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AUTOMATED EDDY CURRENT SYSTEM FOR AIRCRAFT STRUCTURE INSPECTION

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Abstract

Aircraft part diagnostics are crucial during both production and maintenance, with eddy current non-destructive testing (ECNDT) being the method of choice due to its cost-effectiveness, informativeness, productivity, and reliability. ECNDT excels regardless of surface condition or coatings. It's employed for diagnosing various aircraft components, necessitating diverse transducer types, excitation modes, and advanced signal processing. To improve ECNDT, this article explores integrating harmonic and impulse excitation modes in a single tool to enhance informativeness. Building upon a wireless eddy current system, the authors propose a comprehensive method for processing and displaying information suitable for object condition monitoring systems. The system includes automated transducer mode control and experimental data processing algorithms. The constant expansion of tested objects and new materials underscores the need to enhance the theoretical foundations of eddy current non-destructive testing, refine signal processing techniques, and identify informative signs. This demands the development of new automated ECNDT tools, and this article offers a promising avenue for improvement. The results include model and experimental tests of system components, showcasing the potential of this approach to enhance ECNDT effectiveness, automation, and informativeness in the realm of aircraft part diagnostics.

Keywords: aviation material inspection; eddy current; signal characteristics; information parameters; scanning
Type of the work: research article

1. INTRODUCTION

Practical experience in structural design and operation of aircraft enabled researchers to form mandatory measures of structural damage tolerance design for the success and safety of the aviation industry. Such measures include the use of non-destructive testing (NDT) to determine the maximum permissible size of defects, the search for defects in structural elements during operation, and the monitoring of the behaviour of defects. In this regard, aircraft maintenance works play an essential role in ensuring the economics and safe operation of aircraft, and today quality maintenance is mandatory per the requirements of many manufacturers [1–3].

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The world practice of aircraft operation has shown that structural malfunctions rarely occur, but those that do occur are often related to preexisting manufacturing or service-induced damage (e.g. structural material anomalies or fatigue cracking). The main way to prevent related malfunctions is NDT. Successful NDT depends on the selection of the correct technique for the given application, proper calibration and operation of test equipment, surface preparation, flaw shape and orientation, and human factors such as training, experience, alertness, and confidence) [2].

Long-term use of NDT has confirmed that eddy current NDT is characterised by high informativeness, productivity, and reliability of results, which in most cases do not depend on the condition of the surface of the tested objects (TO) and the presence of protective coatings. Because of this, current regulatory documents provide the guidelines for the use of the eddy current NDT for diagnosing wings (detection of fatigue cracks on the inside of wing boxes), bodies, wheel disks, engine parts (engine blades), rotors, axles, fasteners and holes, defects in riveted joints, chassis from high-strength steel [3, 4]. The significant list of objects became possible thanks to the use of primary probes of different designs, different switching modes, excitation modes, improvement of signal processing methods, methods of presentation and interpretation of results, etc. The constant search for new materials and methods of obtaining them also involves the development of eddy current NDT tools by improving the theoretical basis, methods of processing information signals, and identifying informative features, as well as the creation of new automated tools for eddy current NDT.

Focusing on the latest trends in the development of primary probes, double differentiation, and matrix-type probes are distinguished. The last one requires complex methods of signal processing with the involvement of significant resources for calculations, the implementation of which is quite expensive. [5, 6]. However, double differentiation probes are similar to traditional probes from a technical point of view. Due to this, they are suitable for use in the same devices as traditional ones. Double differential eddy current probes (ECP) are effective tools for characteristic aircraft applications concerned with subsurface defect detection in multilayer structures, such as the detection of fatigue cracks in a riveted two-layer structure, the detection of subsurface defects in arc welding, the detection of cracks through repair patches fabricated from aluminium alloy or carbon fibre reinforced plastic composite [7].

