

РАДІОЕЛЕКТРОНІКА ТА ТЕЛЕКОМУНІКАЦІЇ

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RADIO ENGINEERING SYSTEM IDENTIFICATION OF METALS ON THE BASIS OF EDDY-CURRENT CONVERTERS

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ABSTRACT

Context. The task of creating a radio system (RS) for identifying metals in the middle of subgroups of magnetic and nonmagnetic metals based on eddy current devices (ECD) is considered. The object of study is the radio identification system.

Objective. Development of a radio system that allows you to expand the possibilities of ECP by identifying a metal in a subset of non-magnetic (copper, gold, silver, etc.) and magnetic (steel, nickel) materials.

Method. A block diagram of the RS, which uses the processing of ECD signals in the time and spectral regions, is proposed. PC allows to identify the type of metal from which the control object (CO) is made, within the subsets of non-magnetic and magnetic materials, which allows to increase the probability of detecting CO hidden in a dielectric medium, made of non-ferrous, precious or ferrous metals.

The validity of the results obtained from the verification of the technique was tested on a laboratory model of the PC, which consists of an analog eddy current part and a microcontroller with ADC to transfer data to a laptop, which implements the methods of signal processing. The article proposes the hypothesis of an informative parameter and a mathematical model that explains the causes of the signal and its form. The possibility of using RS to solve the problem of metal identification within a subset of non-magnetic and magnetic materials has been experimentally confirmed.

Conclusions. Experimental studies carried out confirmed the efficiency of the proposed RS and the methods for processing the ECP signal, the software that implements it, which allows us to recommend it for the development of devices for identifying the metal from which the test object is made. Prospects for further research are to adapt mathematical and software not only to the base of metal images, but also to create images of complex objects, which will make it possible to identify a hidden metal object and thereby expand its capabilities.

KEYWORDS: eddy current transducer, metal control objects, metal identification.

ABBREVIATIONS

RS is a radio system;
ECD is an eddy current devices;
CO is a control object;
FD is a phase detector;
OK is an object of control;
PI is a pulse induction;
VLF is a very low frequency detection.

NOMENCLATURE

M is a interdependence;
 S_{ef} is an effective area of the metal;

N_0, N_1 are numbers of turns of the corresponding coil and metal;

l is a length of sample;

U_a is a voltage at the output of the synchronous phase detector;

U_e is a voltage at the input of the phase detector;

f_e is a frequency of signal at the input of the phase detector;

f_{upr} is a frequency of reference signal;

φ is a phase shift between reference and voltage in the receiving coil;

U_{upr} is a reference voltage;

Mz is a residual's magnetization;

χ is a magnetic susceptibility, relative units;

σ is a conductivity, sm/m;

U_{IZmax} is a maximum voltage value on the antenna;

ΔU_{IZ} is a change in voltage on the receiving antenna;

V is a linear velocity of the object of control along the antenna turns;

L is a distance between receiving and transmitting antennas;

φ_{start} is a value of initial phase shift;

φ_{max} is a maximum value of the offset of the initial phase;

$\Delta\varphi$ is a change in the initial phase under the control of the object of control;

x is a discrete samples;

m is a number of samples in the sample;

$P(x)$ is a polynomial of approximation of a section from discrete readings;

A_1, A_2 are highest positive maxima of the graphic-digital image;

$K\%$ is an integral parameter that can be used to estimate the difference in signals;

S_1, S_2 are areas under the intersection of two different metals to be compared;

ΔS is a the estimated value of the difference between metals;

$f_{n1}, f_{n2}, f_{v1}, f_{v2}$ are the lower and the upper strips of the spectrum of the two metals to be compared;

Δf is a difference in spectrum width by level -40dB .

INTRODUCTION

The task of identifying the metal from which the metal objects are made are important for a number of branches of the national economy. Usually X-ray, luminescent and chemical methods are used for its solution. However, they need to clear the surface of the objects and do not allow objects to be explored remotely without damaging their surface. In addition, they require the presence of a metal object, which must be placed in the working area of the device, and do not allow the identification of hidden objects in a dielectric environment, for example, the soil. However, there are methods of detecting metal objects and devices built on the eddy current method, which allow to detect hidden objects and dichotomically (black or color) to identify the type of metal. The detected hidden object is extracted from the environment in which it is located, and then, if this is necessary, is investigated by known methods. It is a labor-intensive and complex process that requires considerable time and laboratory research.

