Intelligent Automated Eddy Current System for Monitoring the Aircraft Structure Condition

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***Abstract*— It is known that in the process of operation the materials of aircraft construction are exposed to significant mechanical loads and temperature changes (fluctuations) for a very short period of time. All this leads to various defects and damages to aircraft assemblies and units which 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 technical difficulties caused by the large size of aircraft assemblies or units and limited access to their local places. In such conditions, it becomes especially important to provide the possibility of diagnostics in hard-to-reach places of the object.**

The problem can be solved by applying wireless technologies to transmit signals from the probes to the data processing units. This allows separating the probes unit and the analysis and decision-making unit in space, and simplifies the practical implementation of robotics scanning the surfaces of large assemblies and elements in hard-to-reach places.

The article describes the developed intelligent wireless system for eddy current inspection of aircraft structural materials. A technique for processing and visualization information is proposed that can be used in inspection systems and intelligent decision-making when monitoring the state of large objects. The experimental results of scanning an object are presented as a distribution of the informative parameters values of the probing signal (amplitude, frequency and decrement) over the coordinates of the object.

Keywords*— *aviation material inspection, inspection and intelligent decision-making systems, signal characteristics, information parameters, scanning, c-scan.

I. Introduction

Eddy current non-destructive testing (ECNDT) is one of the most common types of inspecting large products made of structural materials. The modern expansion of the variety of tested objects (TO) and the use of new materials require continuous development and improvement of methods and means of inspection [1]. This process has recently developed in several directions [2, 3, 4]. The eddy current inspection technics based on multi-frequency methods, which allow realized the multi-parameter inspection are becoming more widespread today [5, 6, 7]. In this case, the device's sensor with multi-frequency analysis uses changes 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 excitation of an eddy current probe (ECP) are being increasingly researched which also contributes to the expansion of inspection functionality [8, 9, 10]. Good prospects are shown by the latest results on the study of the use of pulsed eddy current non-destructive testing for the detection and characterization of defects and damages in carbon fiber [11]. This is especially important because this material is widely used in the aviation industry but its relative proneness for impact damage leads to the industrial requirement for effective non-destructive testing techniques to ensure its integrity.

Also studying to improve ECP construction is constantly underway, in particular, the article [12] presents the results of the development and research of double differentiation probes that increase the sensitivity to some types of defects. Due to the high sensitivity many difficult problems of inspection and finding for subsurface defects in multilayer structures can be solved with double differential type EC probes. The main advantage of these probes is high sensitivity by maintaining a stable gap between the probe and the inspected surface.

The implementation of ECNDT has often caused technological difficulties by the large size of aircraft assemblies or units and limited access to their local places. According to this, eddy current inspection in hard-to-reach places becomes a particularly important task. The problem could be solved by using wireless technologies for transmitting ECP signals from the probe unit to the data processing unit [13, 14, 15]. It allows to spatially separate the probes part and the signal processing unit and it greatly simplifies the practical implementation of inspection large aircraft components or components with limited access to them. However, these issues have rarely been addressed comprehensively within the development of the inspection mean.

In addition, there is some interest to use of various modern methods of digital signal processing in the ECNDT tools. Thus, the authors of [16] proposed to use the Hilbert transform to obtain the amplitude and phase characteristics of the signal (ASC and PSC) and their subsequent analysis.

This article is devoted to the development and analysis of an experimental model of the wireless ECNDT system, which implements different (various) excitation modes and different methods of signal processing and displaying information in appropriate ways. The article presents the research of the developed structure of the ECNDT system with wireless connection between transducing unit and the data processing unit. The developed ECNDT system should provide:

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

II. Algorithm for Determining the Attenuation and Natural Frequency of PEC Signals

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

$$u_{ecp}(t,w)=U_m e^{-\alpha(\omega)\cdot t}\cos(2\pi\cdot f(\omega)\cdot t)+u_N(t),\ t\in(t_1,t_2) \quad (1)$$

where: U_m – amplitude of the ECP signal, $\alpha(\omega)$ – signal attenuation, $f(\omega)$ – 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, ω– vector of TO‘s characteristics. It is known that the frequency and attenuation of these oscillations change depending on such characteristics of TO‘s as material, shape and geometry, the presence of defects, etc [17].

Processing and analysis of the signal characteristics consist of the stages shown in Fig. 1. The approximation of the ASC and soothing of the PSC were 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 was used to smooth the PSC function. The method is based on the time sequence of experimental data and the division of the sample $\Phi[j,\omega]$ into three approximately equal groups.