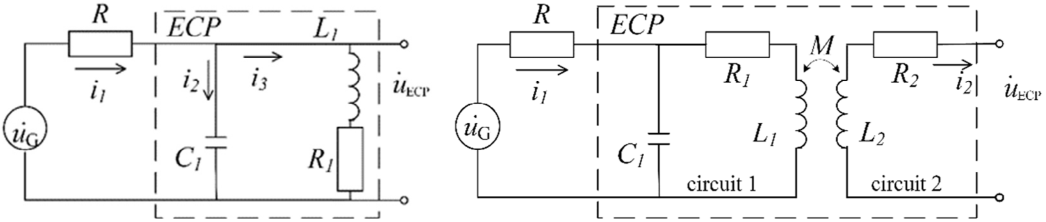
Also, a study of new technical solutions related to the improvement of flaw detector schemes represents a different development direction of eddy current NDT. In particular, it is the use of a self-generator circuit based on a field transistor with an insulated gate, a circuit for controlling the generation frequency, and a circuit of regeneration of self-generator oscillations. Compared to traditional circuits that way makes it possible to increase the terms of sensitivity [8–10]. In addition, there is a study of different methods of ECP excitation and, accordingly, different methods of processing measurement signals. This approach has its advantages and provides an opportunity to use other informative features related to the characteristics of the TO [11, 12].

The purpose of the article is to consider the possibilities of improving eddy current NDT due to the integration of harmonic and impulse modes of ECP excitation in one diagnostic tool in order to increase inspection informativeness. Such an approach allows a more complete analysis of the TO elements condition according to the informative parameters that are characteristic of each of the excitation modes of the probes. The previously obtained results of research and development of a wireless eddy current testing system with the pulse mode of the ECP and signal processing algorithms allow us to propose a generalised scheme of the new system and a generalised method of processing and displaying information that may be suitable for use in systems for monitoring the condition of the large-sized objects [13–15].

2. THEORETICAL PART

2.1. Analysis of the probes impedance in idling mode

In order to develop a signal processing algorithm for a testing system that integrates harmonic and impulse excitation modes of the probe and to understand the processes of the specified excitation modes, it is necessary to analyse the formation of the signal in different types of ECP. The equivalent circuits of typical single-coil are presented in Figure 1A (where u_G – generator signal, R – the generator output resistance, C_1 – the total capacitance formed by the turn-to-turn capacitance of the coil and other probe parasitic capacitances, R_1 – the coil active resistance, L_1 – the coil inductance, i_1, i_2, and i_3 – the currents in the corresponding branches of the circuit) and differential probes in Figure 1B (R_1 and L_1 – the excitation coil active resistance and inductance, R_2 and L_2 – the receive coil active resistance and inductance, M – the magnetic coupling coefficient, i_1 and i_2 – the currents in the branches) [16].



(A) (B)

Figure 1. Equivalent circuit of the single-coil ECP (A) and differential ECP (B) connected to the generator. ECP, eddy current probe.

It is known that the process of solving these schemes is reduced to the analysis of the input complex resistance and for the single-coil ECP equivalent circuit (Figure 1A) [11, 17], it takes the form:

$$\dot{Z}_{\text{eq}}(\omega) = R + \frac{R_1 + i\omega L_1}{1 + R_1 i\omega C_1 + (i\omega)^2 L_1 C_1}, \tag{1}$$

where ω – cyclic frequency, and for the differential ECP equivalent circuit (Figure 1B):

$$\dot{Z}_{\text{eq}}(\omega) = \frac{1}{\omega^2 M} + R_2 + i\omega(L_2 + M). \tag{2}$$

Further analysis of equivalent circuits and Eqs (1) and (2) in the case of harmonic excitation of the probe leads to the formation of a signal containing real and imaginary parts: $u_{\text{ecp}} = \text{Re}U + j\ \text{Im}U$ or $Z_{\text{ecp}} = \text{Re}Z + j\ \text{Im}Z$, where Z is the resistance of the circuit. That signal is conventional for most devices in which scanning results are presented using hodographs. ECP with harmonic excitation allows using the informative parameters like amplitude and phase of the signal.

In the case of a pulsed excitation, the analysis of equivalent schemes and Eqs (1) and (2) requires the calculation of transient response with the total current of the circuit which is considered to be equal to the sum of the forced and free currents. The forced current does not contain information about the properties of TO, so it is not of interest to the ECP signals analysis. The free current has a damping character in time and is described by such components: $Ae^{\alpha t}$, where α is the attenuation coefficient, which depends on the circuit parameters, and it can be determined through the roots of the characteristic equation. According to this, there is a ratio of the components of the circuit, at which the circuit begins aperiodic discharge, and which is described by the critical resistance of the circuit. The critical resistance of the circuit is determined by the characteristic equation of the circuit. As a result of analysis, an output signal in the form of damped harmonic oscillations with a certain natural frequency, attenuation coefficient and the initial phase is obtained. The specified parameters can be used as information in the signal-processing algorithm.

