Pulsed Eddy Current Non-Destructive Testing of the Coating Thickness

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Abstract
Usually the procedure of eddy current non-destructive testing includes harmonic excitation of the object and then evaluation of the received signal amplitude and phase. This article is devoted to pulse eddy current non-destructive testing which is a simple and effective alternative. It is discussed the use of pulsed eddy current testing for thickness evaluation of the non-magnetic coating which is placed on the low magnetic basis. It is described the method of information signal processing which is based on the Hilbert transform. This method makes it possible to obtained a response from fronts of the exciting pulse signal for the system "sensor - object". The experimental results of coating thickness evaluation are given. The frequency and attenuation of a signal which looks like a damped sinusoid are used as informative parameters. It was found a general nature of the dependence these parameters from the coating thickness.

Keywords: pulse eddy current, Hilbert transform, frequency and attenuation of a signal, coating thickness evaluation

1. Introduction

The present-day digital techniques of the signal processing give a chance to increase the efficiency of the non-destructive testing application and enlarge its functional capabilities. Usually, at the traditional eddy current testing is used a harmonic excitation signal for dielectric coating thickness evaluation which consists in analysis of the received signal features such as amplitude and phase [1]. However, at the same time, it is used eddy current non-destructive testing (ECNT) with pulsed excitation of the object. For example, it is considered application of harmonic and pulsed excitation of the electromagnetic field jointly in [2]. These excitation modes were used for pipe wall testing with the purpose to increase a number of checking features. A desired result was achieved due to processing of the additional informative parameters getting from the eddy current transducer (ECT). They were attenuation of the ECT signal and change the position of the zero-crossing time by this signal. The pulsed mode of the ECNT was described in [3]. It was applied for estimation of the metal corrosion amount. The proposed in [3] testing method included estimation of the zero-crossing time by an ECT as well.

Application the Hilbert transform for ECT signals gives possibility to get amplitude and phase characteristics which facilitate to define additional informative features such as signal attenuation and its frequency [4].

So, ECNT with pulsed excitation can enlarge well known techniques at the expense of possibility to analyze signal frequency, phase dispersion, signal decrement and time position of the typical signal points.

Up-to-date information technologies allow separating in space the transformative part of measuring system from a signal processing device due to wireless technologies of data communications [5]. Such a technological decision enables to perform the object testing in tight and distant areas.

The purpose of this article is development and analysis of the ECNT wireless system for measuring of the dielectric coating thickness which is on conductive substance, and the next one is to find information features of the ECT signals in the pulsed mode.

2. Carrying out the experiment

2.1 System description

The architecture of the developed ECNT system is shown on the fig. 1. 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).

2.2 Routine of experiment

At the beginning of the experiment, it was analyzed the influence of specimen material characteristics on the informative signal features of the transformer ECT which worked in the pulsed mode. Specimens from aluminium, bronze and steel were used as testing objects. The thickness of these objects exceeded greatly the depth of eddy currents penetration.

At the next step, it was analyzed the influence of the dielectric covering thickness of the object on the informative signal features of the ECT.

The software for data-processing was developed using the Matlab package. The developed software provides for analyzing an ECT signal in the time domain. The data-processing algorithm is based on the Hilbert transform and produces the amplitude and phase characteristics of a signal.

The exciting coil of the transformer ECT which had *80* winds ($W_1 = 80$) received a pulsed signal from a current source with current strength equal to *5mA* ($I = 5mA$), pulse period - $T = 125 \cdot 10^{-6}\, s$, pulse duration - $\tau = 62.4 \cdot 10^{-6}\, s$:

$$i(t) = \begin{cases} 5\text{mA}, & t_1 + kT_n < t > t_1 + \tau + kT_n \\ 0\text{A}, & t_1 + \tau + kT_n < t > t_1 + T_n(k+1), \quad k = 0,1,2... \end{cases} \tag{1}$$

The ADC digitized the analog informative signal $u(t)$ received from the measuring coil of the ECT ($W_2 = 420$). As a result the data sample $u[j],\ j = \overline{0,....10000}$ was received. Digitization of a signal was performed with a period - $T_d = 4 \cdot 10^{-9}\, s$. Further, data sample $u[j]$ was passed to PC through a wireless communications unit for data processing.

