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USING THE PULSED EDDY CURRENT TECHNIQUES FOR MONITORING THE AIRCRAFT STRUCTURE CONDITION

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Abstract

It is known that during operation, the aircraft construction materials are exposed to significant mechanical loads and changes in temperature for a very short period of time. All this leads to various defects and damages in the aircraft assemblies and units that need to be inspected for the safe operation of the aircraft, their assemblies, and units. In some cases, the implementation of inspection or diagnostic is accompanied by the emergence of technical difficulties caused by the large size of the aircraft assemblies or units and limited access to their local places. Under such conditions, ensuring the possibility of diagnosis in hard-to-reach places of the object becomes especially important. The problem can be solved by applying wireless technologies. It allows spatial separation of the probes and the signal processing units, which simplifies the scanning of the surfaces of the large assemblies and units in hard-to-reach places. In this article, the description of the developed wireless system of eddy current inspection for aircraft structural materials is given. Experimental results of object scanning are given in the form of a distribution of the values of probe signal informative parameters (amplitude, frequency and decrement) along the object coordinates.

Keywords: aviation material inspection; signal characteristics; information parameters; scanning; c-scan
Type of the work: research article

1. INTRODUCTION

The eddy current non-destructive testing (ECNDT) is one of the most common types of inspection done on large products made of structural materials. The modern expansion of the variety of tested objects (TO) and the use of new materials require constant development and improvement of methods and means of inspection [1]. This process has recently been developed in several directions [2]. The eddy current inspection technics based on multi-frequency methods, which allow multi-parameter inspection, have been used more often today [3–5]. In this case, the sensor of the device with multi-frequency analysis

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exploits variations in the electrical conductivity and magnetic permeability of the steel to monitor microstructure evolution during processing. At the same time, the possibilities of using the pulsed mode for the excitation of the eddy current probe (ECP) are increasingly being researched which also contributes to the expansion of inspection functionality [6,7]. The final results, after investigating the application of pulsed eddy current NDT to detect and characterise defects and damage in carbon fibre reinforced plastic materials, have shown good results [8]. It is especially important because this material is widely used in the aircraft industry, but its relative proneness to impact damage leads to the industrial requirement of effective NDT techniques for ensuring its integrity.

Also, studying to improve ECP construction is constantly underway, in particular, an article [9] is presented with the results of the development and research of double differentiation probes, which increase the sensitivity to some types of defects. Due to high sensitivity, many difficult problems, relating to inspection and finding out the subsurface defects in multilayer structures, could be solved with double differential type EC probes application. The main advantage of these probes is achieving high sensitivity by keeping a stable clearance between the probe and the inspected surface.

The implementation of ECNDT has often faced technical difficulties caused by the large size of aircraft assemblies or units and limited access to their local places. According to this the realisation of the eddy current inspection in hard-to-reach places becomes a particularly important task. The problem could be solved by using wireless technologies for the transmission of ECP signals from the probe's unit to the data processing unit [10,11]. It allows to spatially separate the probes part and the signal processing unit, and it greatly simplifies the practical implementation of the inspection of large-size aircraft assemblies or units with limited access to them. However, these issues have been rarely addressed comprehensively within the development of one means of inspection.

In addition, there is some interest in the use of various modern methods of digital signal processing by means of ECNDT. Thus, the authors of [12] have proposed to use the Hilbert transform to obtain the amplitude signal characteristic (ASC) and phase signal characteristic (PSC) and follow their analysis.

The article is concerned with developing and analysing an experimental model of the wireless ECNDT system, which implements different excitation modes and different methods of signal processing and displaying information in appropriate ways. This article presents the research on the developed structure of the ECNDT system with a wireless connection between transducing unit and the data processing unit. The developed ECNDT system should provide:

- the ability to inspect the assemblies or units which have limited access to their local pieces for standard means;
- implementation of various modes of eddy current inspection;
- adaptive choice of method and algorithm for ECP signals processing;
- visualisation of inspecting results in the form of 2D and 3D graphs;
- archiving of inspecting results with their subsequent loading into the database.

