Improvement of the Eddy Current Method of Non-Destructive Testing with Pulsed Mode Excitation

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Abstract. This article is devoted to application of the pulsed mode excitation for eddy current sensor to widen of functional capabilities of the eddy current non-destructive testing. It is presented the sensor simulator which operates in the pulsed mode excitation of eddy currents and the process that generates a response from the "sensor - object" system in the form of damped harmonic oscillations. It is described the method for the sensor signal processing and determination of its amplitude and phase parameters using the Hilbert discrete transformation. It is discussed the statistical treatment of received results and use them for evaluation of testing object physical- mechanical properties. The possibilities of the pulsed eddy current non-destructive testing is showed in the solution of problems for products testing that have various shape and material, in particular relation between sensor's signal frequency and its damping from a coating thickness and object diameter. It is given the experimental results of thickness evaluation of the dielectric coating on magnetic basis. The proposed method was applied to determine of the cylindrical object diameter and material electroconductivity. It is found general character of sensor signal damping and frequency in pulsed mode excitation dependence from dielectric coating thickness and the object diameter.

Introduction

Area of application of the eddy current non-destructive testing (ECNT) is widening constantly because of its reliability and efficiency. That is the reason that methods and means of the ECNT implementation have need for improvement. One of the impotent directions of the ECNT development is rising testing information value [1]. This direction is realized at the expense of improvement of the excitation manner of the electromagnetic field and search new signal's informative parameters of the eddy current transducer (ECT). The grate attention is focusing to improve ECT construction. In turn that has effect on degree of complexity to adapt a transducer and selection of a signal processing method [2].

The most applicable ECNT method uses the harmonic signal for excitation of the electromagnetic field and is based on analyses of informative features such as amplitude and initial phase of sensed signals (or orthogonal constituents of signals if they present on the complex plane) [3]. Among the ECNT methods there is a method which uses pulsed excitation of the electromagnetic field. In the paper [4] it is considered the combined use of harmonic and pulsed excitation mode of the electromagnetic field for pipe wall testing. It extends a number of informative features of a testing object. The positive effect is obtained at the expense of additional informative parameters use. They are attenuation of the ECT signal and change the position of the zero-crossing time by this signal. In the paper [5] is analyzed of application of ECNT pulsed mode for evaluation of metal corrosion extent which defined using the position of the zero-crossing time by ECT signal. In the paper [6] is analyzed of application of excitation pulses which have different duration. It gives possibility to obtain a distance between transducer and a testing object (for short pulse duration) and information about defects of a testing object (for significant pulse duration).

The pulsed mode of the ECNT is used for multilayer materials and objects inspection [7]. The informative signal contains some frequency components at the expense of ECT excitation by the repetitive pulse current. Use those components allow to increase self-descriptiveness of testing and reduce its time at that provides with developing defects in multilayer conducting materials at significant depths.

The resources of mentioned methods are limited by the disuse of all information that contain in the analyzed signal. At the same time utilization of the Hilbert transform for signal processing permits to get amplitude and phase characteristics of the ECT signal which help to evaluate additional informative parameters such as attenuation and frequency of that signal [8, 9].

Thus, pulsed excitation ECNT with present-day methods of signal processing can enlarge known testing methods at the expense of analysis signal parameters such as frequency, phase dispersion, signal decrement and time position of the characteristic points of a signal.

1. Objective and Methods

The purpose of this paper is search a new informative parameters of the ECT signal which can be used for making wider of the ECNT functional capabilities and solving the multiparametric task.

The problem is solving by the methods of simulation and full-scale experiment which based on:

1) researching operation of laying-in (overlay) and through-type ECT at pulsed excitation, and next analysis their signals in a time domain;
2) discovering and analyzing of the informative parameters of ECT signals;
3) discovering the signal informative parameters functional dependence on the testing object characteristics.

2. Carrying Out the Experiment

2.1 System Description

It is impotent to consider complex impedance of the ECT in tasks of the pulsed ECNT.

