

ANALYSIS OF EDDY CURRENT PROBE SIGNAL MODEL FOR STRUCTURAL MONITORING OF AIRCRAFT MATERIALS

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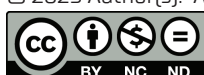
ABSTRACT

We develop a physico-mathematical model of the “eddy current probe – test object” (ECP-TO) system that analytically describes current dynamics in coupled probe circuits while accounting for key physical and electrical parameters. The model, derived from the characteristic equation of transformer-type configurations for nonmagnetic and magnetic targets, explains when the measured response is harmonic or damped harmonic as a function of excitation mode and system parameters, thereby revealing additional informative features for material evaluation. We validate the model numerically using finite element (FEM) simulations (COMSOL, Magnetic Fields, frequency domain) and introduce a digital signal-processing workflow that extracts instantaneous amplitude- and phase-time characteristics during scanning. Experiments on aluminum alloy specimens demonstrate sensitivity to small conductivity variations and identify optimal excitation frequencies for reliable subsurface defect detection; in the tested configuration, an “infinitely deep crack” was detectable to 15.3 mm at 50 Hz. The combined analytical-numerical-experimental approach supports sensitivity-driven ECP design, accelerates inspection parameter selection, and facilitates integration with structural health monitoring (SHM) systems for aerospace structures.

Keywords

eddy current, signal characteristics, dynamics model, numerical modeling, structural health monitoring systems.

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1. INTRODUCTION

Eddy current testing (ECT) is a pivotal nondestructive testing (NDT) method crucial for ensuring the structural integrity of aerospace materials, where safety and reliability are most important. The inherent complexity of modern aerospace components, often fabricated from advanced alloys and composites, presents significant challenges for traditional defect detection methods, particularly in identifying flaws such as cracks, corrosion, and material degradation under operational conditions [1, 2]. Conventional ECT devices and their application methodologies rely on empirical and experimental data-driven models. While effective, these often lack the adaptability required to account for the diverse material properties and operational environments encountered in the aerospace sector [3, 4].

The influence of the geometric parameters of the eddy current probe (ECP) on testing resolution poses a design challenge for ECT systems. Furthermore, the underutilization of analytical models limits such systems' adaptability to the varying characteristics of the test object (TO) [5]. Previous studies [4, 5] indicate that theoretical models in ECT remain underdeveloped, especially for diagnosing alloys used in aerospace. However, analysis of data from such models holds significant potential for enhancing ECT accuracy. Similarly, while empirical methods demonstrate effectiveness in controlled conditions, their limitations in adapting to real-world operational environments have been highlighted by research findings [3]. Existing analytical models are effective for single-layer conductors but encounter difficulties with multilayer structures or non-linear material properties [6]. Their limited efficacy, primarily due to simplifications in electromagnetic equation solutions and insufficient consideration of the skin effect or magnetic interactions, complicates the accurate assessment of ECP parameters, material properties, and TO condition. All of the above are critical for improving accuracy in aerospace component inspection [7].

Conversely, contemporary numerical modeling approaches, particularly those based on the Finite Element Method (FEM), show high efficiency in replicating experimental signals and enable model verification even in complex geometries and multilayer environments [8, 9]. Nevertheless, such models demand substantial computational resources and do not always provide a rapid interpretation of the physical relationship between system parameters and the resulting signal.

These considerations highlight the necessity of strengthening the theoretical foundations underlying eddy current testing in order to improve the design and optimization of ECT tools for aerospace applications. In this context, the present study focuses on analytical modeling of the ECP signal within the "ECP-TO" system, specifically adapted for monitoring the structural integrity of aerospace materials. The research investigates the influence of key parameters – including

ECP geometry, excitation frequency, lift-off distance, and electrical conductivity – on the resulting signal characteristics, aiming to improve the accuracy and reliability of defect detection. This challenge is addressed from the modeling and theoretical standpoint, with the potential for subsequent verification under real-world conditions.

2. THEORETICAL BASIS OF THE DIMENSIONLESS EFFICIENCY COEFFICIENT

2.1. Physico-Mathematical Model of the ECP Signal

To analyze the analytical signal model generated by an “ECP – non-magnetic TO” system, the setup is represented here by an equivalent system of inductively coupled electrical circuit elements (Fig. 1) [6, 10]. In Fig. 1, $u_g(t)$ is the power voltage, R is a resistor, and C_1 represents the total capacitance formed by the coil’s inter-turn capacitance and other probe parasitic capacitances. Parameters R_1 and L_1 correspond to the active resistance and inductance of the ECP’s excitation coil, while R_2 and L_2 represent the active resistance and inductance of the ECP’s measurement coil. The currents in the corresponding branches of the circuit are represented by i_1 , i_2 , and i_3 . The influence of the non-magnetic TO is incorporated into the equivalent circuit by serially connected elements $R_3(\bar{w})$ and $L_3(\bar{w})$, which are dependent on the parameter and characteristic vector of the TO, $\bar{w}$. Inductive coupling between coils L_1, L_2 and $L_3(\bar{w})$ is introduced as M_{12} , M_{13} , and M_{23} , respectively, following the coil numbering convention.