It is known from previous research that the complexity of the circuit and the number of its components affect the degree of the characteristic equation and the critical resistance. Therefore, when designing and setting up the device it should be considered to obtain correct testing results [11, 15].

2.2. Algorithm of ECP signal processing

The developed algorithm of the eddy current NDT system is shown in Figure 2. The algorithm provides automated setting and control of the operation modes of the probes and algorithm for processing experimental data. This makes it possible to take into account the specifics of testing and diagnostic problems involving the integration of harmonic and impulse excitation modes of probes.

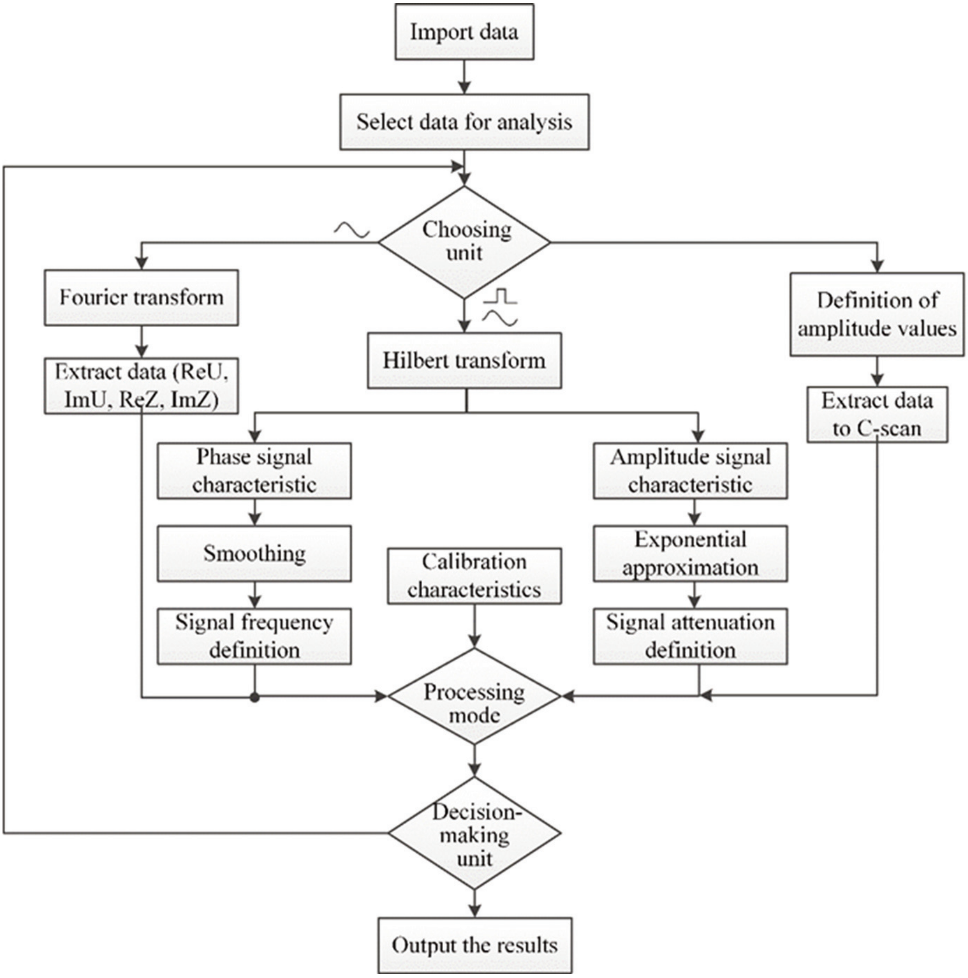


Figure 2. Methodology of ECP signal processing. ECP, eddy current probe.

The signal processing algorithm involves the selection of the probe excitation mode and implements the traditional method of processing the harmonic (continuous) signals or the proposed method—signals as attenuating oscillations or continuous.

The basis of the proposed technique is the use of the Hilbert transformation for obtaining the amplitude and phase characteristics of the signal (ASC and PSC) for analysis. The analysis of the ECP signal transformation with pulsed excitation is discussed in detail in [11, 18].

