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Analysis of formation processes of informative features in eddy current probes with pulsed excitation mode

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Abstract

The modern pulsed eddy current (EC) technique for flaw detection in structure inspections of aircraft and automotive elements, or other responsible constructions is typically carried out in aperiodic mode. At the same time, the unstable characteristic points of the EC signal usually used as informative parameters can restrict the potential of this excitation mode due to influence measurement errors.

The article considers an application of the pulsed EC method of NDT based on the oscillatory mode. To obtain the conditions concerned with different modes of EC probe response oscillations, an equivalent scheme of the “testing object – EC probe” system was developed. The conditions represent the signal formation process and allow analyzing it for impedance and differential probes. The obtained mathematical model of the probe signals allowed for the dependence of proposed signal parameters on the characteristics of the testing object to be evaluated due to simulation. According to this, the frequency and attenuation coefficient of natural oscillations are proposed as the informative parameters. Also, the simulation results are used for developing enhanced algorithmic software for determining and analyzing the EC signals. The proposed informative parameters are experimentally investigated using a set of specimens. The obtained experimental and simulation results are correlated and it confirms the possibility of the proposed methodology to enhance the inspection procedures related to the specimen’s parameters measurements as well as the detected defect sizing.

KEYWORDS: Pulse Eddy Current; Impedance and Differential Probes; Oscillatory Mode; Frequency and Attenuation; Hilbert Transform

1. Introduction

In recent decades, eddy current non-destructive testing (EC NDT) tools have been widely distributed in various industries. They are used in production, operation and monitoring at enterprises, the automotive industry and aviation for responsible structures testing and

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evaluation. It is due to the high sensitivity, reliability and manufacturability of this method [1]. The basis of EC NDT is the analysis of the interaction between a variable electromagnetic field and an object made of electrically conductive material. This interaction is evaluated by the signals of the probes, which register the presence and changes of the electromagnetic field as a result of the presence of the testing object (TO) in it. In EC NDT, the most common is the use of harmonic signals to excite the variable electromagnetic field and the analysis of the amplitude and phase of eddy current probe (ECP) signals [2, 3, 4].

The modern development of EC NDT tools is mostly focused on improving the designs of probes, methods of analyzing information signals, and methods of presenting testing results in a user-friendly format. The performance of EC NDT largely depends on the probe structure, therefore it is of great significance to use suitable probes according to the TO and their characteristics, as noted by the authors of the works [5, 6, 7]. On the other side, the means of EC NDT are being modernized through the improvement of analysis methods of ECP information signals and presenting methods of testing results according to the development of modern digital technology [8, 9, 10]. In recent years, the pulsed excitation of eddy currents is increasingly used for EC NDT [9, 11-14]. It is known that the pulsed character of the electric excitation allows a high peak value of the eddy currents density in the material and broadband signal containing optimized frequencies [9, 11]. All of this allows studying the sample (TO) over a more extended depth and improving the signal-to-noise ratio (S/N), sensitivity and sometimes simplifying technical solutions. In many implementations of the pulse EC NDT the various characteristic point estimates, in particular, the time to the maximum signal level, the height of the amplitude peak, the moments of its rise, and zero crossing are used to evaluate the characteristics of the TO [12]. However, these parameters are unstable to the influence of noise, lead to significant measurement errors, and do not allow realizing the full potential of the pulsed EC NDT. There is also other research about using the ECP in the oscillatory mode, which allows analyzing informative signal parameters like frequency and attenuation [15, 16, 17]. However, the task of determining the correlation between the parameters of the ECP signal and the parameters and characteristics of the TO still remains undefined and requires more research.

This paper studies the processes of signal formation in ECP, which is excited in the pulsed mode. The research aims to analyze the conditions for the occurrence of decreasing harmonic oscillations.

2. Analysis of the physical and mathematical model of the probe

2.1 Formation of the impedance ECP signals

The processes analysis of signals formation in the ECP-TO system consists of a representation of this system like an inductively coupled electrical circuits system [18]. Based on the general rules and methods of calculating linear electric circuits, the "impedance ECP - non-magnetic TO" system can be represented by the equivalent circuit shown in Fig. 1a. The series connected elements $R_2\left(\bar{w}\right)$ and $L_2\left(\bar{w}\right)$ represent a non-magnetic TO on the equivalent circuit with an inductive connection between coils L_1 and $L_2\left(\bar{w}\right)$. It is assumed that the elements that represent the TO depend on the vector of parameters and the characteristics $\bar{w}$ of this TO.