The sums $\sum\Phi[j,\omega]$ in each group and $\sum t_j$ are determined accordingly $\Phi1$, $\Phi2$, $\Phi3$ and t_1, t_2, t_3. Linear regression coefficients are estimated from:

$$\kappa=(\Phi_3-\Phi_1)/(t_3-t_1),\ b=\Phi-\kappa\cdot t \quad (2)$$

where $\Phi=\sum\Phi[j,\omega]/3M$ and $t=\sum t_j/3M$, M – amount elements in group.

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

$$f(\omega)=\Delta\Phi_{lin}[\omega]/(2\pi\Delta T) \quad (3)$$

where $\Delta\Phi_{lin}[\omega]$– 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)).

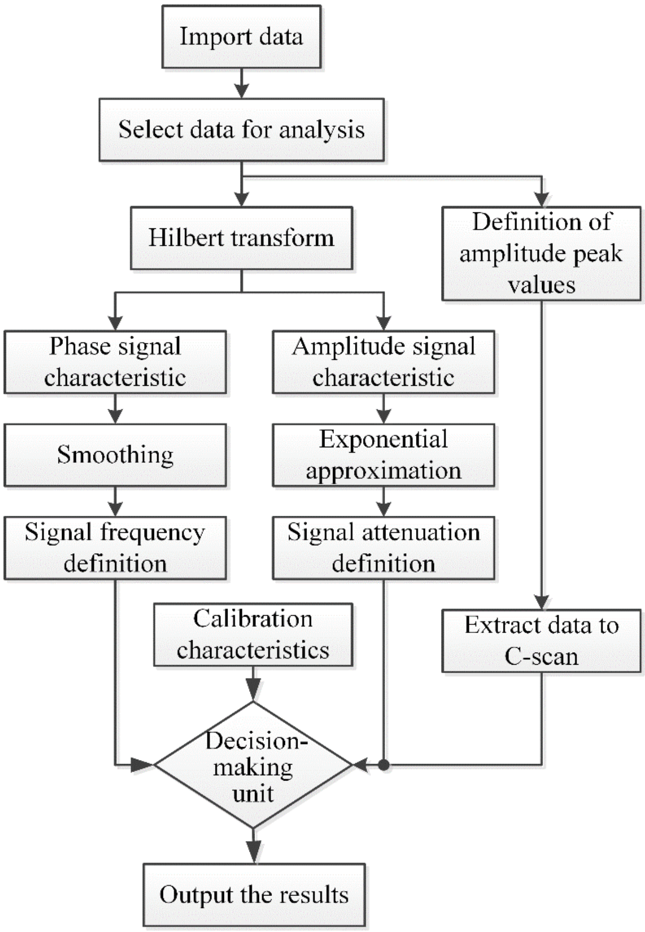

Fig. 1. Methodology of ECP signal processing

The exponential approximation of the ASC function was used to improve the accuracy of determining the informative signal decrement. It was found that in order to improve the accuracy of estimating the factorial exponential approximation, it is very important to take into account the part of the ASC corresponding to the early periods of the informative signal. The early periods correspond to ASC with a maximal slope.

The signal attenuation was determined using the ACS by:

$$a(w)=(1/\Delta T)\cdot \ln(U(t_1,\omega)/U(t_2,\omega)) \quad (4)$$

where $U(t_1, \omega)$, $U(t_2, \omega)$ – the values of ACS at t_1 and t_2 time points.

The decision-making unit checks and evaluates the data and then gives the inspection results. Also, the obtained data about informative parameters are analyzed in the decision-making unit by comparison with their reference values, which are correspond to sample materials, which is accepted as the norm. If the calibration characteristics values are not specified, the system can generate the result based on absolute values. However, it is incorrect to conduct a direct comparison of samples with each other using that result, and additional testing conditions should be considered too.

III. Experimental Investigation

A. The Structure of an Experimental Model

The structure of the developed ECNDT system is shown on the Fig. 2. 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.