The case of continuous excitation of the differential probe is considered below. In this case, the output signal can be represented by the equation:

$$u_{\text{ecp}}(t)=U\left(1+a(t)\right)\cdot\cos\left(2\pi ft+\varphi(t)\right),t\in\left(0,T_c\right), \tag{3}$$

where f − frequency of the exciting signal, $a(t)$, $\varphi(t)$ – functions that depend on the variety of TO parameters, U − signal amplitude, T_c − observation time. As mentioned, signal processing is carried out by determining the Hilbert image of the signal $u_{\text{H}}(t) = \mathbf{H}[u_{\text{ecp}}(t)]$, based on which the ASC and PSC are determined:

$$\breve{U}(t)=\sqrt{u_{\text{ect}}^2(t)+u_H^2(t)}, \tag{4}$$

$$\breve{\Phi}(t)=arctg\frac{u_H(t)}{u_{\text{ect}}(t)}. \tag{5}$$

Considering (4) and (5), the modulating functions associated with the TO parameters are determined by the equations:

$$a(t)=\frac{\breve{U}(t)-U}{U}=\frac{\sqrt{u^2(t)+u_H^2(t)}}{U}-1, \tag{6}$$

$$\varphi(t)=\left(arctg\frac{u_{\text{H}}(t)}{u_{\text{ect}}(t)}+L\left(u_{\text{H}}(t),u_{\text{ect}}(t)\right)-2\pi ft\right)\operatorname{mod}2\pi,\left(-\frac{\pi}{2},\frac{\pi}{2}\right), \tag{7}$$

where L − the PSC expansion operator outside the interval.

Also, in order to confirm the possibility of determining the ASC and PSC of the ECP and evaluating their changes in real-time with high accuracy, a simulation was carried out. The absolute errors of the estimation of the parameters ($a(t)$ and $\varphi(t)$) in the conducted model experiments did not exceed 0.04 at B and 0.02 rad, respectively.

The traditional ECP signal processing is based on informative signal parameters such as amplitude and phase, and also it presents the testing results in the form of a hodograph [19].

3. AN EXPERIMENTAL INVESTIGATION

3.1. The structure of an experimental model

The structure of the developed ECNT system is shown in Figure 3. The system consists of a measuring probe unit (transducing unit) and a results processing unit.

The ECP receives a signal from a signal generator (current source) and generates a signal which is amplified and digitised by an analogue-to-digital converter (AD converter). Received data are saved in storage (buffer) for the next transfer to the processing unit. This transfer is realised with the help of a microcontroller (MC) and wireless communications unit. The Bluetooth module is used for wireless communications and it provides the connection between the processing and transducing units within some distance. The operation of the unit's main components is synchronised by a control block. The processing unit consists of a receiving box and a personal computer with software that realised the signal processing algorithm.

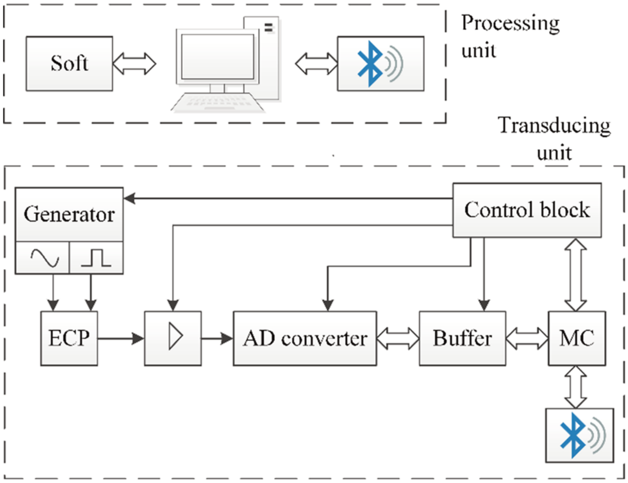


Figure 3. Developed system for ECNDT. ECNDT, eddy current non-destructive testing; ECP, eddy current probe; MC, microcontroller.

3.2. Experimental research and results discussion

The experiments were carried out on a sample made from steel St.20 ($\mu > 1$) with 5 mm thick, 100 mm long, and 30 mm wide. Artificial defects imitating surface cracks 0.2 mm wide and $\delta = \{0.2, 0.5, 1.0\}$ mm deep, were located on one of the surfaces of the sample. The roughness of the sample surface did not exceed 1.6 µm.

