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EVALUATION OF EDDY CURRENT ARRAY PERFORMANCE IN DETECTING AIRCRAFT COMPONENT DEFECTS

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ABSTRACT

Eddy current array (ECA) technology is increasingly being used in the aerospace industry for non-destructive testing of aircraft components. This study evaluates the performance of ECA in detecting defects in aircraft components, focusing on its effectiveness, reliability, and sensitivity. The study evaluates the effectiveness of ECA technology in eddy current defectoscopy by introducing a dimensionless efficiency coefficient, then seeks to validate this coefficient through experimental testing of aircraft component materials with artificially induced defects of various sizes, types, and orientations to simulate real-world scenarios. ECA's sensitivity in detecting small and subsurface defects is analyzed, along with precise defect sizing and positional information. Reliability and repeatability are investigated through repeated measurements. Furthermore, the article analyses the impact of various factors on the performance of ECA, including surface conditions, probe configurations, and inspection parameters. Comparative analysis is performed to assess the advantages and limitations of ECA in comparison to other conventional inspection methods. The findings of this study will contribute to a better understanding of the capabilities and limitations of ECA in detecting aircraft component defects. The results will aid in optimizing inspection strategies, enhancing the reliability of defect detection, and improving the overall maintenance practices in the aerospace industry.

Keywords

eddy current; signal characteristics; information parameters; defect detection; performance evaluation.

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1. INTRODUCTION

The aviation industry, driven by the imperatives of safety and reliability, places paramount importance on effective inspection and evaluation of components as integral facets of maintenance and quality control processes. The need to detect defects in aviation components is critical, aiming to preclude catastrophic failures and ensure the optimal performance of aircraft systems. In light of this, the demand for advanced non-destructive testing (NDT) techniques is constantly increasing, and specific materials and objects require their ongoing development [1–3].

Among the advanced NDT methodologies gaining significant recognition is the eddy current array (ECA) inspection method [4, 5]. Recognized for its numerous advantages over conventional techniques, ECA is emerging as an attractive solution for the detection and evaluation of defects in aviation components [6, 7]. This study examines the multifaceted advantages of ECA, shedding light on its potential to augment safety and reliability in aviation systems.

ECA's utilization of multiple closely spaced coils in an array facilitates improved coverage and heightened sensitivity to small defects. This capability allows for the detection of anomalies that may escape notice through traditional inspection methods, thus elevating the overall effectiveness of inspections. Simultaneous scanning of multiple channels and data collection in a single pass significantly reduces inspection time. Its capacity for faster inspection rates renders it suitable for large-scale inspection campaigns, thereby reducing aircraft downtime during maintenance [7–8].

ECA provides detailed information about the size, shape, and orientation of detected defects. Analysis of amplitude and phase information from collected signals enables accurate characterization of the nature of defects, aiding in their evaluation and subsequent decision-making processes. The digital data produced by ECA can be processed and analyzed using advanced algorithms, enabling quantitative assessment and precise evaluation of defect characteristics. This facilitates informed decision-making regarding the acceptability and repair strategies for aviation components [9].

ECA's capabilities extend to detecting defects both on the surface and within the subsurface of aviation components. This makes it effective for identifying cracks, corrosion, delaminations, and other hidden defects that may compromise the structural integrity of components.

While ECA demonstrates significant promise in revolutionizing aviation inspections, certain challenges associated with its implementation and optimization persist. The complex interplay of factors, including array size, geometry, material properties, and inspection parameters, demands comprehensive evaluation [7, 10]. This study addresses challenges identified in previous research by providing experimental insights into optimizing ECA performance for enhanced defect detection in aircraft components [7, 11, 12].

In specific, the study evaluates the effectiveness of ECA technology in eddy current defectoscopy by introducing a dimensionless efficiency coefficient that considers inspection time, reliability, and sensitivity. It further seeks to validate this coefficient through experimental testing of aircraft component materials with artificially induced defects.

