of 20 mm. The ferrite core material had an initial magnetic permeability of 600. The outer diameters of the EC coils were 9.5 mm and 11.0 mm, respectively, with a coil length of 8.0 mm.

When placed in “air” (sufficiently far from any conductive material to avoid influence), the inductances were 5.2 mH for the 300-turn probe and 15.0 mH for the 600-turn probe. Thus, the probes exhibited different resonance frequencies and were operated at corresponding frequency ranges.

The experimental investigations were performed on a flat rectangular AA specimen (D16T type, 10×10 mm, thickness 3.0 mm) and flat CFRP plates with a thickness of 1.0 mm, supplied by the State Enterprise “ANTONOV.” Different CFRP layer thicknesses were simulated by stacking between 1 and 15 CFRP plates densely on the AA specimen, as shown in Fig. 3a.

Measurements of the EC probe output signal were conducted in the resonant mode, where the inductance of the single-coil EC probe formed part of a parallel

resonant circuit excited by an external generator. The functional scheme of the experimental setup is shown in Fig. 3b. Output voltages were recorded at operating frequencies of 5.0 and 8.5 kHz for the 600-turn probe, and at 14.0 and 20.0 kHz for the 300-turn probe. During measurements, the EC probes were placed directly on the surface of the CFRP plate stack (Fig. 3a).

5. ANALYSIS OF THE OBTAINED RESULTS

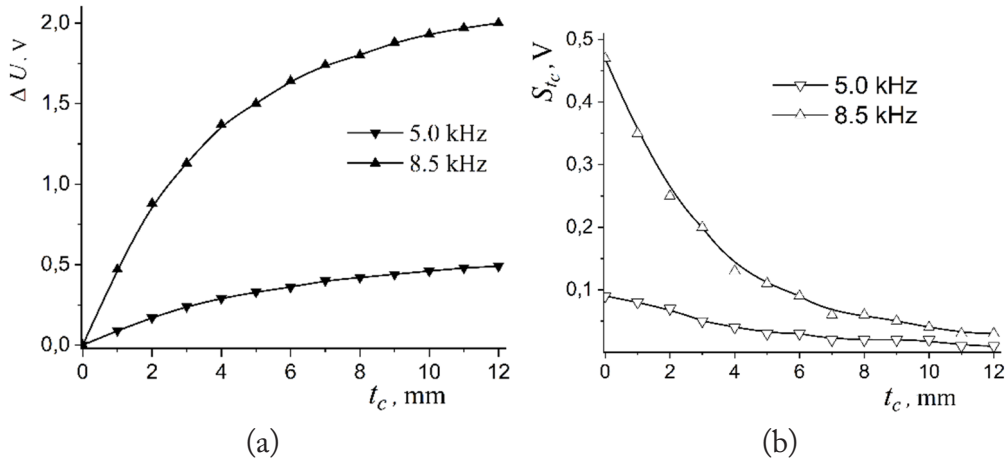


Fig. 4. (a) Changes in the output voltage ΔU for the EC probe with 600 turns and (b) the corresponding dependencies of the sensitivity S_{ic} on the thickness t_c of the CFRP layer at operating frequencies of 5.0 and 8.5 kHz.

The dependencies of the resonant circuit output voltage on the CFRP layer thickness t_c for the AA specimen, measured at operating frequencies of 5.0 and 8.5 kHz using the 600-turn EC probe, are presented in Fig. 4a. In this analysis, the output voltage in the absence of a CFRP surface layer is taken as the reference value. This differs from the approach in [34], where absolute voltage values were reported. Using relative changes improves the interpretation of results and facilitates comparison across different operating frequencies. Specifically, the output voltage is defined as zero when the EC probe is placed directly on the AA specimen without a CFRP layer, which is consistent with the calibration procedure planned for the inspection instrument. The corresponding dependencies of the sensitivity S_{ic} of the output voltage on CFRP layer thickness t_c are shown in Fig. 4b. Sensitivity values were calculated as the difference in output voltage amplitudes for each 1 mm increase in CFRP thickness, evaluated in different regions of the thickness range.

Similar dependences of the output voltage of the resonant circuit on the CFRP layer thickness t_c for the AA specimen at operating frequencies of 14.0 and 20.0 kHz with the 300-turn EC probe, together with the corresponding dependencies of the sensitivity S_{ic} , are presented in Fig. 5.

