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EFFECTIVENESS OF THE TECHNOLOGY OF AUTOMATED EDDY CURRENT FLAW DETECTION WITH ARRAY PROBE

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ABSTRACT

The effectiveness of application of matrix converter method at eddy current testing (ECT) is studied in the work. Advantages of eddy current matrix application are analyzed, which include improvement of sensitivity to small defects, shortening of the total control time and improvement of the probability of detection of various types of defects. To evaluate their effectiveness, a dimensionless coefficient is proposed, which takes into account the inspection time, the reliability of defect detection, and the sensitivity to defects of a certain size. Experimental studies on specimens with artificially induced defects of different dimensions, types and orientation confirmed the rationality of application of this coefficient for testing parameter optimization, in order to improve defect detection in structural elements. The influence of various factors, such as condition of the surface, sensor configuration in the matrix and verification parameters on the productivity of ECT hardware and software with matrix converters was additionally analyzed. Obtained results will promote better understanding of the possibilities and limitations of matrix application in ECT of the components of transport, aviation and defense equipment. It will allow optimizing the strategies of checking the tested products, improving the reliability of defect detection and general maintenance practices in many industries.

KEYWORDS: automated eddy current testing, converter matrix, effectiveness, mathematical modelling, flaw detection, signal processing, numerical methods

INTRODUCTION

The requirement of safety and reliability of operation in modern critical sectors of economy, such as aircraft, defense, automotive, oil and gas, and power generation prioritize effective checking and assessment of the current state of components. The need to detect defects in critical elements and components of structures for various purposes is the decisive factor to prevent irreversible failures and to ensure optimal operation of the system. New engineering solutions in the mentioned sectors and application of new materials increase the demand for advanced methods and procedures of nondestructive testing (NDT) and adaptation of the known methods to new NDT tasks [1–3].

Among the advanced directions of NDT development, the method of matrix eddy current testing (MEDT) is known by its numerous advantages, and it belongs to attractive solutions for detection of defects and evaluation of their characteristics in structural elements in different branches of the economy [4, 5]. MEDT application envisages using several closely located electric coils, combined into converter arrays, which promotes improvement of the coverage area of the tested object (TO) and increased sensitivity to small defects. Such an approach allows revealing anomalies, which may be undetected by single converters, and improves the overall effectiveness of TO diagnostics. At the same time, scanning by several channels and acquisition of a significant volume of data in one pass of the eddy current matrix (ECM) significantly shorten the testing time, which is extremely important at examination of large-sized TO, as it also shortens the equipment downtime during maintenance [6, 7].

MEDT capabilities include defect detection both on the surface and inside TO. This makes it more effective for detection of cracks, corrosion damage, delamination and other hidden defects, which can violate the structural integrity of structural elements. It is of special importance in the context of transport and defense industry, where reliability and safety are critical factors for life protection and preservation [5, 8].

Despite the fact that MEDT demonstrates considerable potential for application in different sectors, certain problems related to its introduction and optimization remain unsolved. ECM application allows obtaining information on the size, shape and orientation of the detected defects, based on the amplitude value of coil signals. However, complex interaction of factors, including the size of the converter array, its geometry, material properties and testing parameters, requires a comprehensive evaluation of their influence [9].

Aggregate analysis of informative parameters of ECM signals, namely amplitude and phase of the harmonic signals, will allow more precise characterization of the defect nature and improvement of the reliability of decision taking in automated systems of eddy current flaw detection. More over, it is rational to process and analyze the considerable volumes of measurement information obtained using ECM in the form of digital data, using advanced information technologies, including artificial intelligence, that may improve data analysis and interpretation, increasing the testing effectiveness and reliability [10, 11]. It will also allow quantitative evaluation of the defect characteristics and will facilitate taking substantiated decisions as to the strategies for the acceptability of further operation or restoration repair of critically important structural elements [12].

THE OBJECTIVE

of the work is to study the effectiveness of ECM technology in flaw detection, using the proposed dimensionless efficiency factor, which takes into account the checking time, reliability and sensitivity, as well as experimental testing of MEDT technology on material with artificial defects with the known characteristics.