2. THEORETICAL BASIS OF THE DIMENSIONLESS EFFICIENCY COEFFICIENT

Given the advantages of ECAs, it seems reasonable to assess their effectiveness in eddy current defectoscopy by means of a dimensionless efficiency coefficient:

$$k_{\text{ef}} = k_T \cdot k_P \cdot k_S \,, \tag{1}$$

where k_T, k_P, k_S are relative coefficients characterizing the reduction in inspection time, increase in inspection reliability, and sensitivity improvement of the inspection tool, respectively. If, in addition to defect detection, an evaluation of a specific parameter of the defect (such as length, depth, or crack depth) is performed, coefficient (1) may be supplemented by a factor characterizing the improvement in the accuracy of estimating this parameter.

The coefficient k_T is determined by the relative reduction in inspection time of the test object, according to equation:

$$k_T = \frac{T_{ECP}}{T_{ECA}} \,, \tag{2}$$

where T_{ECP}, T_{ECA} represent the total inspection time of the test object using a single-element eddy current transducer (ECP) and ECA, respectively.

To account for the scanning trajectory of the test object with a single-element ECP and ECA, let's assume that the width of the test object (or the inspected area of the test object) coincides with the width of the array [10]. Consequently, the array moves only along the x-coordinate, whereas the single-element ECP on the same test object needs to be moved along both the x and y coordinates. In this case, the values of the time intervals T_{ECP}, T_{ECA} can be determined by the equation:

$$T_{ECP} = mn\left(T_p + T_m\right), \tag{3}$$

$$T_{ECA} = \left(m+2\right)T_p + 4\left(m+1\right)T_m \,, \tag{4}$$

where T_p, T_m are the times required, respectively, to move the probe or array to the next positioning point and to perform measurements at a single point, with m, n representing the number of measurement points on the surface of the inspected object.

Since under the adopted assumptions the number n of scan lines of the probe is equal to the number of elements in the array ($n = G$), and since $T_p > 4T_m$, coefficient (2) will be determined by the expression:

$$k_T \approx \frac{Gm}{m+2}. \tag{5}$$

The coefficient k_P can be defined as the ratio of the probabilities P_{ECP}, P_{ECA} of detecting a defect of a certain type and size, respectively, using single-element ECP and ECA matrix, respectively, by the equation:

$$k_P = \frac{P_{ECA}}{P_{ECP}}, \tag{6}$$

It is advisable for this coefficient to be determined experimentally using test samples with artificial or natural defects, provided that the parameters of the electromagnetic field excitation for eddy current and the amplification coefficients of measurement channels are the same for both transducers.

The coefficient k_S can be defined as the ratio of absolute sensitivities $S_{ECP}(l)$, $S_{ECA}(l)$ when detecting a defect of a specific type in the range Δl of its parameter size variation, by the equation:

$$k_S = \frac{S_{ECA}(\Delta l)}{S_{ECP}(\Delta l)}, \tag{7}$$

where parameter l represents a specific defect parameter within it (length, depth of penetration, or crack depth).

This coefficient should also be determined under the condition of the same parameters for both transducers in terms of the electromagnetic field excitation for eddy current and the amplification coefficients of measurement channels.

Thus, the dimensionless coefficient, which allows for a comprehensive assessment of the reduction in inspection time, increase in inspection reliability, and sensitivity of inspection, as well as the relative reduction in the inspection time of the controlled object, may be suitable for determining the efficiency of ECA application.

3. EXPERIMENTAL INVESTIGATION

3.1. Testbed Description

Prior to conducting the experiment, we prepared a specimen using the aluminum alloy 31T5 (AD31T5) widely employed in the aviation industry. This sample features artificially created defects of diverse configurations and sizes. Fig. 1 displays the prepared sample, presenting dimensions of 360 mm in length, 120 mm in width, and 5 mm in thickness. Circular defects with differing cluster densities are present within this sample.