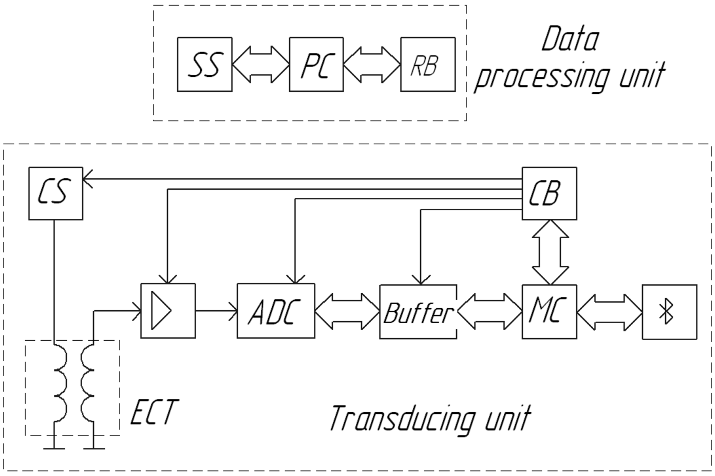

Figure 1. Developed system for eddy current non-destructive testing

2.3 The algorithm of signal processing

The model of the ECT informative signal is presented as a damped harmonic oscillation:

$$u_{ect}(t,h,\gamma)=U_m e^{-\alpha(h,\gamma)\cdot t}\cdot\cos[2\pi\cdot f(h.\gamma)\cdot t]+u_n(t),\ \ t\in(t_1,t_2), \tag{2}$$

where U_m - value of the amplitude of the ECT signal informational component, $\alpha(h,\gamma)$ - signal decrement, $f(h,\gamma)$ - frequency of the signal oscillation, t - current time, (t_1,t_2) - period for analyzing an ECT signal (step response of the exciting signal amplitude), $U_n(t)$ - noise component of a signal.

Frequency and damping of these oscillations change depending on basis material and thickness of dielectric coating. The Hilbert direct images were defined during processing and analysis of the ECT informative signal features for an every data sample (aluminium, bronze and steel testing objects which had different dielectric covering thickness):

$$u_H[j,h,\gamma]=\boldsymbol{H}[u_{ect}[j,h,\gamma]], \tag{3}$$

where $\boldsymbol{H}$ - operator of the discrete Hilbert transformation.

It was evaluated the phase and amplitude curves of the informative signal after that [6]:

$$\hat{\Phi}[j,h,\gamma]=arctg\frac{u_H}{u_{ect}}+\boldsymbol{L}(u_H[j,h,\gamma],u_{ect}[j,h,\gamma]), \tag{4}$$

$$\hat{U}[j,h,\gamma]=\sqrt{u_{ect}^2[j,h,\gamma]+u_H^2[j,h,\gamma]}, \tag{5}$$

where $\boldsymbol{L}$ - operator for sweeping of the signal phase characteristic (SPC) outside of the uniqueness function *arctg* interval.

The frequency $f(h,\gamma)$ and decrement of an ECT signal were selected as informative features for analysis influence of testing object (TO) characteristics on this signal. The SPC was used for defining the medium frequency of the ECT informative signal according to the formula:

$$f(h,\gamma)=\frac{\Delta\hat{\Phi}[h,\gamma]}{2\pi\Delta T}=\frac{\Phi(t_2,h,\gamma)-\Phi(t_1,h,\gamma)}{2\pi\Delta T}, \qquad (6)$$

where $\Delta\hat{\Phi}[h,\gamma]$ – the accumulated signal phase of an ECT at the time of ΔT.
Adoption a hypothesis about linear time variation of the function $\hat{\Phi}[j,h,\gamma]$ allows applying one of the methods of linear regression determination for its smoothing. Take for example the Bartlett-Kenya method. This method is simple comparatively and can be used for analysis of small amount of sampling. The method is based on ordering experimental data at times t and dividing of useful portion of the sample $\hat{\Phi}[j,h,\gamma]$ on three approximate equal groups in magnitude M. The aluminium and bronze samples had amount of sampling $j_{al}=j_{br}=\overline{1500\ldots6000}$ and the steel one had $j_{st}=\overline{1500\ldots3501}$. So, mentioned above groups were equal: $M=M_{al}=M_{br}=1500$, $M_{st}=667$. The sums like $\sum\hat{\Phi}[j,h,\gamma]$ and $\sum t_j$ were found in the each group. Let us denote them like Φ_1,Φ_2,Φ_3 and t_1,t_2,t_3 accordingly. Then, coefficients of linear regression are possible to evaluate by following relations:

$$k=\frac{\Phi_3-\Phi_1}{t_3-t_1}, \qquad (7)$$

$$b=\overline{\Phi}-k\bar{t} \qquad (8)$$

or else

$$b=\frac{\Phi_2}{M}-k\cdot\frac{t_2}{M}, \qquad (9)$$

where $\overline{\Phi}=\dfrac{\sum\hat{\Phi}[j,h,\gamma]}{3M}$ and $\bar{t}=\dfrac{\sum t_j}{3M}$.
Frequency of the ECT signals was defined due to the linear trend of the function $\hat{\Phi}[j,h,\gamma]$:

$$f_L(h,\gamma)=\frac{\Delta\hat{\Phi}_L[h,\gamma]}{2\pi\Delta T}, \qquad (10)$$

where $\Delta\hat{\Phi}_L[h,\gamma]$ – the phase of an ECT signal which accumulated at the time of ΔT.
This phase was got by function of the linear regression for the aluminium and bronze samples – $\Delta\hat{\Phi}_L(h,\gamma)=\hat{\Phi}[j=4500,h,\gamma]-\hat{\Phi}[j=1,h,\gamma]$ and for the steel one – $\Delta\hat{\Phi}_L(h,\gamma)=\hat{\Phi}[j=2001,h,\gamma]-\hat{\Phi}[j=1,h,\gamma]$.
The decrement of the ECT informative signal was defined according to expression:

$$\alpha(h,\gamma)=\frac{1}{\Delta T}ln\frac{\hat{U}(t_1',h,\gamma)}{\hat{U}(t_2',h,\gamma)}, \qquad (11)$$

where $\hat{U}(t_1',h,\gamma)$, $\hat{U}(t_2',h,\gamma)$ – values of the signal amplitude characteristic (SAC) in points of time t_1' and t_2' accordingly. The exponential approximation of the ECT SAC was realized for accuracy rising of defining signal decrement.

3. Discussion of the received results

The fig. 2 demonstrates ECT signals which received at the first stage of experiment when the samples without coating (aluminium, bronze and steel) were tested. Different values of the sample material's electro conductivity and magnetic permeability conduced to signal frequency change and velocity attenuation. The SAC and SPC of those signals were shown on fig. 3 and 4 accordingly.