2. THEORETICAL PART

2.1. Analysis of the differential probe impedance in idling mode

The system of inductively coupled electrical circuits has been used to analyse the formation processes of information signals in the system which consist of the TO (testing objects) and differential probe (separate transmit-receive probe). The equivalent circuit of the system with pulse excitation in idling mode is shown in Fig. 1, where u_G – pulse signal generator, 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 and L_1 – the excitation coil active resistance and inductance, R_2 and L_2 – the receive coil active resistance and inductance, i_1, and i_2 – the currents in the corresponding branches of the circuit.

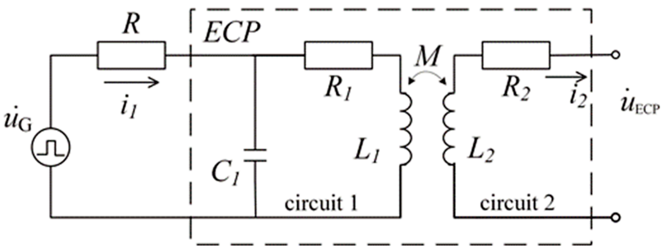


Figure 1. Equivalent circuit of the differential ECP connected to the pulse signal generator.

The power supply voltage:

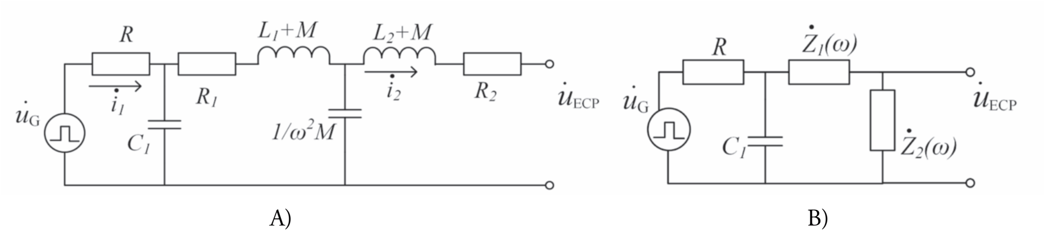
$$u_{\mathrm{G}}(t)=\begin{cases}0, & t\notin n\cdot T_p+\tau,\\ u_0, & t\in n\cdot T_p+\tau, n=0,1,2...\end{cases} \tag{1}$$

where u_0, T_p and τ – the amplitude, period and duration of the pulses, respectively.

Using the principle of 'solution for inductive circuits' described in [13,14], the scheme in Figure 1 is transformed to the scheme shown in Fig. 2A, which after simplifying is presented by the equivalent scheme in Fig. 2B with the following parameters:

$$\dot{Z}_1(\omega)=R_1+i\omega(L_1+M)\ , \tag{2}$$

$$\dot{Z}_2(\omega)=\frac{1}{\omega^2 M}+R_2+i\omega(L_2+M)\ . \tag{3}$$



A) B)

Figure 2. Equivalent scheme of differential ECP (eddy current probe) after the solution of inductive circuits (A) and after its simplification (B).

The output resistance of the equivalent circuit of the differential ECP in idling mode (Fig. 2B) is given by the expression:

$$\dot{Z}_{\mathrm{eq}}(\omega)=\frac{1}{\omega^2 M}+R_2+i\omega(L_2+M)\ . \tag{4}$$

In this case, the appropriate characteristic equation has the 3rd order and it is presented by:

$$\frac{1}{\omega^2 M}+R_2+i\omega(L_2+M)=0\ , \tag{5}$$

or

$$iM(L_2+M)\omega^3+MR_2\omega^2+1=0\ . \tag{6}$$

The obtained expression of the characteristic equation shows that the processes in the differential ECP in pulsed excitation mode are similar to the processes in the system 'single-coil ECP–non-magnetic TO' and under certain conditions can be characterised by the output signal in the form of attenuating harmonic oscillation with a certain natural frequency, attenuation coefficient and initial phase [15].