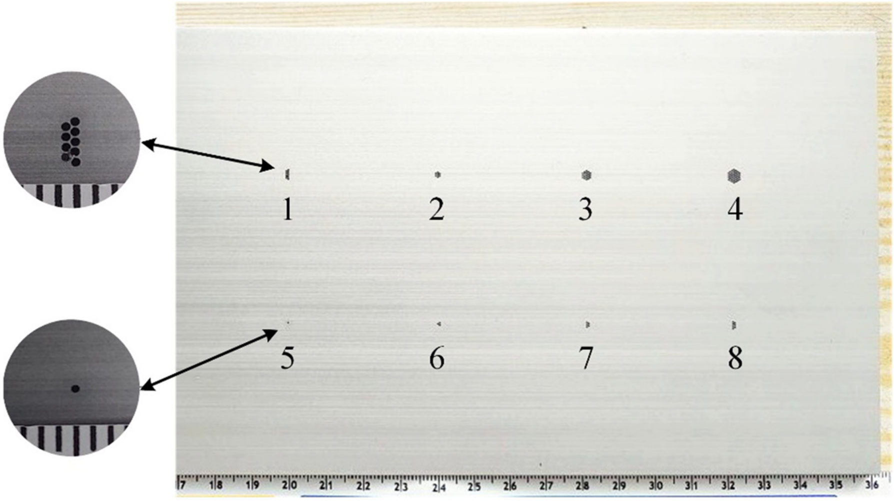

Fig. 1. Sample made of AD31T5 alloy (1–8: defects of various types and sizes)

The circular defects have a depth of 4 mm and a diameter of 0.5 mm. These circular defects are arranged in various cluster densities in close proximity to each other. Note that certain sizes might be too small for adequate testing with the currently available ECA equipment.

This study utilized the Olympus Omniscan MX eddy current flaw detector with a matrix-type eddy current sensor (Fig. 2). It belongs to the category of flexible sensors and is manufactured from a film based on printed circuit board technology [13]. To adapt to the investigated surface, the sensor has the capability to be installed based on the required curvature. It consists of 32 coils, each with a diameter of 3 mm, thus comprising 2 absolute-type transducers.

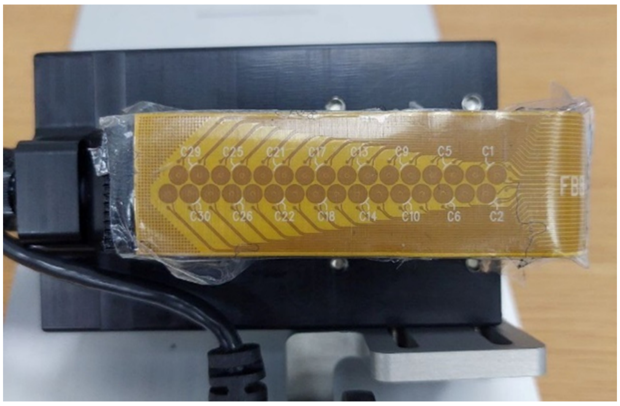

Fig. 2. Airplane in a steady-state turn

The defectoscope incorporates multiplexing of individual matrix elements to prevent mutual interference of adjacent elements. The Olympus Omniscan MX flaw detector with the eddy current array includes special software for creating C-scans and simultaneously displaying signals in the form of a hodograph.

3.2. Experimental research and results discussion

The scanning results in the form of C-scans for a portion of the defects in the test sample are presented in Fig. 3 (for convenience, the scanning results are divided into two zones: defects 1–4 and defects 5–8). The following settings were used in the conducted experiment: operating frequencies of 80 kHz, 160 kHz, and 320 kHz, signal amplitude on the excitation coils 1 V, signal amplification in the measurement channel 78 dB.