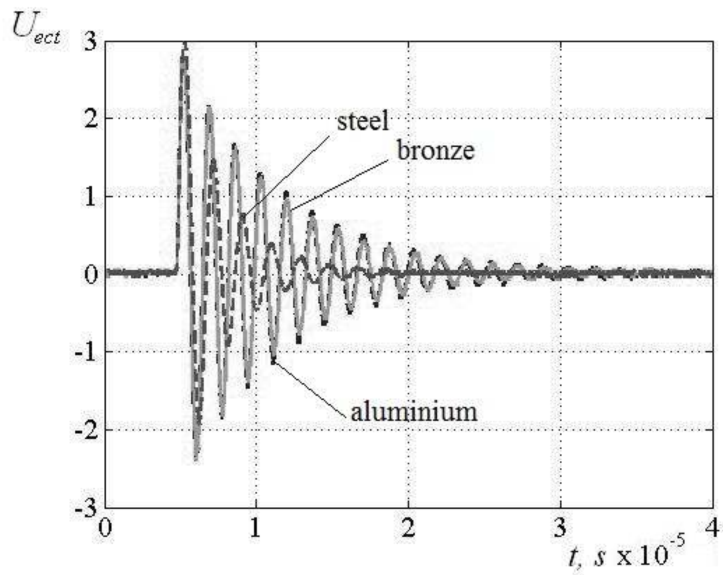

Figure 2. The plot of ECT signals

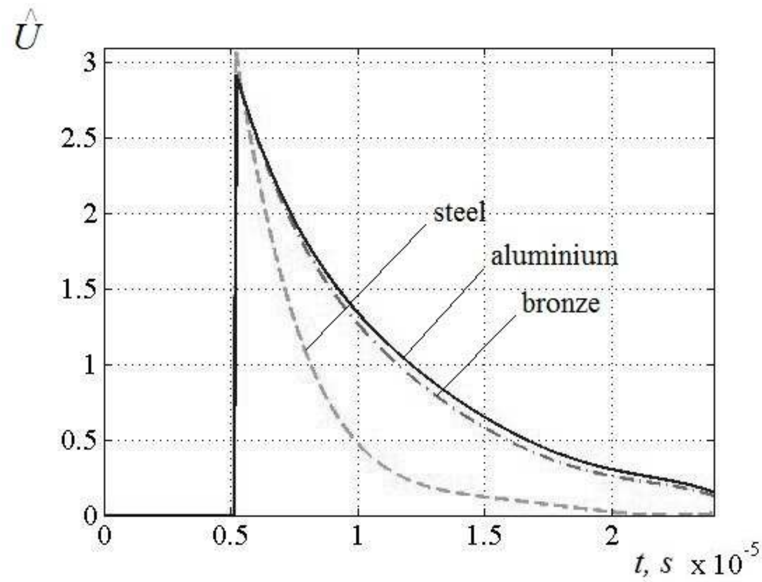

Figure 3. Amplitude characteristic of ECT signals

The fig. 5 demonstrates the signal curves received at a steel sample testing. A steel sample had various thickness of dielectric coating. The curve 1 corresponds to a segment of ECT signal received from a sample without coating. The curve 2 corresponds to a sample with coating *1.62mm* and the curve 3 corresponds to a sample with coating *4.90mm* . Evidently, the coating thickness increasing leads to decreasing of the influence of eddy currents on an ECT informative signal. At the same time the signal amplitude increases while its frequency remains constant.