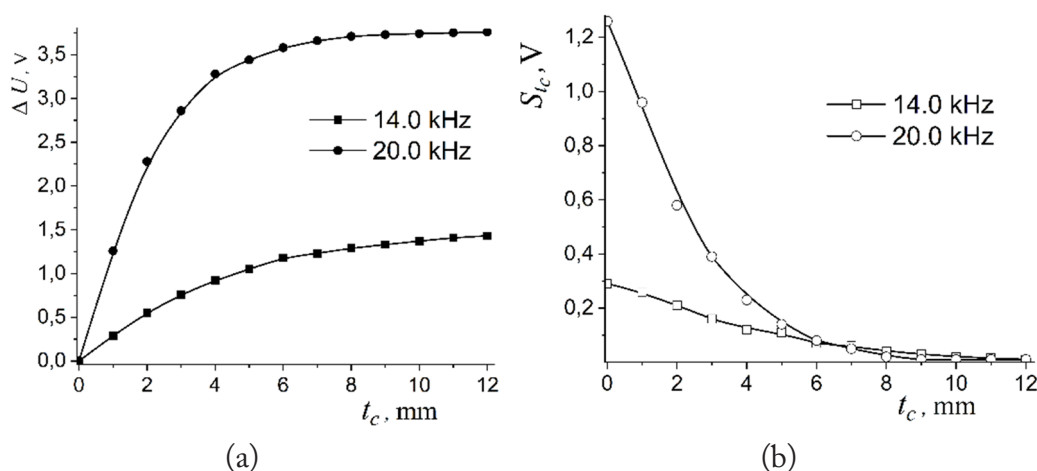


Fig. 5. (a) Changes in the output voltage ΔU for the EC probe with 300 turns and (b) the corresponding dependencies of the sensitivity S_{ic} on the thickness t_c of the CFRP layer at operating frequencies of 14.0 and 20.5 kHz.

The results presented in Fig. 4 and Fig. 5 demonstrate the feasibility of measuring CFRP layer thicknesses up to 12 mm on AA structures using the EC technique. The output voltage amplitude increases with CFRP thickness t_c , asymptotically approaching the output voltage corresponding to point “0” in Fig. 2 (EC probe in “air”) for the studied operating frequencies.

The growth rate of the output voltage is inversely proportional to CFRP thickness t_c , as confirmed by the sensitivity curves S_{ic} in Fig. 4b and Fig. 5b, whose shapes are close to exponential. At an operating frequency of 20 kHz with the 300-turn EC probe, the maximum output voltage change (greater than 3 V) was observed as the CFRP thickness increased from 0 to 12 mm (Fig. 5). At lower frequencies, the corresponding voltage changes were significantly smaller.

However, the 20 kHz/300-turn probe combination can be considered optimal only for measuring CFRP thicknesses in the range of 4–6 mm, since sensitivity in the initial portion of the thickness range is highest at this frequency. In the upper portion of the range (beyond 9 mm), the voltage change per 1 mm increase in CFRP thickness is approximately 0.01 V—too small for reliable measurement (Fig. 5b). For measurements across the full thickness range up to 12 mm, the 8.5 kHz/600-turn probe is preferable, as it provides more uniform sensitivity across the entire operating range (Fig. 4).

Note that proportionality between the rate of change of a value and the value itself is characteristic of an exponential dependence. This nonlinearity, clearly evident in the results of Fig. 4a and Fig. 5a, must be considered in the design of a resonant EC meter for CFRP layer thickness measurement on AA structures. This can be addressed by incorporating a linearization block in the instrument.

6. CONCLUSIONS

This study demonstrated the applicability of eddy current (EC) techniques for measuring the thickness of CFRP layers covering AA components. Two single-coil EC probes were developed – one with a 300-turn coil and one with a 600-turn coil – and their performance was evaluated by analyzing the dependence of resonant circuit output voltage on CFRP layer thickness at different operating frequencies. The results confirmed that the EC method enables non-contact measurement of CFRP thicknesses up to 12 mm on AA substrates.

The findings will support the development of a dedicated EC instrument for CFRP thickness measurement. To complete this development, the required measurement ranges must be defined for two-layer aircraft structures (CFRP with AA components) currently in the design stage. Preliminary tests of the prototype thickness meter have already been performed to demonstrate feasibility to designers.

In addition, the proposed EC technique is sensitive to disintegration (delamination) between the AA substrate and CFRP layer, or between successive CFRP layers. This property makes the method suitable for in-service inspection of two-layer aerospace structures. In such applications, initial measurements at selected reference points would serve as baseline data for subsequent periodic monitoring throughout the service life of the structure.

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