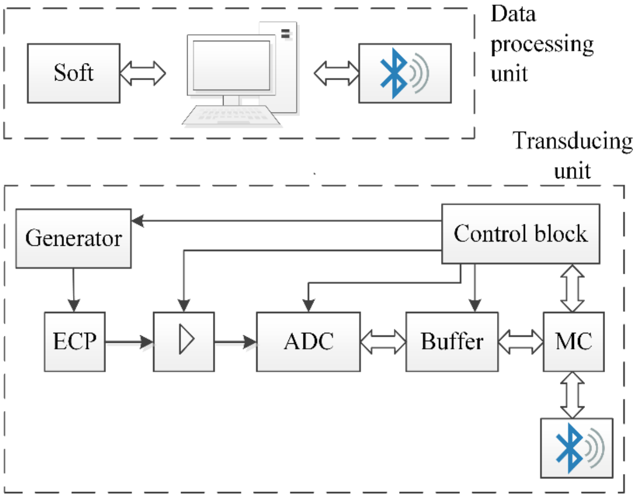

Fig. 2. Developed system for eddy current non-destructive testing

The exciting coil receives a pulsed actuating signal from the signal generator (current source) and the measuring coil generates a signal that is amplified and digitized by an analog-to-digital converter (ADC). The received data is saved in storage (buffer) for the next transfer to the data-processing unit. This transfer is realized due to a microcontroller (MC) and a wireless communications unit. The Bluetooth module (third power class) is used as the wireless communications unit and has an external antenna to provide the connection between data-processing and transducing units at a certain distance. The maximum distance between the units to a good connection is 300 m. The operation of the main components of the converter block is synchronized by the control block. The data-processing unit consists of a receiving box and a personal computer with special software.

The transducing unit with the ECP is presented in Fig. 3.

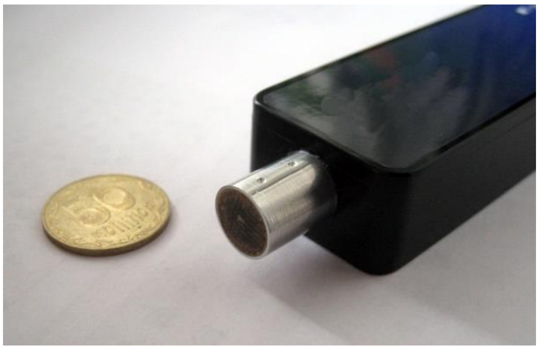
Fig. 3. The transducing unit of the ECNDT system

A plate made of metal alloys with artificial cracks of various depths (h from 0.1 mm to 3 mm) and a width of 1 mm (Fig. 4) was used to test the system availability. The plate material is marked AD31T5 and consists of aluminum, magnesium, and silicon (Al-Mg-Si). This material is used in aircraft and helicopter cabins and aircraft window openings.

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

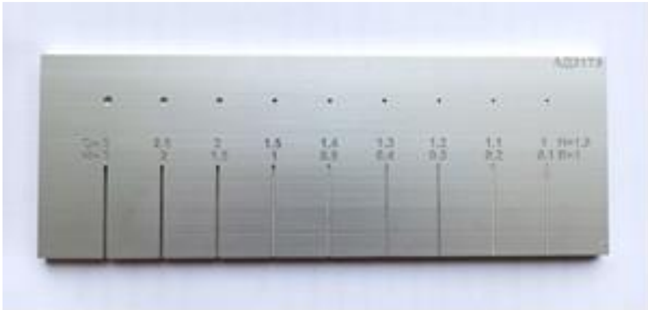
Fig. 4. The specimen

B. *Experimental Research and Results Discussion*

The pulse current with a period T_n=50 μs and duration τ=175 ns was applied to the primary coils of the differential ECP for excitation. The received signal from the secondary coils of the ECP had the form of attenuating harmonic oscillations (Fig. 5) and was presented by equation (1). The analysis of the received ECP signals was carried out using the developed software, which is based on the ECP signals processing in the time domain using the Hilbert transform and obtaining the ACS and PSC and their subsequent analysis.

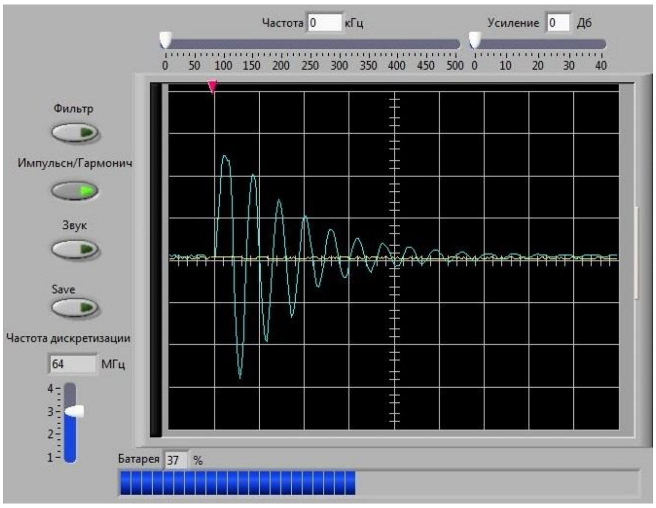

Fig. 5. Received signal

The maximum peak amplitude values were selected from a set of ECP signals obtained after TO scanning. The distribution of peak values of the ECP amplitude in the reference to all scanned points of the TO surface is shown in Fig. 6a similarly to the C-scan, where 1 – TO, 2 – signal amplitude [18]. The distribution of amplitudes shows that a crack in the TO leads to a significant increase in the amplitude values near it, but a decrease above the crack itself, which is shown in Fig. 6b. On Fig. 6 shows the distribution of the peak amplitude values without values received from space near the TO boundaries. This is due to the influence of edge effects on the TO boundaries.