The object of study The object of development and research is the radio engineering system of metal identification.

The subject of study The subject of research is the form of the waveform of the eddy current devices (ECD) at the output of the phase detector RS obtained from con-

trol objects made of different magnetic and nonmagnetic metals.

The purpose of the work Industrial ECD solves the problem of dichotomy identification of the objects being investigated, detecting and dividing them into two subsets (magnetic or black) and (non-magnetic or colored). However, it remains important to identify the metals in the middle of subsets, that is, the definition of the object is made of copper or gold, steel or nickel.

1 PROBLEM STATEMENT

Development of radio engineering system, which provides remote identification of metals on the basis of the previously developed methodology.

Among the set of parameters x_i characterizing the signal (amplitude, phase change of the signal during scanning, transition of the signal through zero, change of polarity, etc.), it is necessary to find those that characterize the metal as much as possible, measure their values and create a base of graphical-digital images of metals of this signal, which is an array of identification parameters $x = \{x_i\}$, $i = 1, 2, \dots, N$, where N is the number of parameters characterizing the signal and comparing it with those found in the database.

Matching the characteristics of the image of the measured signal with that in the database and is the identification criterion – P . The similarity criterion reflects the percentage similarity of the signal from the new metal to the signal from the database, where m is the percentage similarity of each of the informative parameters of the new signal to informative parameters from the database. Criterion P is calculated by averaging only the minimum values (K) of the vector m :

$$P = \sum_{k=1}^K \frac{m_k}{K}.$$

The problem of constructing and recognizing graphic-digital images of the PC output signal is considered in this article.

2 REVIEW OF THE LITERATURE

There are now a large number of ECD, including those that are produced serially. All of their plural can be divided into two classes: tonal VLF and pulse PI [1]. Devices of type PI that work with pulse signals [1] and in essence are low-frequency radar stations [1, 2, 3]. The ECD in the modern market is represented by metal detectors from the manufacturers: Minelab, Fisher, Garret [1, 3].

The tonal include devices such as VLF, which to indicate the presence of an object using the sound difference frequency between the reference and rebuilt under the influence of the object frequencies. The difference in frequency allows the operator to listen the tone of the signal to determine the object. Qualified operator can distinguish colored metal from black.

Information about the object under study is in the amplitude, phase, or frequency of the signal received by the antenna, and it is considered that one of these parameters is informative and the others are interfering.

The amplitude method [4] is widely used for signal analysis in the case when the informative parameter is the amplitude of the signal, and the interfering phase or frequency. The device tracks the amplitude of the input signal and when it reaches a certain threshold, it sends information to the indicator device indicating the presence of the object. By the amplitude of the signal, one can also determine from which metal (black or color) the object of control is made. In this case, changing the phase or frequency of the signal does not affect the readings of the metal detector. Most modern metal detectors use metal identification at the threshold level of the signal, which allows only dichotomous analysis.

Phase and frequency methods are mainly used in devices for non-destructive control of parameters of metal objects [5, 6] and are used with significant influence of the interfering factor on the amplitude of the signal. In them, the amplitude detector is replaced by phase or frequency. These two methods can also be used to search for hidden objects. So, on the principle of phase shift measurement, a metal detector CM6000-Di52HM manufactured by the US, which allows you to detect hidden metal objects.

The theoretical work on the development of methods for identifying the type of metal from which a hidden object is constructed, based on the measurement of phase shifts between reference and informative signals, are presented in [6] and [7]. However, the authors [6, 7] failed to realize the identification of metals in the middle of subsets of magnetic and nonmagnetic materials. The proposed methods allow only dichotomous identification (magnetic – nonmagnetic material). In papers [8, 9] and [10], we propose methods for processing the ECD signal, which allow the identification of metals in the middle of subgroups of magnetic and nonmagnetic materials.