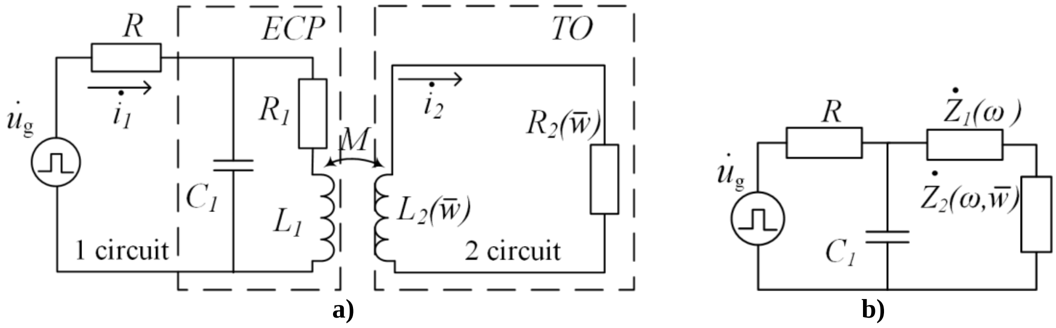


Figure 1. Equivalent circuit of the ECP-TO system with a pulse generator (a) and simplified equivalent circuit (b)

The applied method of characteristic equations [14, 18] for the solution of electric circuits shows that the introduction of TO made of non-magnetic material into the field of the coil leads to a change in its electrical parameters - active resistance and inductance, which affect three parameters of the ECP signal – attenuation α, frequency of natural oscillations ω_0 and the initial phase ν (in the presence of a frequency ω_0 reference signal). These signal parameters can be used in a pulsed EC NDT with an oscillation mode to determine the TO characteristics set.

The input resistance for the equivalent circuit of the impedance ECP - TO (Fig. 1) is determined by the expression:

$$\dot{Z}_{eq}(\omega,\bar{w}) = R + \frac{\dot{Z}_1(\omega)+\dot{Z}_2(\omega,\bar{w})}{1+\dot{Z}_1(\omega)i\omega C_1+\dot{Z}_2(\omega,\bar{w})i\omega C_1}. \quad (1)$$

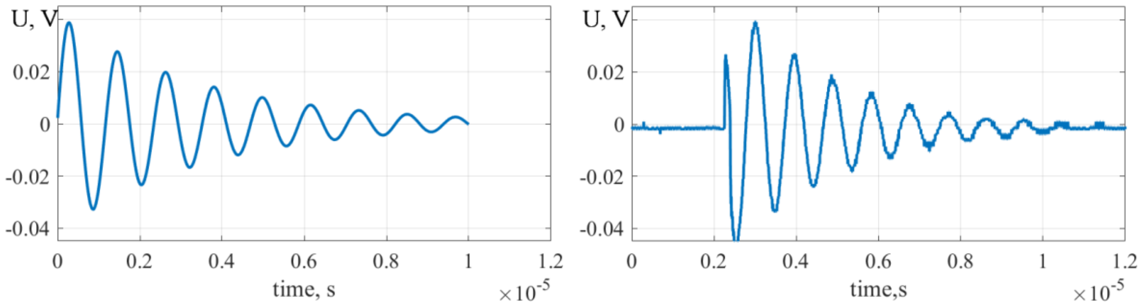
The corresponding characteristic equation of an electric circuit has a 3rd-order and is written as:

$$\begin{gathered} C_1R\left(L_1L_2(\bar{w})-M^2\right)p^3+\left(C_1RL_1R_2(\bar{w})+C_1R_1L_2(\bar{w})R+L_1L_2(\bar{w})-M^2\right)p^2+ \\ +\left(L_2(\bar{w})R+C_1R_1R_2(\bar{w})R+L_2(\bar{w})R_1+L_1R_2(\bar{w})\right)p+RR_2(\bar{w})+R_1R_2(\bar{w})=0 \end{gathered}. \quad (2)$$

As a rule, the Cardano formula is used to determine the roots of the cubic equation (2) in the domain of complex numbers [19]. The current on the ECP has the form of a decreasing harmonic oscillation in the case of complex conjugate roots, and therefore the characteristic equation roots have the general form $p_{1,2}(\bar{w}) = -\alpha(\bar{w}) \pm i\omega_0(\bar{w})$. It means that the frequency ω_0 and the attenuation α depend on the characteristics of the ECP (which is a constant) and the parameters of the TO (which change depending on the condition). Thus, the attenuation coefficient and the natural frequency of the ECP signal can be recommended as informative parameters of the pulse EC NDT.