Fig. 7 shows the dependence of the values of the natural frequency (a) and attenuation (b) of the ECP differential signal on the crack depth in the TO. These dependencies can be described by formulas: a polynomial of the 3rd degree in the case using natural frequency as an information parameter and a logarithmic dependence in case of signal attenuation. Obviously, the dependences obtained in this way could be used to quantify of the cracks parameters.

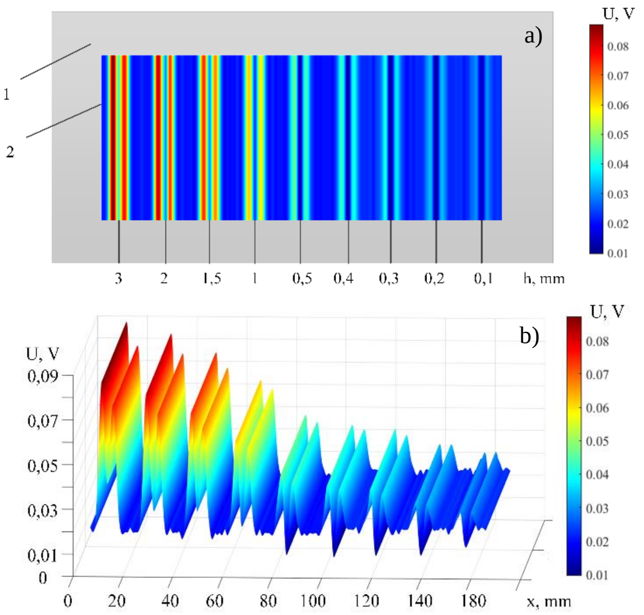

Fig. 6. The transducing unit of the ECNDT system

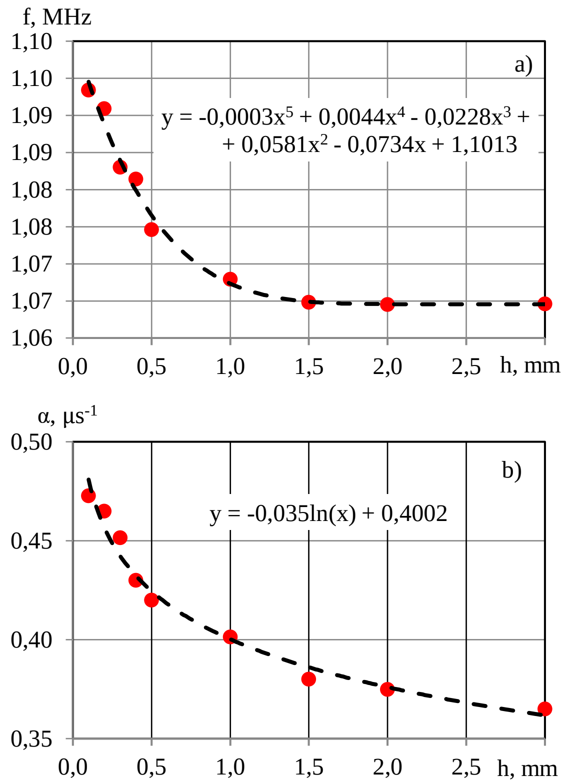

Fig. 7. The dependence of the values of ECP signal natural frequency (a) and ECP signal attenuation (b)

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

IV. Conclusion

Our review shows that pulsed excitation in ECNDT in combination with digital signals processing based on the discrete Hilbert transform significantly complements the known methods by using such signals parameters as natural frequency, peak amplitude, signal attenuation and temporal position of characteristic signal points for analysis. An automated eddy current system is developed to inspect large-sized components or assemblies of aircraft to which access is limited.

This system applies wireless technologies to transmit signals and uses the new signals processing technique described in this article. The inspecting system provides real-time analysis and visualization of the received data and uses this data to make decisions about the condition of the large objects. The technique was tested and checked on an example of pulsed ECNDT signal processing for inspection the plate with cracks of various depths.

The article presents the results of inspecting a metal alloy plate with artificial cracks of different depths. It is experimentally established that in the process of crack inspection in a sample, the relative error in determining the crack size by the frequency of the information ECP signal does not exceed 0.2%, by the amplitude – 1.5%.

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