In addition, the results of the analysis of the processes of 'single-coil ECP–TO' systems in the conditions of pulse excitation show that the characteristic equations are had the 4th and 5th order for the case of 'differential ECP–non-magnetic TO' and 'differential ECP–magnetic TO' respectively. The roots of characteristic equations could also be transformed and reduced to the form $p_{1,2}\left(\bar{w}\right)=-\alpha\left(\bar{w}\right)\pm i\omega_0\left(\bar{w}\right)$.

Thus, the analysis of the amplitude-time and phase-time characteristics of attenuating harmonic oscillations, which under certain conditions occur in the circuits of ECP in the pulsed excitation mode, significantly expands the informative possibilities of the pulsed method of ECNDT (eddy current non-destructive testing).

2.2. Algorithm for determining the attenuation and natural frequency of the PEC signals

The informative signal of the ECP could be presented by a model of harmonic oscillation with Gaussian noise:

$$u_{\mathrm{ECP}}\left(t,\bar{w}\right)=U_m e^{-\alpha\left(\bar{w}\right)\cdot t}\cdot cos\left(2\pi f\left(\bar{w}\right)\cdot t\right)+u_N\left(t\right),\, t\in\left(t_1,t_2\right), \tag{7}$$

where: U_m – amplitude of the ECP signal, $\alpha\left(\bar{w}\right)$ – signal attenuation, $f\left(\bar{w}\right)$ – signal frequency, t – current time, (t_1,t_2) – period of the signal analyses, $t\in(t_1,t_2)$, $u_N(t)$ – signal noise term, $\bar{w}$ – vector of TO's characteristics. It is known that the frequency and attenuation of these oscillations are changed depending on TO's characteristics such as – material, shape, geometry, defect presence, etc [15].

Processing and analysis of the signal characteristics consist of steps presented in Figure 3. The approximation of the ASC and soothing of the PSC have been used to reduce the influence of noise and increase the accuracy of determining the attenuation coefficient and the frequency of natural oscillations of the ECP signal.

The method of the Bartlett-Kenya linear regression has been used to smooth the PSC (phase signal characteristics) function. The method is based on time sequencing of the experimental data and division of the sample $\Phi\left[j,\bar{w}\right]$ into three approximately equal groups. It is defined as sums $\sum\Phi\left[j,\bar{w}\right]$ in each group and $\sum t_j$ – accordingly Φ_1,Φ_2,Φ_3 and t_1,t_2,t_3. Coefficients of the linear regression are evaluated by:

$$k=\frac{\Phi_3-\Phi_1}{t_3-t_1},\; b=\bar{\Phi}-k\cdot\bar{t}, \tag{8}$$

where $\bar{\Phi}=\dfrac{\sum\Phi\left[j,\bar{w}\right]}{3M}$ and $\bar{t}=\dfrac{\sum t_j}{3M}$, M – amount elements in the group.

The natural frequency of the ECP signal was determined using the PCS by:

$$f\left(\bar{w}\right)=\frac{\Delta\hat{\Phi}_{lin}\left[\bar{w}\right]}{2\pi\,\Delta T}, \tag{9}$$

where $\Delta\hat{\Phi}_{lin}\left[\bar{w}\right]$ – the trend of the function of the ECP signal phase which is accumulated over time Δt (for example, in time of (t_2-t_1).