2.2 Modeling of impedance probe signal formation

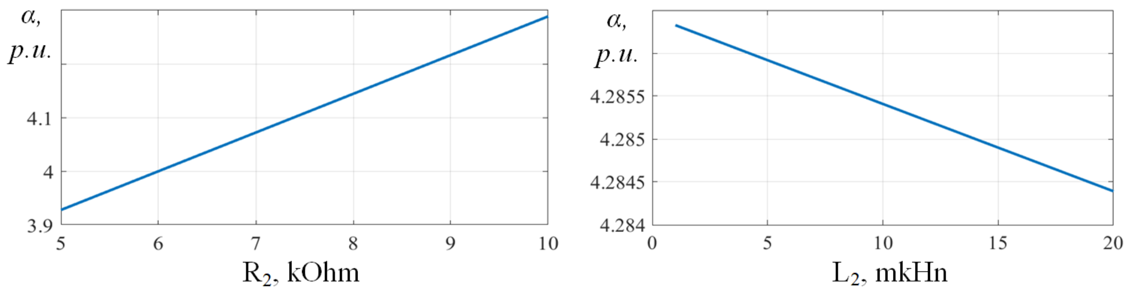
The analysis of the impedance of the circuit (Fig. 1) allows forming the physical-mathematical model of the probe signal and simulating of that signal. Fig. 2a. shows a fragment of the simulated ECP signal obtained for the model parameters: U = 0.045 V, R = 5 Ohm, C_1 = 350 pF, R_1 = 1 Ohm, L_1 = 0.1 µH. Also fragment of the experimental ECP signal is shows in Fig. 1b to comparison with simulated [14]. In this case, the relative error does not exceed 7%, which confirms the adequacy of the model.



a) **b)**

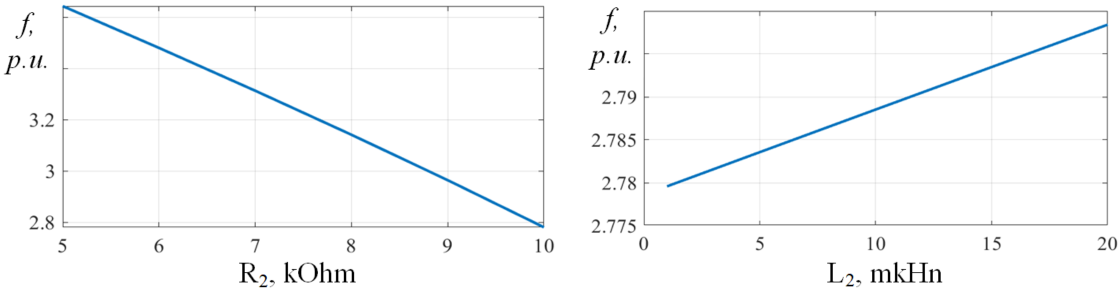
Figure 2. Fragments of simulated (a) and experimental (b) ECP signals

It is known that the effect of changing the TO characteristics to the ECP signal is described by changing the parameters R_2 and L_2 (Fig. 1), and therefore their effect can be simulated and investigated according to the proposed model. On Fig. 3 shows the results obtained in the process of researching the attenuation of the ECP signal due to the variation the TO parameters, which are represented by the active (a) and reactive (b) resistances. On Fig. 4 shows the research results of the frequency of the ECP signal due to the variation the TO parameters (also represented by a change in the active (a) and reactive (b) resistances). Data are given in relative units (p.u.).



a) **b)**

Figure 3. Dependence of ECP signal attenuation on changes in TO parameters: active (a) and reactive (b) resistances



a) **b)**

Figure 4. Dependence of ECP signal frequency on changes in TO parameters: active (a) and reactive (b) resistances

The dependences obtained by simulating have linear character and require further research and comparative analysis with experimental data. This is necessary to determine the correlation between the parameters of the electrical circuit and the specific characteristics of the TO.

3. Conclusions

The conducted modeling research of the formation processes of ECP signals with pulsed excitation mode testifies to the expediency of analyzing the conditions of decaying harmonic oscillations and shows the connection between the TO parameters and the ECP parameters. Such an approach to the analysis of ECP signals may be useful in the future for finding correlation dependencies between signal parameters and specific parameters and characteristics of the TO condition. Thus, the obtained results of the research on the formation of ECP signals allow an analytical describing the influence of the change in the TO characteristics on the electrical parameters of the ECP-TO system, which are reflected in the probe signal.

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