The purpose of this work is to explain the features of the radio engineering system of metal identification [11], built on the basis of the eddy current detection method of metal objects, the development of a mathematical model of the output signal of the ECD and software that implements the methods of identification of metals. Unlike the known [4, 6, 7], it is possible to determine the metal from which the object of control is made from a set of nonmagnetic (gold, copper, silver) and magnetic (steel, nickel) metals. The proposed model allows to describe the signal at the output of the phase detector RS, built on the basis of circuitry solutions of the input cascades of the serial metal detector CM6000-Di52HM [11], which is further processed by the methods proposed in [8, 9, 10] and allows you to realize the goal.

3 MATERIALS AND METHODS

The basis of the ECD is the excitation of eddy currents on the surface of the investigated metal OK, which arise as a result of the interaction of the electromagnetic field provided by the radiation (transfer) coil of the antenna system. Antenna system has two coils (transmitting and receiving). Transmitter emits a low-frequency signal (frequency 6.6 kHz), and the receiving register Foucault

currents are given in OK. They cause a secondary electromagnetic field, which is recorded by the receiver coil of the antenna system, is processed by the electronic unit and transmitted to the indicator device. The signal excited by the electromagnetic field in the output coil of the antenna system of the ECD is complex and depends on the conductivity of the investigated object and its magnetic properties [6].

The basis for explaining the emergence of an informative parameter is taken by Brusini's model [7], which he proposed in his dissertation paper. It considers a mathematical model consisting of three objects (from the receiving and transmitting coils and a metal sample that moves over the coils and is the object of control). Schematically, the interaction between objects of the system is shown in Fig. 1.

The transmitter of the antenna emits a low-frequency signal that interacts with the receiving antenna directly (parasitic signal) and through an OK, which re-emitting the signal.

The input coil shows the voltage from the transmitter $U^{(p)}$ and the sample $U^{(s)}$:

$$U_2^{(p)}(t) = -i\omega M_{02} I_0 e^{i\omega t},$$

$$U_2^{(s)}(t) = -i\omega M_{12} I_1 e^{i\omega t},$$

$$I_1 e^{i\omega t} = -\frac{M_{01}}{L} \left[\frac{i\omega L(R - i\omega L)}{R^2 + \omega^2 L^2} \right] I_0 e^{i\omega t},$$

where M is a reciprocity, which is determined by the connection between the elements of the system, R is the sample resistance, L is the inductance of the sample.

Phase shift between voltages

$$\varphi(t) = \arctg \left[\frac{\text{Im}(U_2^{(p)}(t) + U_2^{(s)}(t))}{\text{Re}(U_2^{(p)}(t) + U_2^{(s)}(t))} \right],$$

$$M_{01,12} = \chi \mu_0 \frac{N_0 N_1}{l} S_{ef}, \quad \chi = \mu_r - 1, \quad M_{td} = \chi \mu_0 \frac{N_0 N_1}{l} S_{td},$$

$$td = 1, \quad f_{Disk} \cdot t_{pron}, \quad S_{td} = S_{min}, S_{max},$$

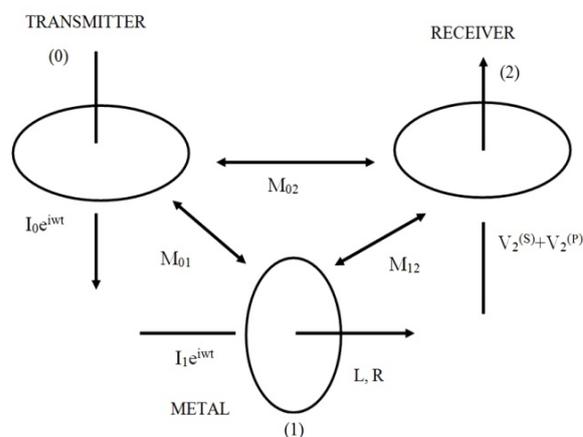


Figure 1 – Model of interaction of the investigated metal with coils of the antenna system