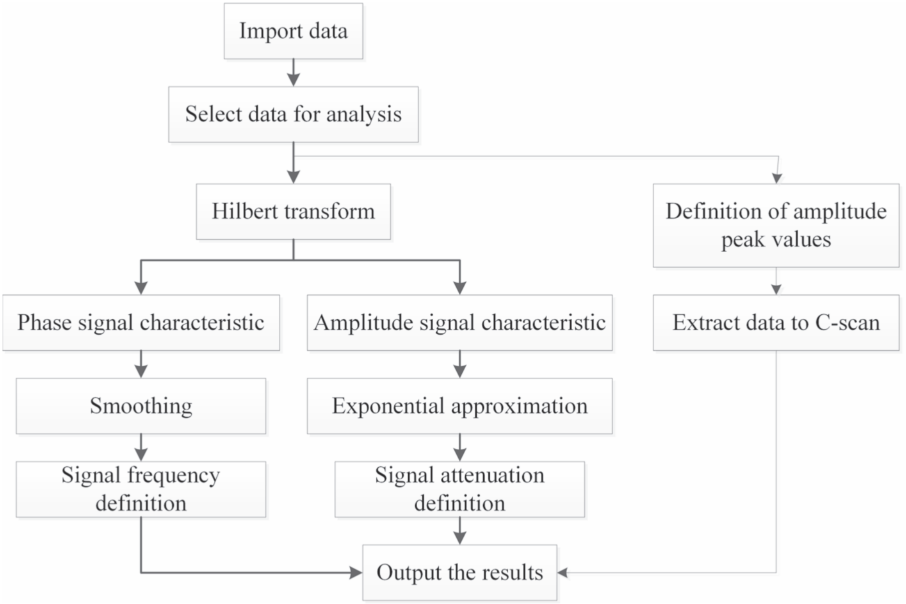


Figure 3. Methodology of ECP signal processing.

The exponential approximation of the ASC (amplitude signal characteristics) function has been used to raise the definition accuracy of an informative signal decrement. It is determined that it is very impotent to consider the part of the ASC which corresponds to the early periods of the informative signal for raising the accuracy factor exponential approximation estimation. The early periods correspond to ASC with a maximal slope.

The signal attenuation was determined using the ASC as follows:

$$\pm\left(\overline{w}\right)=\frac{1}{\Delta T}ln\frac{\widehat{U}\left(t_1,\overline{w}\right)}{\widehat{U}\left(t_2,\overline{w}\right)}\ , \tag{10}$$

where $\widehat{U}\left(t_1,\overline{w}\right), \widehat{U}\left(t_2,\overline{w}\right)$ – the values of ASC at t_1 and t_2 time points.

3. AN EXPERIMENTAL INVESTIGATION

3.1. The structure of an experimental model

The structure of the developed ECNT system is shown in Figure 4. The transducing unit consists of a double differential ECP which contains two primary coils and two secondary ones. The parameters of ECP are R_1 = 8.2 Ohm, L_1 = 100.8 µHn, R_2 = 14.4 Ohm, L_2 = 353.8 µHn.

The exciting coil receives a pulsed actuating signal from a signal generator (current source) and the measuring one 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 data-processing unit. This transfer is realised due to a microcontroller (MC) and wireless communications unit. The Bluetooth module (third grade of power) is used as the wireless communications unit and it has an external antenna to provide the connection between the data-processing and transducing units at some distance. The maximum distance between units to a good connection is 300 m. The operation of the transducing unit's main components is synchronised by a control block (control box). The data-processing unit consists of a receiving box and a personal computer (PC) with special software.

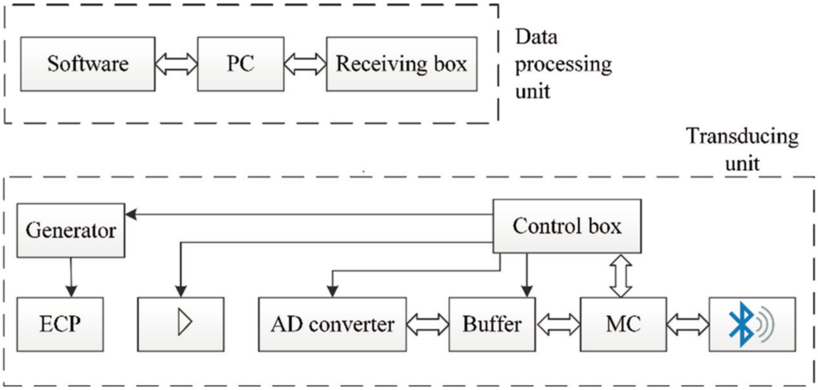


Figure 4. Developed system for ECNDT. AD converter (analogue-to-digital converter); ECNDT (eddy current non-destructive testing); ECP (eddy current probe); MC (microcontroller); PC (personal computer).