Circuit analysis was performed using classical electrical circuit theory, specifically applying the “decoupling” method for inductive circuits [11, 12].

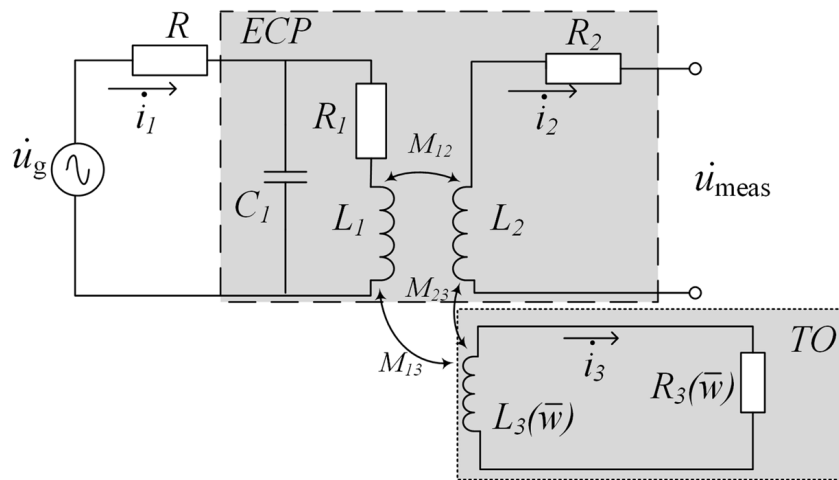


Fig. 1. Equivalent circuit diagram.

From previous analyses of “parametric ECP – TO” systems, it is known that the characteristic equation for a “transformer-type ECP – non-magnetic TO” system will be fourth-order [13]. The corresponding characteristic equation for the electrical circuit shown in Figure 1 is:

$$\begin{aligned} & [(R_1 + R) + p(L_1 + C_1 R R_1) + p^2 C_1 R L_1] \\ & \times [R_2 R_3(\bar{w}) + p(R_2 L_3(\bar{w}) + L_3(\bar{w}) R_3(\bar{w})) + p^2 (L_2 L_3(\bar{w}) - M_{23}^2)] \\ & - [-p M_{12}(1 + p C_1 R)] \cdot [-p (M_{12} R_3(\bar{w})) - p^2 (M_{12} L_3(\bar{w}) + M_{23} M_{13})] \\ & + [-p M_{13}(1 + p C_1 R)] \cdot [p (M_{13} R_2) + p^2 (M_{13} L_2 + M_{12} M_{23})] = 0 \end{aligned} \quad (1)$$

where $p = \omega j$. To write (1) as a complete polynomial in the form $a_4 p^4 + a_3 p^3 + a_2 p^2 + a_1 p + a_0 = 0$, all terms must be multiplied and then grouped by powers of the parameter p [11].

$$\begin{aligned} a_4 &= C_1 R (L_1 L_2 L_3(\bar{w}) - M_{23}^2) - C_1 R M_{12} (M_{12} L_3(\bar{w}) + M_{23} M_{13}) \\ &\quad - C_1 R M_{13} (M_{13} L_2 + M_{12} M_{23}), \\ a_3 &= C_1 R L_1 (R_2 L_3(\bar{w}) + L_2 R_3(\bar{w})) + (L_1 + C_1 R R_1) (L_2 L_3(\bar{w}) - M_{23}^2) \\ &\quad - M_{12} (M_{12} L_3(\bar{w}) + M_{23} M_{13}) - M_{12}^2 C_1 R R_3(\bar{w}) - M_{13} (M_{13} L_2 + M_{12} M_{23}) \\ &\quad - M_{13}^2 C_1 R R_2, \\ a_2 &= C_1 R L_1 R_2 R_3(\bar{w}) + (L_1 + C_1 R R_1) (R_2 L_3(\bar{w}) + L_2 R_3(\bar{w})) + (R_1 + R) (L_2 L_3(\bar{w}) - M_{23}^2) \\ &\quad - M_{12}^2 R_3(\bar{w}) - M_{13}^2 R_2, \\ a_1 &= (L_1 + C_1 R R_1) R_2 R_3(\bar{w}) + (R_1 + R) (R_2 L_3(\bar{w}) + L_2 R_3(\bar{w})), \\ a_0 &= (R_1 + R) R_2 R_3(\bar{w}) \end{aligned}$$