The preliminary analysis displays that in such mode there arises decaying oscillations given by the produced oscillatory circuit which consists of an inductance coil and its parasitic interturn capacitance. According to this the equivalent circuit of the system - parametric ECT and testing object can be presented like in Fig. 1.

A testing object (TO) is presented in this circuit by the contour $L_2(\bar{p})\,R_2(\bar{p})$ where inductance $L_2(\bar{p})$ connecting with element L_1 through mutual inductance $M_{12}(\bar{p})$ and $\bar{p}$ is a vector of parameters of a TO. The resistance and inductance of the 1-st contour coil are indicated as R_1, L_1; R is an active resistance of the circuit; U is a signal of the sensor excitation; $\dot{I}_1$ and $\dot{I}_2$ are currents in the contours.

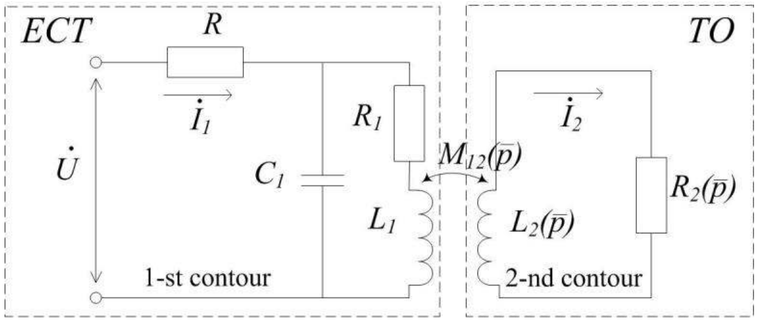

Fig. 1. The equivalent circuit of the system - parametric ECT and testing object

In case of the ECT is operated from the harmonic signal source, it is possible to get the system of equations in a complex form (according to Kirchhoff's laws):

$$\begin{cases} \dot{I}_1 R + \dot{I}_1 \dfrac{R_1 + j\omega L_1}{1 + j\omega C_1 R_1 - \omega^2 L_1 C_1} + \dot{I}_2\, j\omega M_{12}(\bar{p}) = \dot{U}, \\ \dot{I}_1\, j\omega M_{12}(\bar{p}) + \dot{I}_2 R_2(\bar{p}) + \dot{I}_2\, j\omega L_2(\bar{p}) = 0. \end{cases} \quad (1)$$

The current $\dot{I}_1$ is easy to be measured, for instance, through the voltage drop on R, or with the help of an ECT's additional measuring coil.

Using the Kramer formula it is possible to solve the system of equations (1) and get:

$$I_1 = \frac{U\left(R_2(\bar{p}) + j\omega L_2(\bar{p})\right)}{\left(R + \dfrac{R_1 + j\omega L_1}{1 + j\omega C_1 R_1 - \omega^2 C_1 L_1}\right)\left(R_2(\bar{p}) + j\omega L_2(\bar{p})\right) + \omega^2 M_{12}^2(\bar{p})}. \quad (2)$$

In case of the ECT operates in pulsed mode it is necessary to consider the transient processes in its circuit.

2.2 The Structure of an Experimental Model

The architecture of the developed ECNT system is shown on the Fig. 2. The transducing unit consists of a transformer ECT which contains two coils. The exciting coil receives a pulsed actuating signal from a current source and the measuring one generates a signal which is amplified and digitized by an analog-to-digital converter (ADC). Received data are saved in a storage buffer for next transfer to the data-processing unit. This transfer is realized due to a microcontroller and wireless communications unit. The wireless communications unit is realized on the base of the Bluetooth module (third grade of power) which has an external antenna and provide with connection between the data-processing and transducing units at some distance. Operation of the transducing unit main components is synchronized by a control block (CB).

The data-processing unit consists of a receiving box (RB) and personal computer (PC) with special software (SS).