The transducing unit with the ECP is presented in Figure 5.

Figure 5. The transducing unit of the ECNDT system.

A metal alloy plate with artificial cracks of different depths (*h* from 0.1 mm to 3 mm) and a width of 1 mm (Fig. 6) was used to test the system availability. The material of the plate has been marked as AD31T5 and consists of aluminium, magnesium and silicon (Al–Mg–Si). This material is used in the cabins of aircraft and helicopters and aircraft window cross.

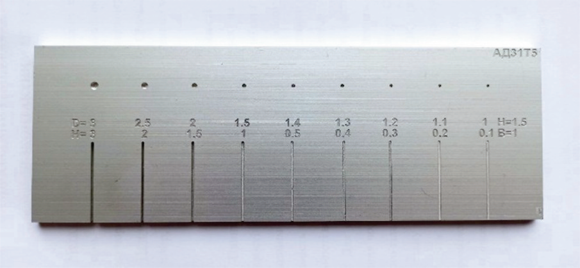
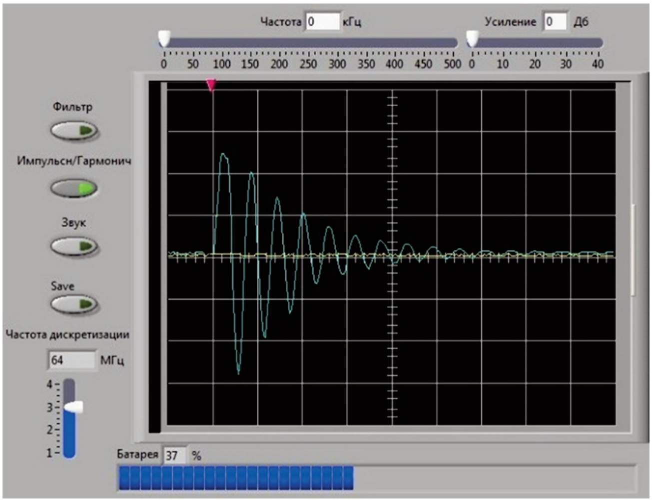


Figure 6. The specimen (tested object).

The plate was scanned with a step of 1 mm during the inspection by the double differential probe which is the part of transducing unit.

3.2. Experimental research and results discussion

The pulse current with period T_n = 50 μs and duration τ = 175 ns has been applied to the primary coils of differential ECP to excitation. The received signal from the secondary coils of the ECP had the form of attenuating harmonic oscillations (Fig. 7) and it is presented in Eq. (7). The analysis of the received ECP signals was performed using the developed software, which is based on ECP signals processing in the time domain using the Hilbert transform and obtaining the ASC and PSC and their subsequent analyses.


Частота 0 кГц
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Частота дискретизации 64 МГц
Батарея 37 %