The derived physico-mathematical model of the “ECP – non-magnetic TO” system provides a valuable tool for designing new and optimizing existing ECP configurations and developing algorithms for processing measurement signals. This analytical formulation of the system’s processes enables a detailed analysis of inspection process parameters – including frequency, geometric and electromagnetic coil parameters, and the impact of the total capacitance C_1 within the overall circuit. This approach makes it possible to determine the conditions that maximize system sensitivity to specific defect types or material properties. Furthermore, the proposed

model facilitates the adaptation of system parameters to solve the inverse problem of estimating defect dimensions and characteristics based on measured (experimental) data. Consequently, this model transforms theoretical understanding into practical solutions, significantly enhancing the effectiveness of ECT and promoting the integration of ECT tools into structural health monitoring (SHM) systems for aerospace structures.

2.2 Finite Element Model of ECP Signal

To analyze the ECP signal model, Finite Element Method (FEM) numerical simulations were performed using the COMSOL Multiphysics software package. The simulation utilized the “AC/DC Module” with the “Magnetic Fields” interface, which solves Maxwell’s equations in the harmonic regime to analyze magnetic and eddy current fields. The geometric model includes a transformer-type ECP with an excitation coil (295 turns, inner radius 1.7 mm) and a measurement coil (810 turns, inner radius 1.7 mm), both positioned coaxially. The flat non-magnetic TO is represented by an aluminum plate (with thickness of 15 mm, electrical conductivity $\sigma = 3.5 \cdot 10^7$ S/m, relative magnetic permeability $\mu_r = 1$). The excitation source is a sinusoidal voltage with a frequency of $f = 50$ Hz. The lift-off distance from the ECP to the TO surface is 0.5 mm. Boundary conditions include zero magnetic flux at the outer boundaries of the model to simulate an isolated space.

A 2D cross-sectional view along the symmetry axis of the model is shown in Figure 2. The ECP setup (Fig. 2) is designed as 2D axisymmetric. It consists of an excitation coil (1) and two differentially connected receiver coils (2) positioned at a certain distance on opposite sides. Air is selected as the material of the air field (3), and aluminum alloy is selected as the material of the tested specimen (4).

Figure 2 demonstrates the skin effect, where eddy currents are induced in the TO concentrated near its surface, thereby reducing the penetration of the electromagnetic field into its depth. Figure 3 illustrates the distribution of eddy currents beneath the ECP at a depth of 1 mm (curve 1) and 5 mm (curve 2) within the TO. Since the model is axisymmetric with respect to the central axis, the graph displays only half of the region, which correlates with the lengths shown in Figure 2.

Figure 3 illustrates that the maximum eddy current density is formed near the coil’s edge and decreases as the distance from the center increases. At a depth of 1 mm (curve 1), the current values are significantly higher than at a depth of 5 mm (curve 2). This behavior is consistent with the skin effect, where the electromagnetic field primarily excites the surface layers of the TO while deeper regions are shielded. These simulation results indicate that even at a depth of 5 mm, a detectable difference in the curve’s shape and amplitude is maintained,

which can be detected by a suitable probe. This suggests the possibility of obtaining diagnostically significant information from subsurface material layers, provided the coil geometry, excitation parameters, and receiver system characteristics are appropriately chosen. Thus, the simulation not only confirms the classic nature of the current distribution but also opens up prospects for developing eddy current systems capable of inspecting defects at various depths in aviation materials.

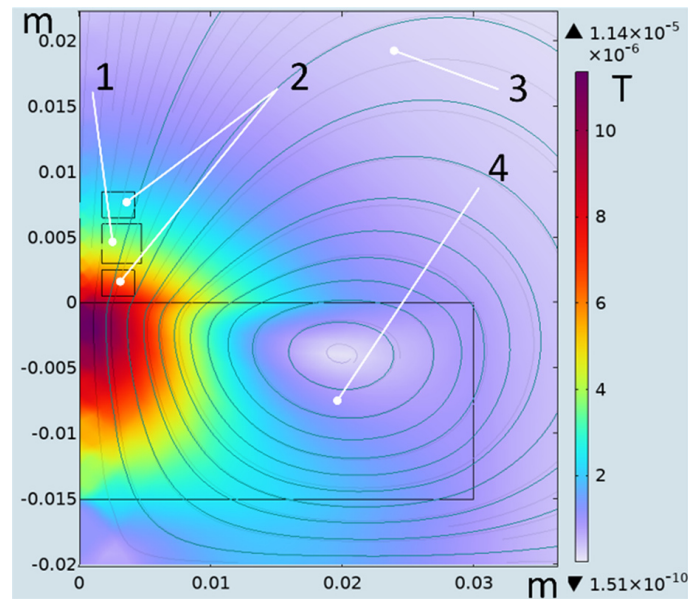


Fig. 2. Magnetic flux density.