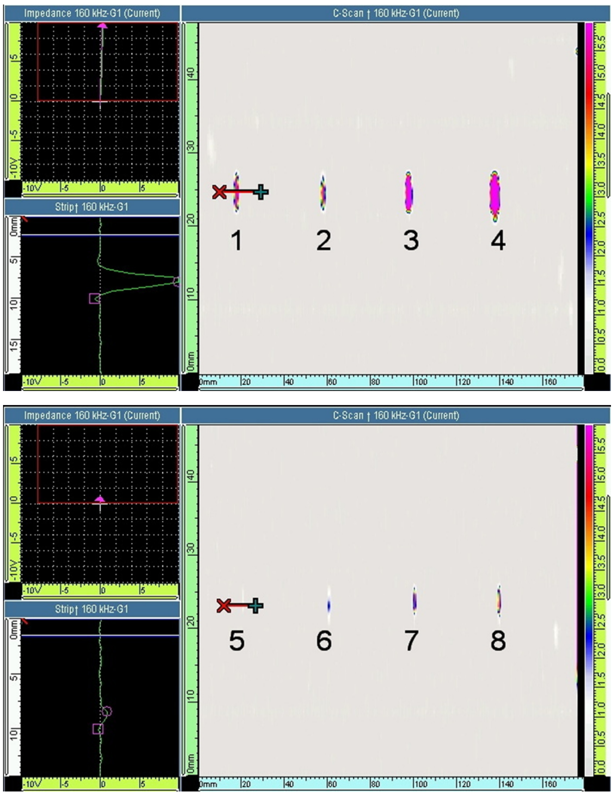

Fig. 3. Scanning results in the form of C-scans for sample sections

Fig. 3 shows that the color representation of defects 5 and 6 (Fig. 3b) is the least noticeable under the specified instrument settings. Detecting defect 5, which is represented by a single hole with a diameter of 0.5 mm, is challenging without prior adjustment and calibration of the matrix transducer, indicating the need for a more careful selection of the scanning mode for defects of this size.

For adequate interpretation of inspection results, it is important to adjust the sensitivity level using the color (amplitude) scale, which enhances the visualization of defects. However, increasing sensitivity raises the risk of false positives due to higher noise levels, which may result in both defects being missed and normal areas of the object under inspection being rejected as defects.

A quantitative assessment of defects can be obtained from the amplitudes of signals during the passage through the matrix of the defective area. The obtained amplitude values of defect signals are summarized in Table 1.

As the results indicate, there is a certain dependence of the defect signal amplitudes on their sizes and areas (cluster shapes of holes) for defects 1-8 (Fig. 1). Obviously, for a more detailed analysis of this dependence, it is advisable to distinguish a subgroup of similar defects in the form of continuous clusters of holes. This subgroup should include defects 1, 6, 7, and 8 with vertical lengths of 2.9, 1.1, 1.7, and 2.3, respectively. Comparing the signal values for these defects, it is evident that for defect 6 with a length of ~1.1 mm, a signal with an amplitude of at least 1 V was obtained, indicating the high sensitivity of the transducer to small-sized defects under the given control process settings.

Table 1: Experimental data of the test specimen investigation.

No. of defect	**The number of holes n (length in mm)**	**Signal amplitude from the defect (V)**		
		80 kHz	**160 kHz**	**320 kHz**
1	9 (2.9)	4.6	10.6	10.6
2	7 (1.7)	2.7	7.9	7.9
3	19 (2.9)	5.7	10.7	10.8
4	37 (4.1)	7.5	10.9	10.9
5	1 (0.5)	-	1.1	1.6
6	3 (1.1)	1.0	2.7	4.3
7	5 (1.7)	2.0	6.2	10.3
8	7 (2.3)	3.4	8.3	10.5

Furthermore, the dependencies of signal values at frequencies of 80 kHz and 160 kHz on the length of defects are close to linear. This provides grounds for their use in the quantitative assessment of defect sizes. However, a decision should be made beforehand regarding the classification of defects into a specific class, since different classes and frequencies will have different functional dependencies.

4. CONCLUSIONS

This study highlights the pivotal role of ECA technology in non-destructive testing within the aerospace industry. Focused on assessing ECA's efficacy in defect detection, the research emphasized effectiveness, reliability, and sensitivity. Firstly, we proposed a dimensionless coefficient, which allows for a comprehensive assessment of the reduction in inspection time, increase in inspection reliability, and sensitivity of inspection, as well as the relative reduction in the inspection time of the controlled object, as being suitable for determining the efficiency of ECA application. Through experimental tests on aircraft components with simulated real-world defects of various types, sizes, and orientations, the study revealed significant advantages of ECA in aviation inspections. The use of multiple closely spaced coils enhanced coverage and sensitivity, detecting anomalies that traditional methods might miss. Simultaneous scanning and data collection in a single pass reduced inspection time, suitable for large-scale campaigns and minimizing aircraft downtime. The experimental investigation, utilizing an Olympus Omniscan MX flaw detector, offered insights into defect detection, acknowledging challenges associated with specific defect sizes and emphasizing array tuning. This research deepens our understanding of ECA's capabilities and limitations in detecting aircraft defects. The ongoing refinement of ECA technology promises further advancements in non-destructive testing for aviation safety and reliability.

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