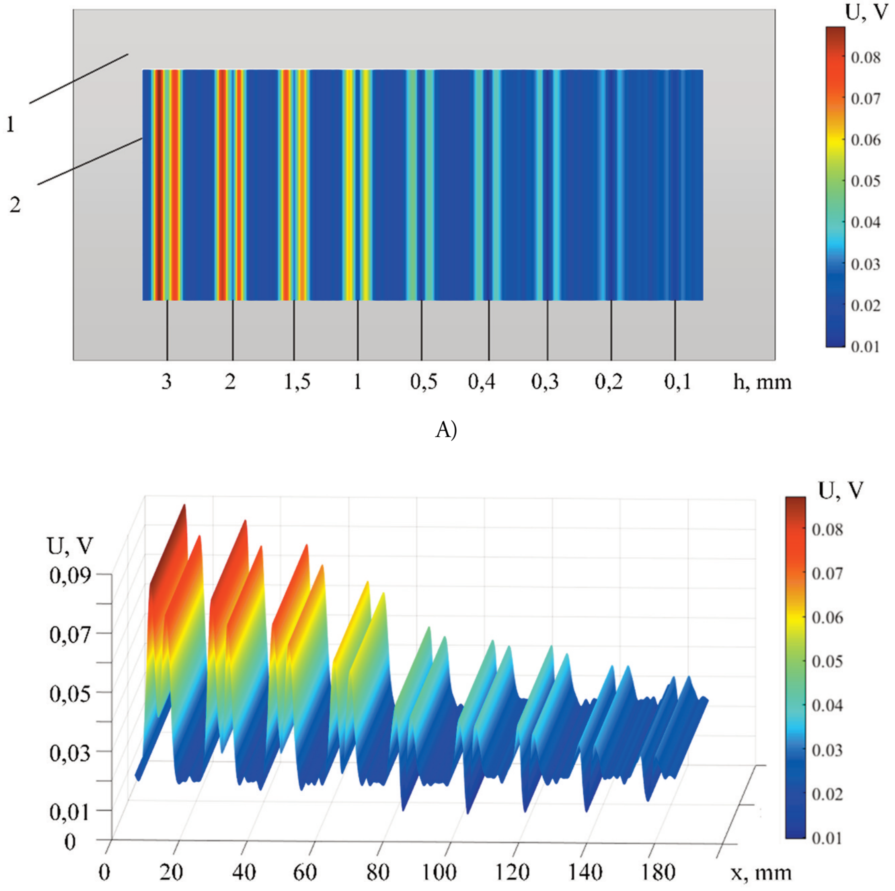
Figure 7. The received ECP signal on the screen of the developed software.
ECP − eddy current probe.

The maximum peak values of the amplitude were selected from the set of ECP signals which had been obtained after scanning the TO (tested objects). The distribution of peak values of the ECP amplitude in reference to all scanned points of the TO surface is shown in Figure 8A like C-scan [16]. The amplitude values distribution shows that the crack in the TO leads to a significant increase in the amplitude values near its, but a decrease over the crack itself and it demonstrates the Figure 8B. In Figure 8 the distribution of the peak amplitude values is given without values received from space near the boundaries of the TO. It has caused the influence of edge effects on the boundaries of the TO.

Figure 9 shows the dependence of the values of natural frequency (a) and attenuation (b) of the differential ECP signal on the crack depth in TO. These dependencies could be described by formulas: a polynomial of 3rd degree in the case of the use of natural frequency as an information parameter and a logarithmic dependence in the case of signal attenuation. Obviously, the dependences obtained in this way could be used to quantify the parameters of cracks.

The distribution of the peak amplitude values, the natural frequency oscillations and the attenuation which are received from the ECP signal are illustrated in Figure 10A–C resp. The curves illustrated the changes of the signal in the vicinity of the coordinates of the depths cracks h = 1, 2 and 3 mm (they have coordinates x = 8, 26 and 44).

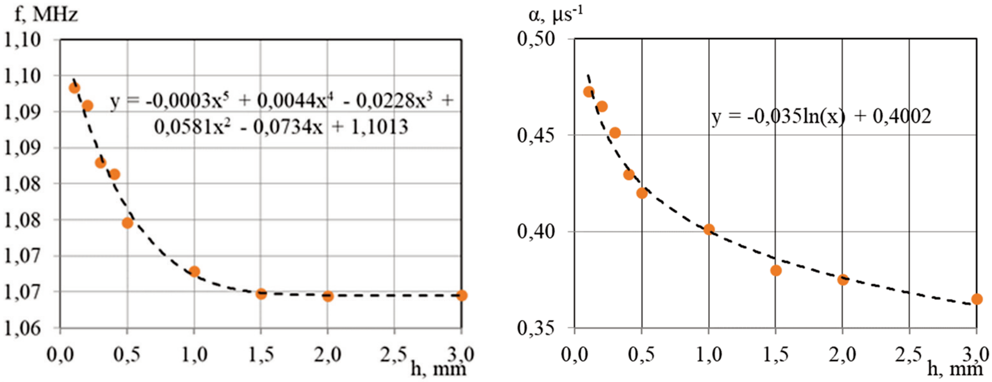
The graphs show that in the locations of cracks there is a change in the distribution of signal parameters: a decrease in the values of the instantaneous frequency of signal oscillations in the vicinity of the crack and an increase directly above it. The signal attenuation changes according to the depth of the crack and the coordinates are similar to frequency changes.