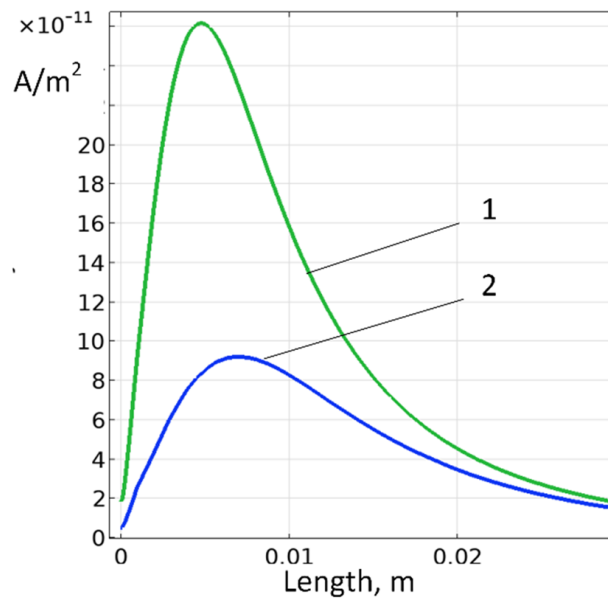


Fig. 3. Eddy current density in the TO.

The results of the numerical modeling, presented in Figure 4, demonstrate the dependence of the ECP signal on the electrical conductivity of the TO. Here, curve 1 represents the ECP signal without TO near, while curves 2 and 3 correspond to ECP signals when inspecting a TO with electrical conductivities of $3.4 \cdot 10^7$ S/m and $3.5 \cdot 10^7$ S/m, respectively. It simulates aluminum with minor deviations in electrical conductivity. The results show that a $38 \mu\text{V}$ change in the ECP signal corresponds to a $0.1 \cdot 10^7$ S/m change in the electrical conductivity of TO. This indicates sufficient sensitivity of the ECP to local variations in material properties.

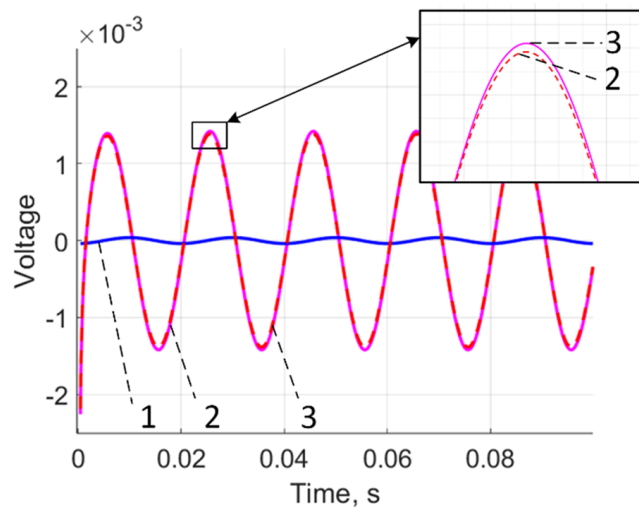


Fig. 4. Simulated ECT signal under varying test object conductivity.

The results demonstrate that compensating for the base component increases the sensitivity to changes in the object's electrical conductivity. This confirms that even minor variations in material properties are reflected in the voltage characteristics, which is crucial for the practical implementation of eddy current testing in the SHM of aircraft structures. Such signal assessment facilitates the development of tools and adaptive methods for SHM for defect detection in complex aerospace structures.

3. EXPERIMENTAL INVESTIGATION

A dual-differential ECP with a diameter of 15 mm was used for the experimental study. The probe windings had inductances of $L_{exit} = 6.3$ mH and $L_{measur} = 47$ mH. The tested specimen (TS) was an aluminum D16T alloy sample with an artificial defect (an infinitely deep crack) created by joining the ends of two 25 mm thick plates. The defect was covered with up to 17 layers of 0.9 mm thick aluminum plates [14]. This approach allowed for the simulation of varying defect depths during measurements.