2.3 Technique of Experimental Data Processing

Informative signal model of the ECT is presented as an additive mixture of harmonic oscillation and Gaussian noise:

$$u_{ECT}(t, \bar{p}) = U_m e^{-\alpha(\bar{p})\cdot t} \cdot \cos(2\pi\ f(\bar{p})\cdot t) + u_N(t), \quad t \in (t_1, t_2), \quad (2)$$

where: U_m – amplitude component of the ECT informative signal, $\alpha(\bar{p})$ – signal decrement, $f(\bar{p})$ – signal frequency, t – current time, (t_1, t_2) - period of the ECT signal analyses, $t \in (t_1, t_2)$, $u_N(t)$ – signal noise term. Frequency changing and attenuation of these oscillations depend on TO's characteristics such as – material, shape and geometry, defect presence, dielectric coating thickness [11].

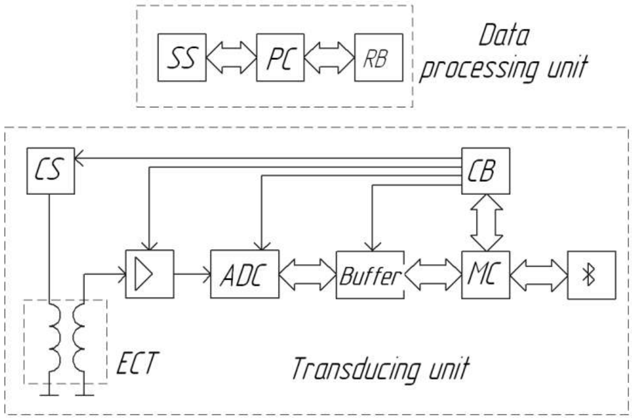

Fig. 2. Developed system for eddy current non-destructive testing

The order of the signal processing is illustrated on the Fig. 3. The frequency and attenuation of a signal are considered as its informative parameters.

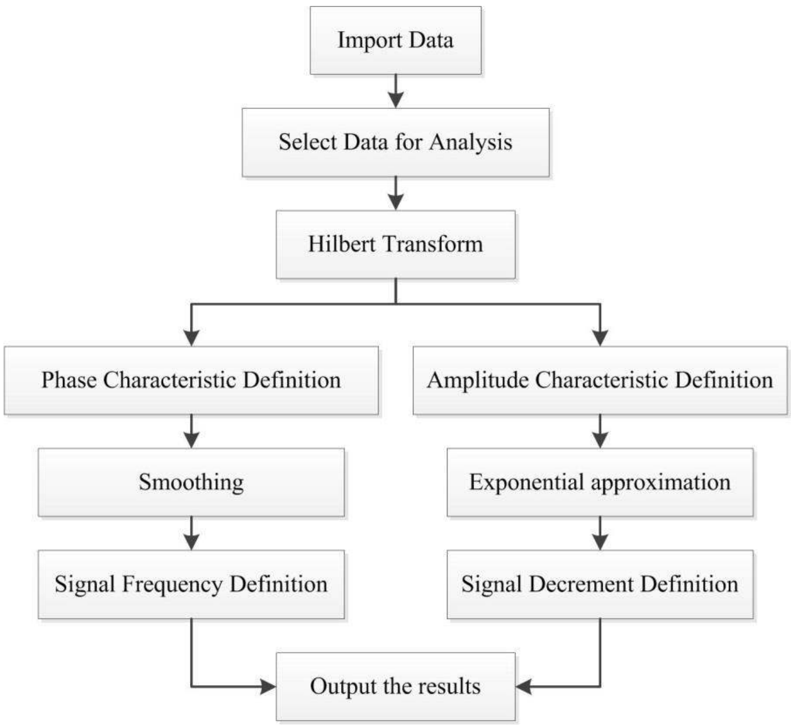

Fig. 3. ECNT signal processing

Processing and analysis of the informative signal characteristics consist in:

1) definition of the Hilbert image of the ECT signal:

$$u_H[j, \bar{p}] = \mathbf{H}[u_{ECT}[j, \bar{p}]], \tag{3}$$

where **H** – operator of the Hilbert transform;