THEORETICAL SUBSTANTIATION OF ECM EFFICIENCY FACTOR

Analysis of the advantages of ECM application showed that, compared to the traditional converters this methodology ensures a higher sensitivity to small defect detection, reduction of the overall control time and increased probability of detection of various defect types [13, 14]. In view of that, it was proposed to assess the effectiveness of ECM application in flaw detection by a dimensionless coefficient, which is found from the following formula:

$$k_{\mathrm{ef}} = k_t k_{\mathrm{P}} k_{\mathrm{S}}, \tag{1}$$

where k_t, k_{P}, k_{S} are the relative coefficients characterizing reduction of testing time, increase of testing reliability and improvement of the testing device sensitivity, respectively. If evaluation of a specific defect parameter (for instance, its length, depth or crack depth) is performed alongside defect detection, coefficient (1) can be completed by a multiplier, characterizing the increase of the reliability of this parameter assessment.

The coefficient, which characterizes the reduction in inspection time, is determined by relative shortening of the time of TO examination by the following formula:

$$k_t = \frac{T_{\mathrm{ECC}}}{T_{\mathrm{ECM}}}, \tag{2}$$

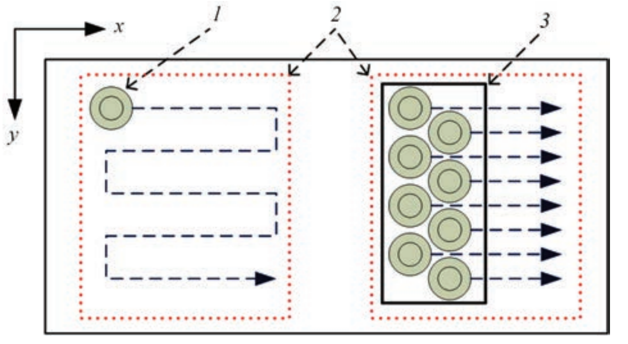

Figure 1. Trajectories of ECC and ECM scanning over TO surface: *1* — ECC; *2* — scanning area; *3* — ECM

where T_{ECC}, T_{ECM} is the total testing time, when using the traditional single eddy current converter (ECC) and ECM, respectively.

To assess the testing time, it is necessary to take into account the duration of movement by a single ECC and by ECM along the trajectory of TO surface scanning [8]. Let us assume that: 1) transverse size (along the y coordinate) of the tested area coincides with ECM transverse size, along which the sensors are located (Figure 1); 2) ECM moves only along x coordinate, while for covering such a TO surface area, it is necessary to move ECC both along x coordinate and along y coordinate. In this case, values of time intervals T_{ECC}, T_{ECM} are determined by the following expressions:

$$T_{\mathrm{ECC}} = mn(t_{\mathrm{r}} + t_{\mathrm{m}}), \tag{3}$$

$$T_{\mathrm{ECA}} = mt_{\mathrm{r}} + nmt_{\mathrm{m}}, \tag{4}$$

where t_{r} and t_{m} are the time required, respectively, for repositioning the ECC or ECA probe to the next measurement point and for performing a measurement at an one point; m, n is the number of measurement points on TO surface along x and y axes, respectively.

As in the accepted assumptions the number of ECC scanning lines is equal to the number of elements in the array (n), and $t_{\mathrm{r}} >> t_{\mathrm{m}}$, then coefficient (2) can be approximately represented by the following expression:

$$k_t \approx n. \tag{5}$$

The coefficient, which characterizes the improvement in inspection reliability, can be determined as the ratio of the probabilities of detection of defects of a certain type and size during application of ECC (P_{ECC}) and ECM (P_{ECM}) by the following formula:

$$k_{\mathrm{P}} = \frac{P_{\mathrm{ECC}}}{P_{\mathrm{ECA}}}. \tag{6}$$

It is rational to determine this coefficient experimentally, using test specimens with artificial or natural defects under the condition that the parameters of excitation of eddy current electromagnetic field and the gain factors of measurement channels are the same for ECC and ECM.