$$S_{\min} = 0.1 \cdot S_{zrazka}, \quad S_{\max} = S_{zrazka},$$

$$S_{zrazka} = \frac{\pi \cdot d^2}{4} = 4.9 \cdot 10^{-4} \text{ m}^2, \quad f_{Disk} = 6600 \text{ Hz},$$

$$t_{pron} = 0.073 \text{ sec},$$

where χ is a magnetic susceptibility, S_{ef} is a effective area of the metal, N_0, N_1 are number of turns of the corresponding coil and metal, l is a sample length. The parameter defining the influence of the OK on the signal in this model [5, 7] is the interinduction M , M_{02} is a technical constant determined by the flow coupling between the two coils, M_{01} та M_{12} – these are variables that depend on the properties of the sample and its position relative to the antenna coils. When the OK moves, the relationship between mutual inductances M_{01} and M_{12} changes, which is determined by the change in the effective magnetic susceptibility $\chi = \mu - 1$ and the change in conductivity σ , which is introduced into the system of connected objects.

The signal from the receiving U_e and the transmission U_{upr} of the coils comes to the FD [12], the scheme of which is shown in Fig. 2, which allocates a signal proportional to the cosine of the phase difference between U_e and U_{upr} .

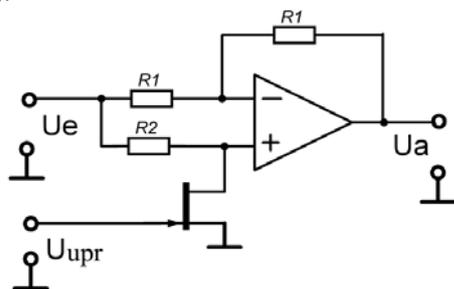


Figure 2 – Phase detector scheme [12]

Output signal FD is determined by the dependence [12]:

$$\dot{U}_a = \begin{cases} 0, & f_e \neq f_{upr}; \\ \frac{1}{2} \dot{U}_e \cos \varphi, & f_e = f_{upr}. \end{cases}$$

where U_a is a voltage at the output of the synchronous FD, U_e is a voltage at the input of the FD, f_e is a signal frequency at the input of the phase detector, f_{upr} is a frequency of the reference signal (frequency, which is emitted by the antenna system RS), φ is a phase shift between reference and voltage in the receiving coil, U_{upr} is a reference voltage.

At the output of the FD, a change in the phase shift between signals in the transmitting and receiving coils of the antenna system occurs when the OK passes over the coils. When scanning an object by antenna system, the heterogeneous object passes first over the transmission turns, between the transmitter and the receiving coils and over the receiver. The signal form on the output of the FD is shown in Fig. 3.

With further move of the antenna system over the OK from its center to the transmission coil there is a similar signal but a mirror shape. The maximum amplitude of this signal is less than the first. This is due to the residual

magnetization of OK [5, 13]. Signal at the input of the phase detector RS

$$U_e = -\frac{\partial \Phi}{\partial t} \text{ V}; \quad \Phi = \iint_S \vec{B} \cdot \vec{\partial S} \text{ Wb}; \quad B = \mu_0(H + M_z) \text{ Tl},$$

where M_z is a residual magnetization, which is determined by the magnetic and conducting properties of the control object, H is a the magnetic field strength created by the transmitting antenna.

The voltage U_e depends on the speed of the antenna passing over the OK and on the residual magnetization of the M metal from which the OK is made.

When the antenna move over the OK, there are currents Foucault whose density increases when the OK reaches the center of the coils [7]. After passing through the center of the antenna system, the metal has residual magnetization [5] and begins to interact with the other shoulder of the antenna system, which leads to a decrease in the amplitude of the signal. A difference in signal amplitudes occurs when passing one and the other antenna system shoulder. This difference is an informative parameter in the FD signal, which defines the material from which the object of control is made.

To confirm the hypothesis of the effect of residual magnetization that occurs during scanning, a signal is investigated at the output of the phase detector for OK's made of monolithic metal and from a set of thin plates isolated from each other (Fig. 4). In the experiment, a duralumin solid sample measuring 20x25x3 mm and a set of duralumin foil plates of the thickness of 0.08 mm of the same size were used.