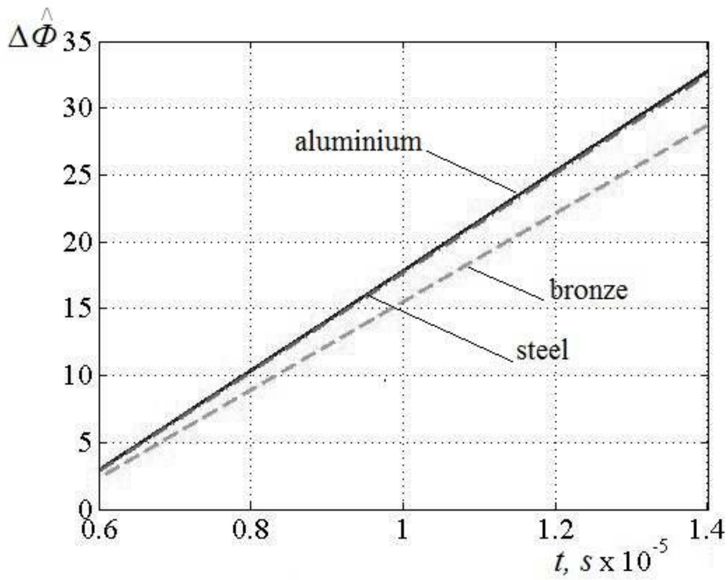

Figure 4. Fragment of the ECT signal phase characteristic

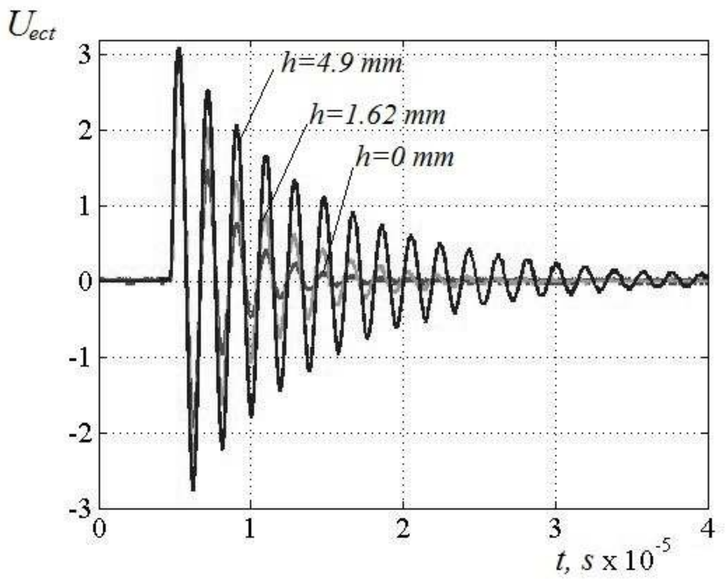

Figure 5. Dependence of the ECT signal amplitude from coating thickness

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 for steel sample with *1.90mm* coating.
The results of signal frequency definition are shown on the fig. 7. The ECT signal frequency is a function of dielectric coating thickness. As can be seen from plots it is complicated to assess coating thickness on such informative parameter as frequency. However, it is observed considerable influence of material magnetic permeability on a value of the ECT signal frequency. This influence becomes stronger at coating thickness is decreased.

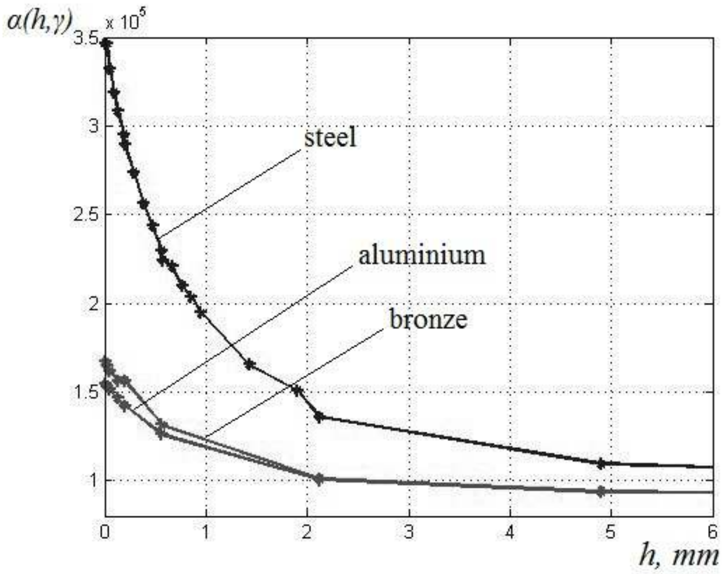

Figure 6. Dependence of the ECT signal decrement

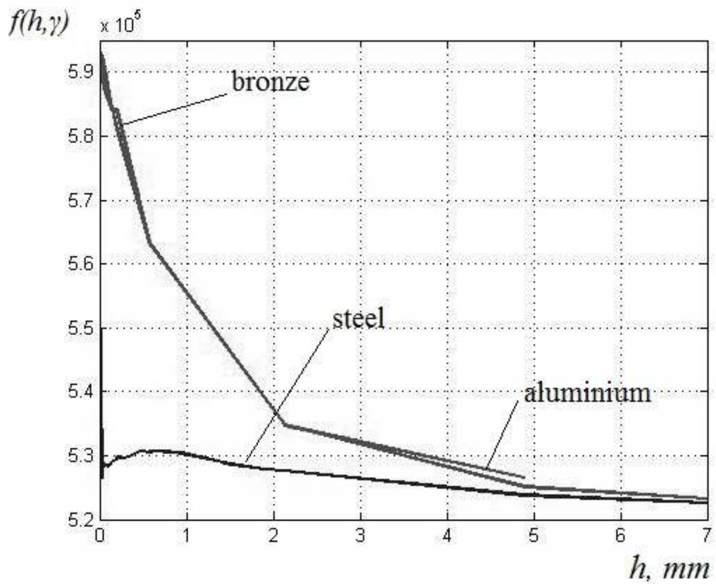

Figure 7. Dependence of the ECT signal frequency

4. Conclusions

It is ascertained that decrement of the transformer's informative signal depends on coating thickness and material magnetic permeability at dielectric coating testing in the pulsed mode. This dependence has exponential nature.

The proposed system of pulsed ECNT gives possibility to test objects in the tight area at the expense of Bluetooth using. It was demonstrated possibility to use such parameters as decrement and frequency of the informative signal for analysis of the pulsed ECNT signals. It is ascertain the general character of these parameters dependence on coating thickness of the samples.

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