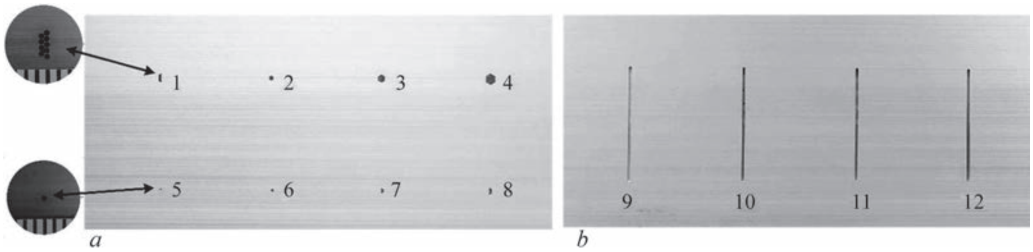

Figure 2. Specimen from AD31T5 alloy: 1–12 — defects of different types and dimensions

Coefficient k_S can be defined as the ratio of absolute sensitivities $S_{ECC}(l)$ and $S_{ECM}(l)$ at detection of a certain type of defect in the range of the change of its parameter size Δl by the following formula:

$$k_S = \frac{S_{\text{ECM}}(\Delta l)}{S_{\text{ECC}}(\Delta l)}, \tag{7}$$

where parameter l is the specific parameter of the defect (length, depth of location, crack depth, etc.).

The latter coefficient should also be determined under the condition of similar for both the converters parameters of excitation of eddy current electromagnetic field and measurement channel gain factors. As an example, if the amplitude method of defect detection is used, and the test specimen has two defects of dimensions $l_1, l_2 \in \Delta l, l_1 < l_2$, and these defects generate in the converters the signals of amplitudes $U_{ECM}(l_1)$, $U_{ECM}(l_2)$, and $U_{ECC}(l_1)$, $U_{ECC}(l_2)$, the converter sensitivities will be defined as follows:

$$S_{\text{ECM}}(\Delta l) = \frac{U_{\text{ECM}}(l_2) - U_{\text{ECM}}(l_1)}{l_2 - l_1}; \quad S_{\text{ECC}}(\Delta l) = \frac{U_{\text{ECC}}(l_2) - U_{\text{ECC}}(l_1)}{l_2 - l_1}, \tag{8}$$

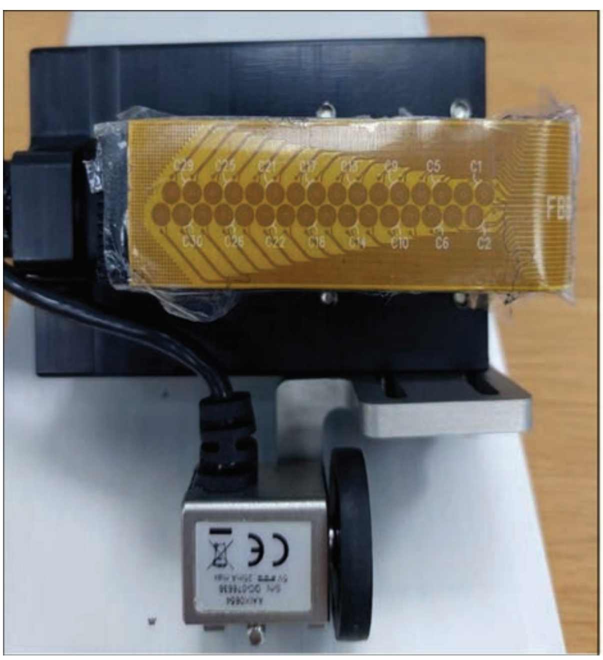

Figure 3. Eddy current matrix used in the experiments

and coefficient (7):

$$k_S = \frac{U_{\text{ECM}}(l_2) - U_{\text{ECM}}(l_1)}{U_{\text{ECC}}(l_2) - U_{\text{ECC}}(l_1)}, l_1, l_2 \in \Delta l. \tag{9}$$

Thus, a dimensionless coefficient was proposed for comprehensive assessment of the reduction of testing time, increase of testing validity and its sensitivity, which is quite suitable for determination of the effectiveness ECM application.

In case it is impossible to experimentally determine the coefficient components k_p and k_S they can be taken equal to a unity, and the approximate value of k_{ef} can be assessed as $k_{ef} \approx k_t$.