2) definition of the phase and amplitude characteristics of the ECT informative signals:

$$\Phi[j, \bar{p}] = \operatorname{arctg}\frac{u_H}{u_{\text{всп}}} + \mathbf{L}(u_H[j, \bar{p}], u_{ECT}[j, \bar{p}]), \tag{4}$$

$$U[j, \bar{p}] = \sqrt{u_{ECT}^2[j, \bar{p}] + u_H^2[j, \bar{p}]}, \tag{5}$$

where $\mathbf{L}$ – operator of unwrap signal phase characteristics (SPC) beyond the bounds of one-valuedness of the arctg function.

3) smoothing of the function (4) using the method of the Bartlett-Kenya linear regression. The method is based on time sequencing of the experimental data and division of the sample part $\Phi[j, \bar{p}]$ on three approximately equal groups'. It is defined sums of the type $\sum\Phi[j, \bar{p}]$ 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 the following ratio:

$$k = \frac{\Phi_3 - \Phi_1}{t_3 - t_1}, \quad b = \bar{\Phi} - k\bar{t} \quad \text{or} \quad b = \frac{\Phi_2}{M} - k \cdot \frac{t_2}{M}, \tag{6}$$

where $\bar{\Phi} = \frac{\sum\Phi[j,\bar{p}]}{3M}$ and $\bar{t} = \frac{\sum t_j}{3M}$;

4) definition of the signal frequency from the linear trend of the function (4):

$$f_L(\bar{p}) = \frac{\Delta\hat{\Phi}_L[\bar{p}]}{2\pi\Delta T}, \tag{7}$$

where $\Delta\hat{\Phi}_L[\bar{p}]$ – accumulated for period $\Delta T \in (t_1, t_2)$ phase of the ECT signal defined per function of the linear regression.

5) utilization of exponential approximation for function (5) to rise the definition accuracy of a informative signal decrement. It is determined that it is very impotent to consider the part of the amplitude characteristic of a signal (ACS) which corresponds to the early periods of the informative signal for accuracy rising of factor exponential approximation estimation. The early periods correspond to ACS with a maximal slope.

6) definition of informative signal decrements using formula:

$$\alpha(\bar{p}) = \frac{1}{\Delta T}\ln\frac{\hat{U}(t_1', \bar{p})}{\hat{U}(t_2', \bar{p})}. \tag{8}$$

Where: $\hat{U}(t_1', \bar{p})$, $\hat{U}(t_2', \bar{p})$ – magnitude of the approximated slope at time $t_1', t_2' \in \Delta T$.

3. Experimental Research and Results Discussion

3.1 The Cylindrical Objects Testing

Two types of cylinders were used as testing objects. They made of aluminum and bronze and had diameters in the range of 34 ÷ 35 mm. Fig. 4 demonstrates frequency-diameter diagrams for aluminum (curve 1) and bronze (curve 2) samples, and also shows their linear trend (curve 3, 4). The analysis of these diagrams displays that change of a diameter leads to signal frequency change. That change has about linear character of the functional dependence.

There is also linear dependence of the diameter-signal decrement (Fig. 5, curve 1 for aluminum samples and curve 2 for bronze ones).