The signals received at the output of the phase detector are shown in Fig. 5. As we see for a monolithic sample, there is a difference in signal amplitudes when passing over different shoulders of the antenna system and there is no set of plates for it, which confirms the possibility of using it as an informative parameter.

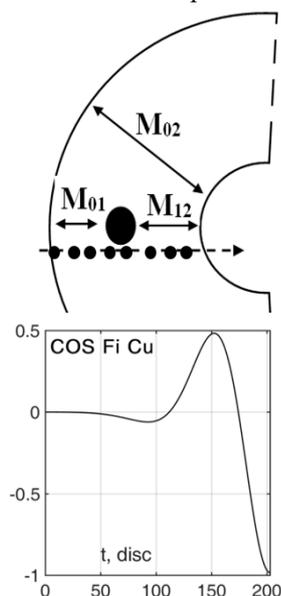


Figure 3 – To explain the shape of the signal at the output of the FD

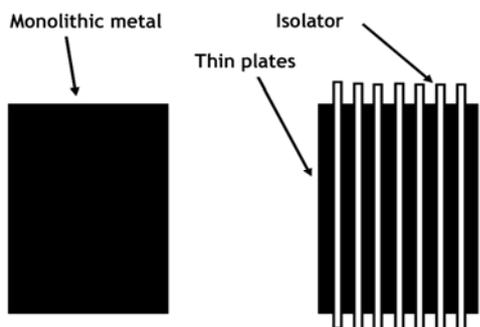


Figure 4 – Types of OK that were used to explain the effects of Foucault's currents



Figure 5 – Signals at the output of the FD for the OK from the set of plates (left) and the monolithic metal

The values of M_{01} and M_{12} and the voltage at the output of the phase detector were calculated for different locations of the OK relative to the antenna system. The results of calculating these values for duraluminium OK are given in Table 1. The coordinates of the places of accommodation were measured in relative units, where 0 is the beginning of the reference, the coordinate of the last turns of the transmission coil, and 200 is the center of the antenna system.

When the OK moves, the ratio between the mutual inductances M has changed, which is determined by the change in the effective magnetic susceptibility and the change in conductivity, is introduced into the system of connected objects. Calculations can be made for other materials. To do this, we must use the data presented in table 2. As we see the signal at the output of the FD depends on the values of the magnetic susceptibility χ , the specific conductivity σ and x – the coordinate of the position of the OK relative to the antenna, that is, is a function $U_a = f(x, \chi, \sigma)$.

Let's record the mathematical expression for the signal at the output of the phase detector, using the signals that arrive at the input of the phase detector are harmonic. This allows us to offer a mathematical expression that takes into account the characteristics of the motion of the OK relative to the antenna system coils and allows for a signal similar to the experimental. In the absence of an OK in the area of the antenna system on the receiving coil from the transmission signal is given by frequency ω , the instantaneous value of where $U_{0Z} = U_{0Z_{max}} \cos(\omega t)$,

where $U_{0Z_{max}}$ – the maximum value of the signal given in the receiving coil of the antenna system.

Table 1 – The values of M_{01} and M_{12} and the received voltage at the output of the OK

Coordinates	M_{01}	M_{12}	Voltage
0	-9,9523e-10	-1,0477e-10	-0.0000 + 0.0013i
100	-9,9502e-10	-1,0498e-10	-0.0522 - 0.1028i
150	-9,9492e-10	-1,0508e-10	0.4804 + 0.1520i
200	-9,9481e-10	-1,0519e-10	-0.9770 + 0.0567i

Table 2 – Characteristics of metals are required for calculations

Metal	χ -magnetic susceptibility, r.u.	σ -conductivity, sm/m
Steel	100	7 690 000
Nickel	100-600	11 500 000
Copper	$-9,63 \times 10^{-6}$	59 500 000
Silver	$-23,1 \times 10^{-6}$	62 500 000
Gold	$-34,4 \times 10^{-6}$	45 500 000

If the antenna system moves in parallel with the metallic OK and crosses it along the axis passing through the center of the antenna system, then the phase and amplitude of the induced signal changes at the output of the receiving coil.