EXPERIMENTAL STUDIES

MATERIALS AND INSTRUMENTS USED

In order to conduct investigations, a specimen from aluminium alloy 31T5 (AD31T5), widely used in aircraft industry, was prepared. This specimen has artificially introduced defects of different configuration and size (Figure 2, *a*, *b*) and is of the following dimensions: 360 mm long, 120 mm wide and 5 mm thick. In the test specimen the longitudinal defects have the width of 1 mm and depth of 1–4 mm. In addition, the specimen surface has defects which are clusters of a different number of holes (Figure 2, *a*) and cracks of different depth (Figure 2, *b*). The holes have the depth of 4 mm and diameter of 0.5 mm each, and they are arranged in different numbers and in close proximity of each other. However, some dimensions of the thus formed defects can be too small for adequate testing with ECM used in the study.

In this investigation we used eddy current flaw detector Olympus Omniscan MX with ECM (Figure 3), which belongs to the category of flexible sensors and is made from film by the printed circuit board technology [15]. For adjustment to the examined surface, the sensor can be mounted on a base with the required curvature. ECM consists of 32 coils, each of 3 mm diameter.

The flaw detector implements multiplexing of individual matrix elements to prevent the mutual influence of adjacent elements, and its specialized software allows generating signal C-scans with simultaneous representation of the signals in the form of hodographs.

EXPERIMENTAL PROCEDURE AND RESULT DISCUSSION

Scanning results in the form of C-scans of the studied specimen surface are shown in Figure 4 (for convenience, the scanning results are divided into three zones and defect numbering in keeping with Figure 2 is used). The following settings were used in the conducted experiment: working frequencies of 80, 160, 320 Hz, signal amplitude in the excitation coils of 1 V, signal amplification of 78 dB in the measurement channel.

The sensitivity level of 78 dB was selected for adequate interpretation and comparison of testing results, which satisfied (by the amplitude scale) all the TO scanning modes and provided clear visualization (visibility) of the defects. Higher sensitivity increases the risk of faulty operation because of a higher noise level and it may lead to the situation, when defects will be overlooked, while defectfree TO areas will be considered defective [16].

Quantitative assessment of defect parameters can be obtained by the signal amplitudes after ECM passing through a defective area. Obtained values of defect signal amplitudes are summarized in Table 1.

Figure 4, *a*, *b* shows the results of scanning TO areas with a different number of holes. Analysis of their scanning results shows that the highest sensitivity is achieved at the frequency of 320 Hz. However, if we take into account the relative position of the holes in one cluster (for instance, defects 2 and 8 have the same number of holes, but differ by their relative location), then the frequency of 80 Hz yields a difference in amplitude greater than 600 mV, but with frequency increase the influence of the geometry becomes less noticeable by amplitude. So, defect 2 is characterized by the same amplitude value at frequencies of 160 and 320 Hz.

The given data lead to the following conclusions. First, the signals from defects 9–12 differing by the artificial defect depths, practically do not differ by amplitudes at each of the frequencies. Such a result meets the theoretical expectations, as the depth of eddy current penetration into aluminium at the frequency of 80 kHz is ~ 0.3 mm at the specific electrical conductivity of aluminium of ~ 36 MS/m, and the minimal depth of defects 9–12 is 1 mm. Secondly, for defects 1–8 (Figure 2) a certain dependence of defect signal amplitude on their dimensions and total area (shape) is observed.

For a more detailed analysis of this dependence, let us single out a subgroup of defects of one type in the form of an extended set of holes. Defects 1, 6, 7, 8 belong to this group. Values of signal amplitudes of these defects, arranged in the ascending order of defect size (or number of holes *n*) for different working frequencies are given in Table 2 and in Figure 5.

Analysis of the derived graphs leads to the following conclusions.