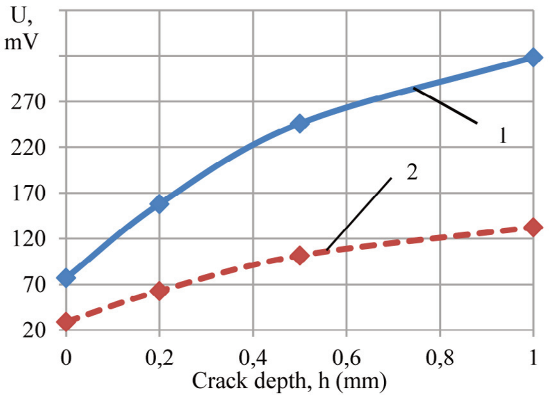


Figure 4. Dependence of $A(h)$ with pulsed (1) and harmonic (2) excitation of the ECP. ECP, eddy current probe.

Experimental signal amplitude values of the single-coil ECP with continuous excitation are presented in Figure 4 (curve 1), and the peak values of the signal amplitude of the same ECP with pulsed excitation are presented in Figure 4 (curve 2). Analysis of these figures shows that the signal amplitude of the ECP with pulsed excitation has a weak dependence on the crack depth h. Instead, an increase in the depth of the crack in the TO leads to an increase in the values of the signal amplitude of the ECP with harmonic excitation. A slight change in the peak values of the signal amplitude of the ECP with pulsed excitation is observed in the $h = 0 \div 0.5$ mm, and the sensitivity, in this case, is lower than for the ECP signal with harmonic excitation ($S_{A\_pulsed} = 1.3$ mV/mm $< S_{A\_harm} = 0.3$ mV/mm).

The results of the analysis of the signal attenuation of the single-coil ECP during its pulsed excitation are shown in Figure 5A. The graph shows that the nature of the dependence of the ECP signal attenuation on the TO crack depth is close to linear form, therefore, the attenuation is an informative parameter suitable to use for testing and assessing the crack depth in the TO. In the performed experiments, the relative error in determining the crack depth did not exceed ±0.5%, and the average sensitivity to the crack depth was estimated as $S\alpha = 0.2\ \mu s^{-1}$/mm.

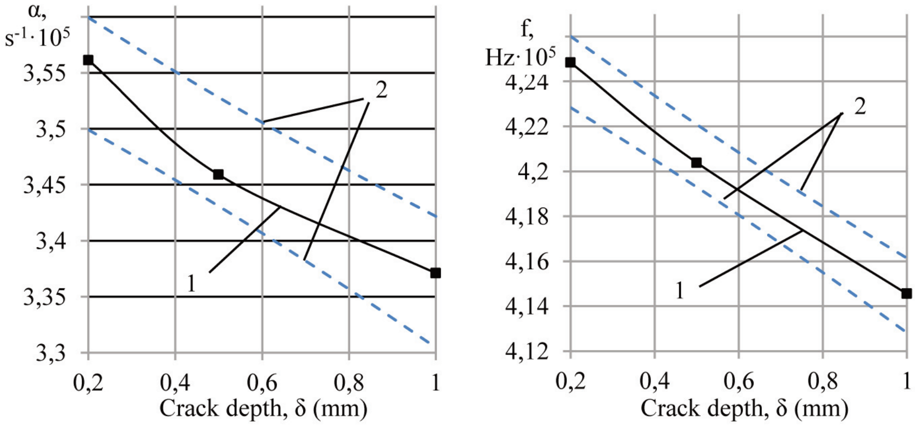


Figure 5. Dependence of the attenuation (A) and frequency (B) of the single-coil ECP signal (curve 1) and the boundaries of their confidence intervals (curve 2). ECP, eddy current probe.

The results of determining the variation of the natural frequency oscillations of the ECP signal with pulsed excitation as a function of the crack depths in the sample are shown in Figure 5B. The graph of dependence $f(\delta)$ has a linear character in the section, and the value of the natural frequency oscillations of the ECP signal decreases with an increase in the crack depths in the sample.

4. CONCLUSION

The automated eddy current NDT system that integrated harmonic and pulsed excitation of ECP in one diagnostic tool in order to increase the informativeness of inspection has been developed. The proposed signal processing algorithm has a wide range of options for informative parameters depending on the probe excitation mode. The conducted analysis of the determination of ASC and PSC for harmonic excitation demonstrates the possibility of implementation of a quite universal algorithm for signal processing based on the Hilbert transformation. The article presents some experimental results of using the components of the eddy current inspection system, and the proposed algorithm for probe signals processing in both excitation modes has been tested. The developed automated eddy current system for structure inspection has shown quite good results in the case of using the amplitude as the informative parameter for both excitation modes but needs comprehensive research in the evaluation of PSC and informative parameters related to it in the future.

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