The instantaneous signal value given in the receiving coil will look like:

$$U_Z = U_{1Z_{max}} \left(1 + m \cos\left(\frac{V}{L}t\right)\right) \cos(\omega t + \varphi(t)),$$

where $U_{1Z_{max}}$ is a the maximum voltage value on the antenna, $m = \frac{\Delta U_{1Z}}{U_{1Z_{max}}}$, ΔU_{1Z} is a change in voltage on the receiving antenna when passing OK over the antenna, V is a linear velocity of the OK along the antenna turns, L is a distance between receiving and transmitting antennas, $\varphi(t) = \varphi_{start} + \frac{\Delta \varphi}{\varphi_{max}}t$, φ_{start} is an initial phase shift value, φ_{max} is a maximum value of the offset of the initial phase (table 3), $\Delta \varphi$ is a change of initial phase under the action of OK.

Table 3 – Initial phase shift value

Metal	φ_{max} , deg.
Steel 10	72°
Copper electro technical	-120°

After forming U_Z by synchronous FD, a signal is proportional to the phase shifts in the antenna system, which arise due to the influence of the OK on the inter-induction between the antennas.

The synchronous detector allocates a signal that is proportional to the speed of the movement of the OK and the nature of its change. In Fig. 6 for the example shows a signal simulated for OK made from electro technical copper.

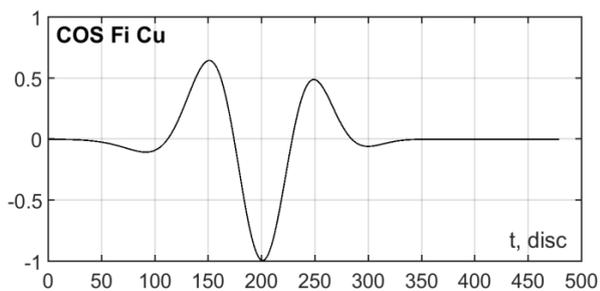


Figure 6 – Signal from copper OK, modeled on the proposed model

Further processing of the U_a signal was carried out by the methods proposed by the authors in [8, 9, 10]. This is the spectral method and the method of graphic images, the comparison criteria in which are the spectral characteristics of the received signals (for the first method) and the critical points of the time signal (for the second one). Let's consider briefly the signal processing by the method of graphic-digital images [10]. To do this, we need to digitize the signal from FD, normalize it by duration and amplitude, and transform it into a graphic image whose information parameters are the extrema of the signal and the point of transition through zero. The digitized signal is approximated by polynomial functions in the regions determined by the maxima and minima of the FD signal. For each approximation interval, we set the number of discrete points $x_{1,1}, x_{1,2}, \dots, x_{1,m}$ obtained experimentally in the process of digitizing the signal, and write the approximation interval polynomial [14–16]:

$$P(x) = a_1 + a_2x + a_3x^2 + \dots + a_{n-1}x^n.$$

Next, we convert the approximated signal into a graphic image [10, 11], in which the continuous change of the signal is replaced by characteristic lines (points of placement of extremums and zeros). Which differ in coordinates, height and polarity. The corresponding time

signals (Fig. 2) graphic images for steel and copper are presented in Fig. 7 (blue is marked by extremes, red is the point of transition through the zero level), where A_1 and A_2 are the largest positive graphic-digital image maxima.

An integral parameter that can be used to estimate the difference in signals is $K\%$ [17]:

$$K = \frac{A_1 - A_2}{A_1} \cdot 100\%.$$

Identify the type of metal and verify the correctness of the identification of the metal by the spectral method [8, 9]. The informative parameters in it are the area under the outburst spectrum and the spectrum band at the level of -40 dB of the signal taken from the FD.

The spectral density $S^*(f)$ [8] as well as the signal at the output of the FD depends on μ_r, μ_a, σ , and in the frequency region is described by the expression $S^*(f) = S(f)R(f)$, where $R(f)$ and $S(f)$ – fading factor when passing through the multilayer environment in which the OK is located and the spectrum of the signal, respectively [9].