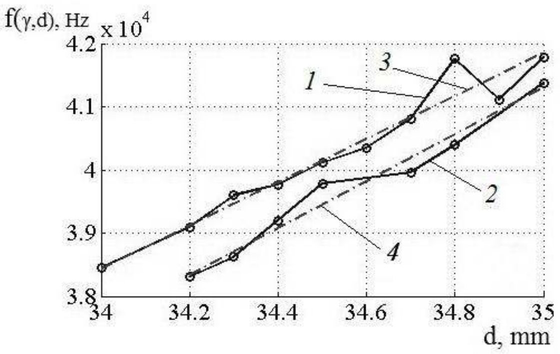

Fig. 4. Dependence of the signal ECT frequency on the TO diameter

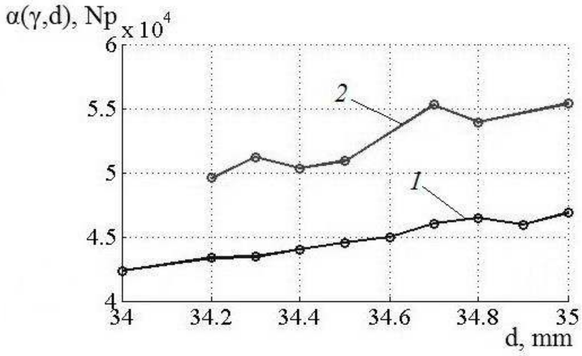

Fig. 5. Dependence of the signal ECT decrement on the TO diameter

3.2 Testing of the Thickness of a Dielectric Coating on the Electroconductive Base

As the testing objects were used samples from aluminum, bronze and steel (conductivity $\gamma_{al} = 4{,}87 \cdot 10^7$ Sm/m, $\gamma_{br} = 2{,}75 \cdot 10^7$ Sm/m, $\gamma_{st} = 1{,}45 \cdot 10^6$ Sm/m) with thickness that exceeds of the eddy currents penetration. It was analyzed influence of the change of the dielectric coating thickness on the signal ECT parameters.

It was used selection of a signal value for smoothing of the signal phase. For aluminum and bronze amount of sampling were $j_{al} = j_{br} = \overline{1500 \ldots 6000}$ and for steel - were $j_{st} = \overline{1500 \ldots 3501}$. The obtained selections were divided on three approximately equal groups: $M = M_{al} = M_{br} = 1500$; $M_{st} = 667$.

On the Fig. 6 is shown the plot of the received dependence $\alpha = F(h)$. This plot demonstrates increasing of the signal decrement at the thickness of dielectric coating decreasing within the same material. Using comparative analysis of these curves it is possible to conclude that form of the signal decrement curve change is exponential relative to the thickness of the coating on any basis. The Fig. 6 displays also that material characteristics of the sample basis have an influence on the slope level of received curves. Slightly deviation of the result from general functional dependence can be effect of the hidden fault presence, sample characteristics change or definition error of the coating thickness real value.

The results of signal frequency definition are shown on the Fig. 7. The ECT signal frequency is a function of dielectric coating thickness. The dependence $f(h)$ displays a single-valued result only for nonmagnetic materials. The coating thickness sensitivity increases at its value decrease in this case.

3.3 Pulsed Eddy Current Defectoscopy with a Multidifferential ECT

As the testing objects were used samples from aluminum alloy AD 31E5 which had the crack opening 1mm and the depth within 0.1 ÷ 3.0 mm. It was analyzed the influence of a crack depth on a signal of the multidifferential ECT. The signal frequency was evaluated using selection from the signal phase characteristic by the volume $j = \overline{1500 \ldots 4999}$. The results of the signal frequency definition are shown on the Fig. 8. The received curve displays exponential dependence of the signal frequency from a crack depth h. The curve line that correspond a small crack depth has slight deviation from a trend line. This conforms to the error about 0,2% (±0,4mkm).