1. At less than 80 KHz working frequencies, the converter is capable of detecting defects smaller than

Table 1. Data of TO experimental study

Defect number	Defect parameter	Size, mm	Amplitude of signal from defect, V		
			80 kHz	160 kHz	320 kHz
1	Length	2.9	4.6	10.6	10.6
2		1.7	2.7	7.9	7.9
3		2.9	5.7	10.7	10.8
4		4.1	7.5	10.9	10.9
5		0.5	0.02	1.1	1.6
6		1.1	1.0	2.7	4.3
7		1.7	2.0	6.2	10.3
8		2.3	3.4	8.3	10.5
9	Depth	1.0	7.7	11.3	11.6
10		2.0	7.8	11.8	11.9
11		3.0	7.9	12.0	12.3
12		4.0	8.0	12.3	12.4

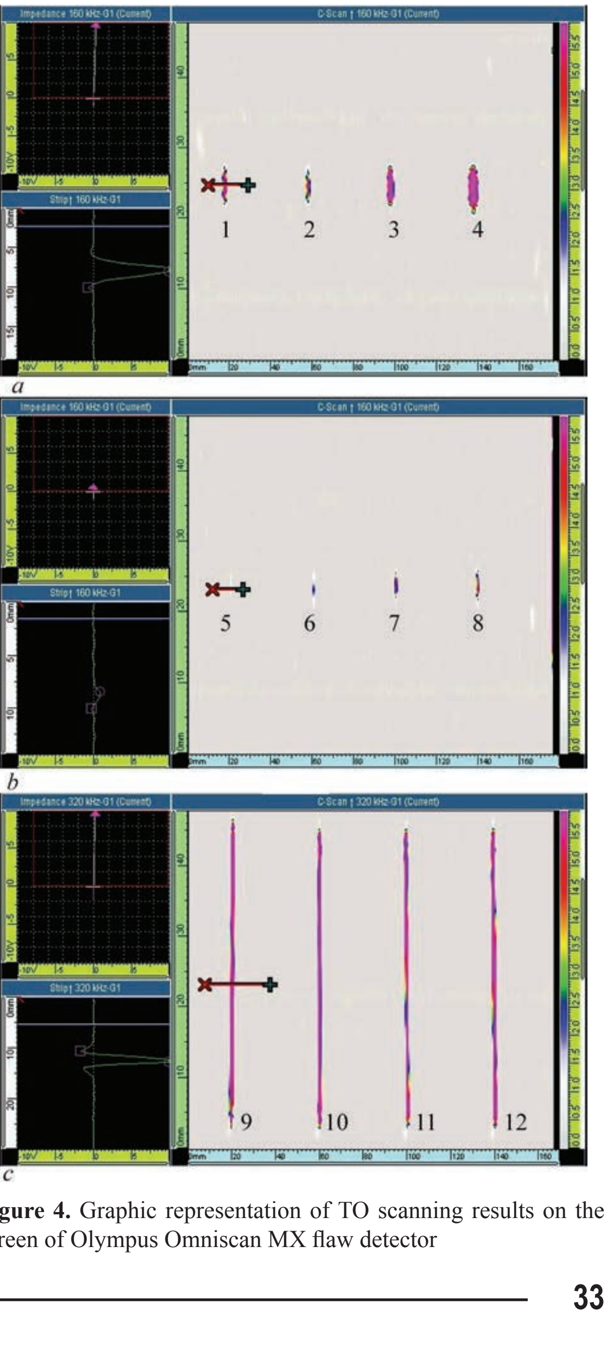

Figure 4. Graphic representation of TO scanning results on the screen of Olympus Omniscan MX flaw detector

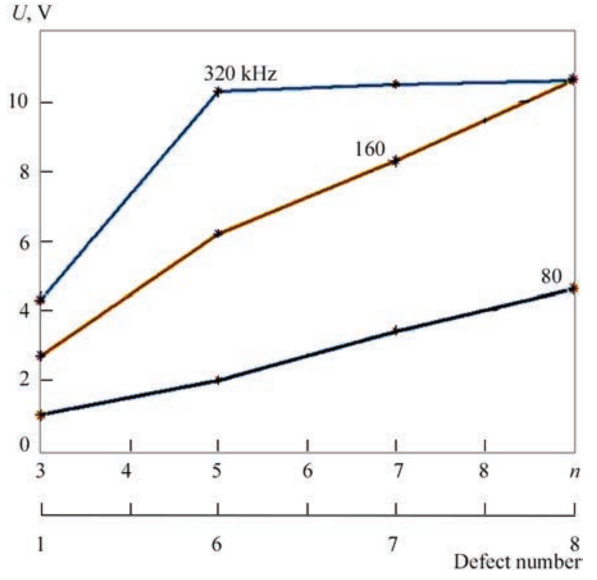

Figure 5. Graphs of dependence of amplitudes of signals from defects 1, 6, 7, 8 on their size and working frequency

the dimensions of ECM coils (coil diameter is 3 mm). For instance, a signal of not less than 1 V amplitude was received from defect 6 of ~ 1.1 mm length, which is indicative of the high sensitivity of the converter to small-sized defects.