We assume that all parameters, except for the magnetic permeability and conductivity are the same. Then the spectral density of the output signal depends only on μ_r and σ their values can be determined from which metal is made of OK.

In the proposed radio system both methods are used simultaneously, which increases the probability of identification of the metal from which the OK is made.

4 EXPERIMENTS

Experimental studies were conducted on a layout, based on which tonal VLF system was adopted (very low detection frequency). The layout diagram is shown in Fig. 8.

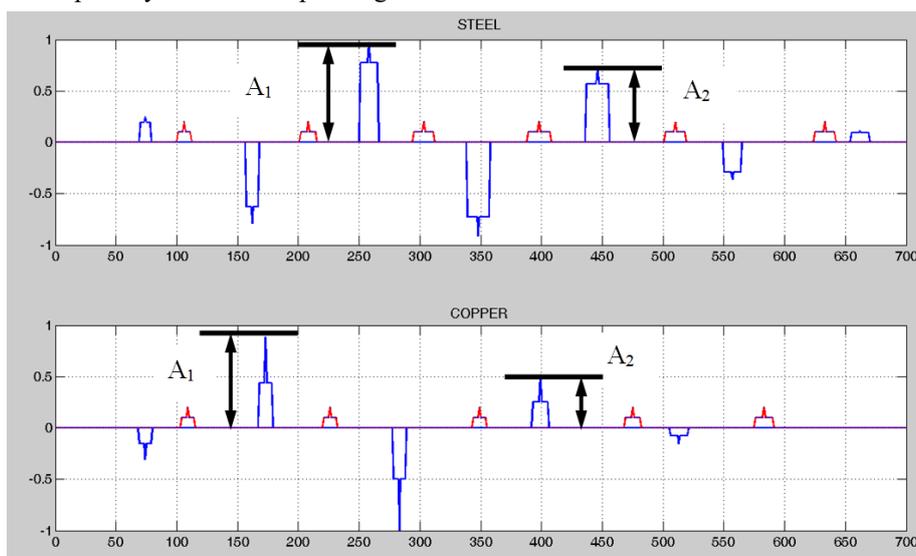


Figure 7 – Graphic images of signals of a number of steel and copper OK's (different sizes and different orientations relative to the antenna system)

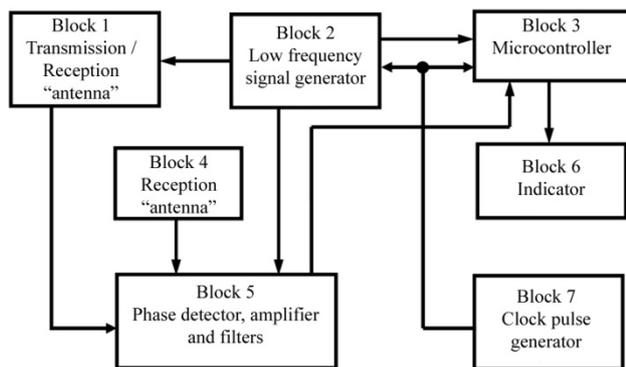


Figure 8 – The block diagram of the layout of the radio engineering system

The RS layout consists of transmitting and receiving antennas (blocks 1 and 4), a low frequency signal generator (block 2) that excite the transmitter of the antenna system, a block 5 that provides amplification and phase detection of a signal, a pulse generator (block 7) required for synchronization of the operation of the blocks of the RS, the microcontroller (block 3), which performs the normalization of the signal in amplitude and duration according to a specially developed algorithm, and the indicator block 6 necessary for processing the digitized signal in accordance with the developed x methods for assessing signals and indicating the result of identification.

The microcontroller block 3 processes the output signal of block 5 according to the method developed by the authors developed in [2, 10], which allows the identification of metals, based on the comparison of the signal taken from the output of the phase detector and recorded in the memory block of the microcontroller unit. In Fig. 9 shows the shape of the signal at the output of the FD for the OK made of steel, which is obtained theoretically and

experimentally measured on the RS model. As we see the coincidence of signals is sufficient, so that the proposed hypothesis of physical processes in the work of RS considered lawful.