A)

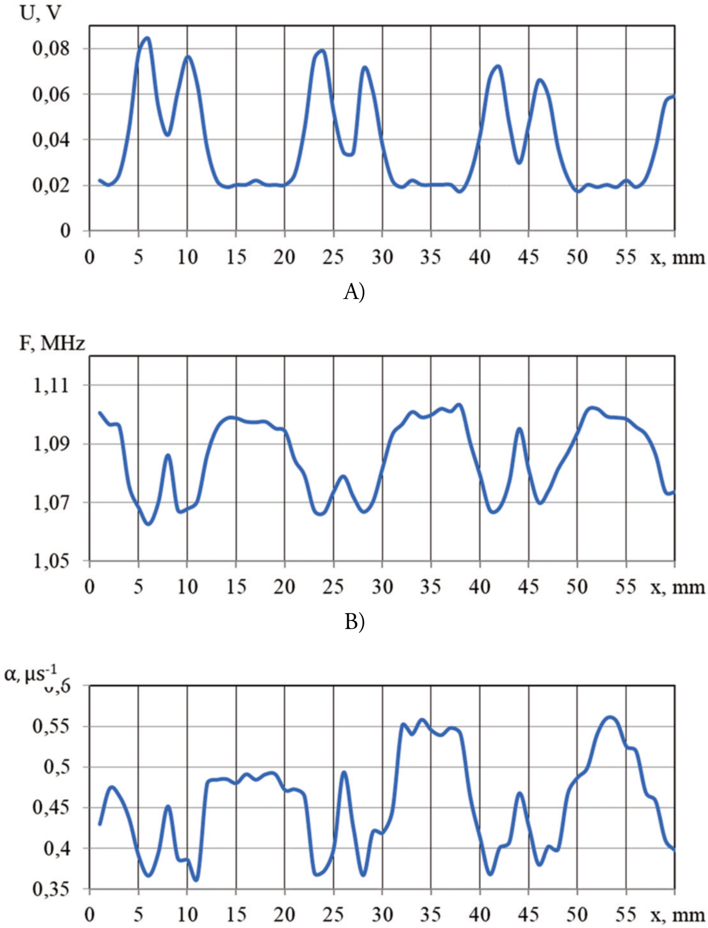
B)

Figure 8. Distribution of signal amplitude on the surface of TO in C-scan mode (A) and 3D visualisation mode (B): 1 – TO, 2 – signal amplitude. TO − tested objects.



A) B)

Figure 9. The dependence of the values of ECP signal natural frequency (A) and ECP signal attenuation (B). ECP − eddy current probe.



A)

B)

C)

Figure 10.The dependence of the ECP signal parameters on the coordinate: amplitude values (A), natural frequency (B) and signal attenuation (C). ECP – eddy current probe.

4. CONCLUSION

Our review shows that the pulsed excitation in ECNDT in combination with digital signals processing based on discrete Hilbert transform significantly complements the known methods by using to analyse such signals parameters as natural frequency, peak amplitude, attenuation of the signal and temporal position of characteristic signal points.

The eddy current system for inspecting the large size of the aircraft assemblies or units and limited access to their local places is developed. This system applies wireless technologies to transmit signals and uses the new signals processing technique described in this article. The technique was tested and checked for processing of signals of pulsed ECNDT to inspect the plate with cracks with various depths.

In the article, the results are given after inspecting the metal alloy plate with artificial cracks of different depths. It is experimentally established that in the process of crack inspection in the sample, the relative error in determining the crack size by the frequency of the information ECP signal does not exceed 0.2%, and the amplitude is 1.5%. The presented graphs illustrate the application of such parameters as amplitude, frequency and attenuating-like informative features during pulsed eddy current testing.

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