2. Presented dependencies at frequencies of 80 and 160 kHz are close to the linear ones, giving grounds for their use for quantitative assessment of defect dimensions. However, a decision should be first taken on the defects belonging to a certain class, as different functional dependencies will be in place for different classes and frequencies.

3. Converter sensitivity is increased with increase of working frequency, but the range is reduced at the same time. For instance, at the frequency of 320 kHz this range is limited by the value of ~ 1.1 mm. However, there is a greater possibility of expanding it into the range of smaller defect dimensions.

Thus, for defects 1–8 there exists a certain dependence of signal amplitudes on their size and areas (shape of the hole set) (Figure 2, *a*). It is obvious that for a more detailed analysis of this dependence, it is necessary to single out a subgroup of defects, which are of the same type by the hole cluster shape. Defects 1, 6, 7 and 8 with the length of 2.9; 1.1; 1.7 and 2.3 mm along the vertical, respectively, should be included into this subgroup. Comparing the signal values for these defects, it is obvious that for defect 6 of ~ 1.1 mm length a signal with not less than 1 V amplitude was received, which is indicative of the high sensitivity of ECM to fine defects at the assigned scanning settings.

One can also see from Figure 4, *b* that the colour representation of defects 5 and 6 is the least noticeable at the above-mentioned scanning settings. Detection of defect 5, represented by one hole of 0.5 mm diameter is complex, without preliminary ECM setting up and calibration, which points to the need for a more thorough selection of the scanning mode for defects of this size.

Table 2. Experimental data on studying TO defects, arranged by defect size

Defect number	Number of holes *n* in the defect/defect length, mm	Amplitude of signal from defect at different working frequencies, V		
		80 kHz	160 kHz	320 kHz
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
1	9/2.9	4.6	10.6	10.6

Figure 4, *c* shows the results of scanning of a TO area with cracks of different depth. In keeping with the results (Table 1), the highest sensitivity was achieved at the frequency of 160 kHz. Proceeding from the experimental data, it can be assumed that increase of the crack depth by 0.1 mm will lead to a change in voltage by approximately 30–33 mV, which is suitable for measurement, taking into account the flaw detector capabilities.

The coefficient of effectiveness of ECM application provided $k_P \approx k_S \approx 1$ is determined by a gain in reducing the time of obtaining measurement information: $k_{ef} \approx k_t = n = 32$.

On the whole, the conducted experiment results confirmed the high productivity and effectiveness of eddy current flaw detection (ECFD) technology based on application of ECM and at the same time they allowed revealing the limitations and weak points of this technology that requires further investigation, in order to determine the optimal operating modes of such converters in different ECFD tasks and to conduct process automation.

CONCLUSIONS

This study emphasizes the key role of ECM technology to control products from electrically conducting materials in many industries. During investigations the attention was focused on testing reliability and sensitivity, as well as evaluation of ECM productivity at defect detection. A dimensionless coefficient was proposed, which allows assessment of the improvement of testing reliability and sensitivity, as well as relative reduction of the time of object testing that is acceptable for determination of the effectiveness of ECM application.

Experimental data derived on TO with defects of different types, dimensions and orientations, revealed significant ECM advantages for eddy current flaw detection. Use of several closely located coils improved the coverage and sensitivity to small-sized defects during their detection, which could be missed in the case of application of flaw detectors with the traditional single-element ECC. TO scanning and data acquisition in one ECC passage from a considerable area of its surface enabled reducing the control time and simplifying the mechanical part of the means of automated eddy current testing that is essential in the case of examination of objects of considerable dimensions.

Improvement of the technology of ECT with ECM application enables expansion of functional capabilities of this kind of control and improvement of technical characteristics of control means that will promote increase of safety and reliability of operation of critically important structures and mechanisms for various purposes.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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