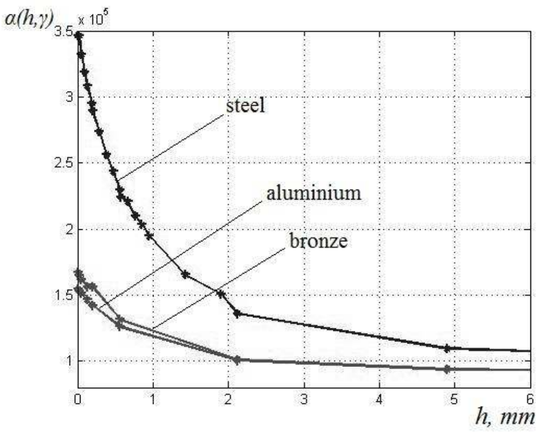

Fig. 6. Dependence of the ECT signal decrement on the coating thickness

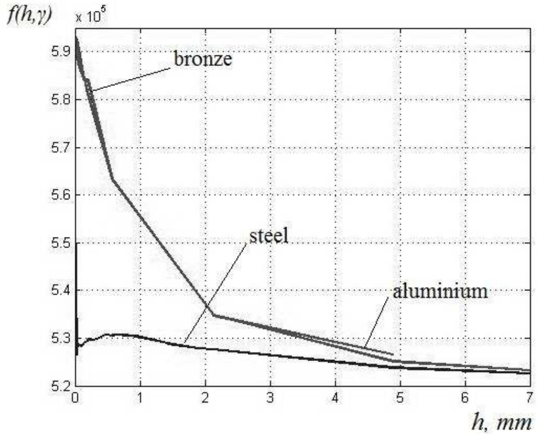

Fig. 7. Dependence of the ECT signal frequency on the coating thickness

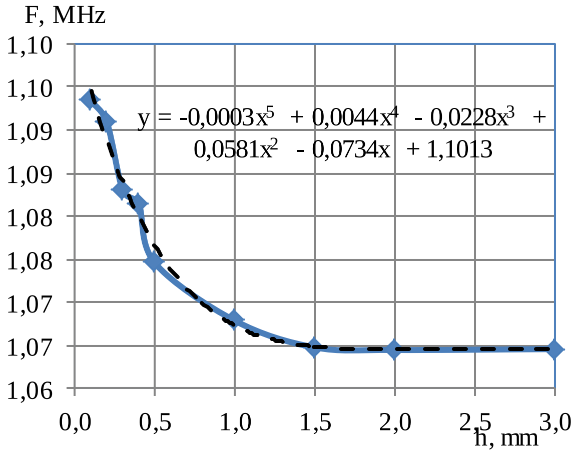

Fig. 8. Dependence of the ECT signal frequency on the crack depth

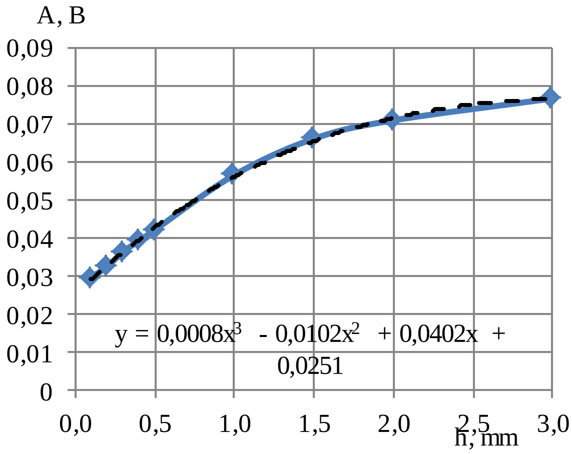

Fig. 9. Dependence of the maximum value of the ECT signal amplitude on the crack depth

Fig. 9 demonstrates dependence of the maximum value of the multidifferential ECT signal amplitude on the crack depth. This dependence can be described by the polynomial of the third degree. The dependences from Fig. 8 and 9 can be used for evaluation of crack parameters.

4. Conclusions

Experimental researches of the pulsed mode excitation for eddy current sensor displayed possibility to use the frequency, amplitude and decrement of the sensor's signal as informative parameters. It was proposed the procedure of the sensor's signal analysis which applied for cylinders diameter control, dielectric coating thickness testing and evaluation of cracks depth.

It was found that frequency of the through-type ECT signal had linear dependence upon an object diameter and independence from material conductivity. On the other hand, decrement of that signal has related to material conductivity of an object.

The decrement of the overlay ECT signal had exponential dependence on coating thickness and magnetic permeability of the object material. It was developed relation between amplitude and frequency of the signal and crack depth for the multidifferential overlay ECT. It makes sense the further researches of that type sensor to direct toward crack parameters evaluation.

Acknowledgments

The authors would like to thank Valentin Uchanin for the multidifferential eddy current sensor which was used for experiment research, and for his helpful consultation.

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