During the investigation, the concept of “noise-limited defect detection depth” [7] was employed to evaluate the limiting values for defect depth. The number of covering plates was progressively increased until a detectable signal was no longer observed.

Figure 5 presents the experimentally obtained dependencies of the relative amplitude level of the ECP signal on the signal frequency, acquired by scanning a TS with varying defect depths (h). Each curve corresponds to a specific defect depth, ranging from 0.9 mm (one layer of plates) to 15.3 mm (17 layers).

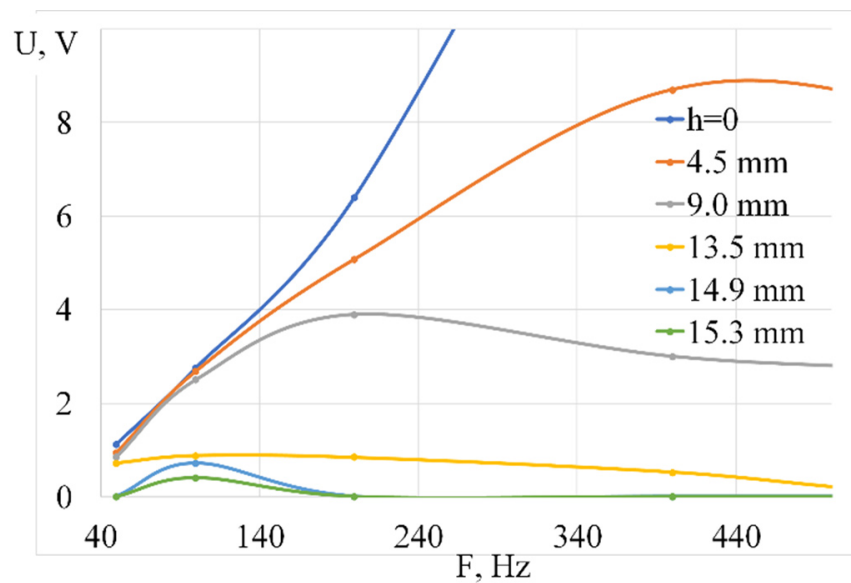


Fig. 5. Dependence of the signal amplitude on scanning a test object with varying defect depths.

The obtained curves shown in Figure 5 demonstrate a characteristic behavior that is crucial for ECT of deep-lying defects. For each defect depth, there is an optimal frequency at which the maximum signal level from the defect, sufficient for its detection, is achieved. This occurs because the penetration depth of the electromagnetic field (which is inversely proportional to the square root of the frequency) must be sufficient for effective induction of eddy currents in the defect area.

The results from Figure 5 show that as the depth h increases, the frequency corresponding to the amplitude peak shifts towards lower values. This is a direct confirmation of the physical principle of the skin effect: lower frequencies must be used to inspect deeper layers of the material. Thus, the experimental results confirm the possibility of effective detection of hidden defects.

In particular, this study has established that, for the tested configuration, the maximum detection depth for an “infinitely deep crack” can be estimated at 15.3 mm

at a frequency of 50 Hz. Furthermore, the results demonstrate that integrating numerical modeling into the inspection process can significantly reduce the time required to configure optimal testing parameters under real-world diagnostic conditions.

4. CONCLUSION

This study developed and analyzed a physico-mathematical model of the “ECP – TO” system, providing an analytical description of current dynamics that accounts for key physical and electrical parameters. This model is particularly relevant for improving defect detection accuracy in aerospace structural materials. Numerical modeling using Finite Element Method (FEM) simulations, together with experimental investigations on aluminum alloy samples, confirmed the model’s sensitivity to changes in electrical conductivity. The experimental further demonstrated a methodology for determining the optimal frequency for detecting subsurface defects at depths exceeding 15 mm at 50 Hz.

The results show that combining analytical calculations, numerical modeling, and experimental validation is a valuable and necessary approach for developing advanced ECT-based inspection tools. This integrated methodology supports the design of sensors and the formulation of signal processing methodologies, facilitating the selection of the optimal component base. Ultimately, these efforts contribute to creating more adaptive inspection tools, recommendations, and diagnostic techniques for aviation components.

While current mathematical tools have limitations in fully capturing all physical regularities, their further development will reduce the need for extensive experimental research. Future refinements will require only partial model adjustments based on real-world data to adapt to complex inspection tasks, such as those involving multilayer structures.

Overall, these advancements represent an important step towards improving structural health monitoring (SHM) capabilities for aerospace components, paving the way for more adaptive, efficient, and reliable diagnostic solutions.

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