In the RS model, a signal was measured at the output of the phase detector of block 5 (the input of the ADC of the AtMega32 microcontroller [18, 19] of block 3), which, with the help of the developed software, normalized the signal by amplitude and duration and transmitted to the indicator device – a laptop, which calculated the necessary parameters of identification.

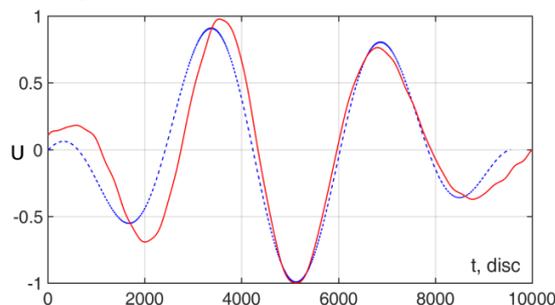


Figure 9 – Signals at the output of the FD theoretical (dashed lines) and experimental (solid line) for the OK made of steel

The values of K% for the theoretical and experimentally received signals have the following values [20]:

$$K_{theor} = \frac{0,93 - 0,80}{0,93} \cdot 100\% = 14\%;$$

$$K_{exp} = \frac{0,96 - 0,78}{0,96} \cdot 100\% = 18\%.$$

In Table 3 the characteristics of graphic images of some metals, investigated in this work (the base of graphic images) are given.

Table 3 – The coefficients of graphic-digital images for different metals

Sample name (column) and number in order of extremum (line)	1	2	3	4	5	6	7
Steel	0.3055	-0.9471	0.9461	-0.9007	0.9826	-0.5326	0.1844
Coordinates of extremes	8	18	28	36	46	57	69
Coordinates of zeros	12	23	32	41	52	65	
Copper	-0.2551	0.8720	-0.9963	0.4949	-0.1403		
Coordinates of extremes	7	18	29	41	52		
Coordinates of zeros	11	23	36	49	56		
Silver 86,8% pure	-0.2462	0.8406	-0.9917	0.5086	-0.1494		
Coordinates of extremes	7	17	28	40	50		
Coordinates of zeros	10	22	35	47	57		
Titanium	0.5026	-0.9139	1.0000	-0.5525			
Coordinates of extremes	5	14	26	35			
Coordinates of zeros	8	20	31	41			
Gold 90,0% pure	-0.2354	0.8405	-0.9624	0.5098	-0.1512	0.0540	0.0350
Coordinates of extremes	9	20	30	42	54	63	65
Coordinates of zeros	13	25	37	50	61		
Lead	-0.3122	0.9769	-0.9954	0.4797	-0.1736		
Coordinates of extremes	6	15	25	36	47		
Coordinates of zeros	1	9	20	31	43		
Bismuth	0.2011	0.2887	-0.9310	1.0000	-0.4570	0.2582	
Coordinates of extremes	3	7	16	25	36	45	
Coordinates of zeros	10	20	32	42			
Aluminum	-0.3073	0.8535	-1.0000	0.4309	-0.1411	0.0240	-0.042
Coordinates of extremes	7	18	27	38	50	57	60
Coordinates of zeros	11	22	34	46	56	58	

For each OK in the columns 1,2, ... the values and coordinates of the sequences of extremums are given, as well as the coordinates of the points of the signal passing through the zero level.

As can be seen from Table 2, each metal has a different arrangement of extremums and zero points, so their values can identify the type of metal from which the object is made. To do this, you need to create an image for an object from an unknown metal, calculate its coefficients, and compare them with those that are already in the base, and find the corresponding image, thereby determining the type of metal.

In Table 4 and 5 the spectral characteristics of the investigated materials are given [20].

5 RESULTS

The percentage difference is calculated for the areas under the bypasses according to the following formula: [8, 9]:

$$S = \left| \frac{S_1 - S_2}{S_1} \right| \cdot 100\% , \quad S_1 \geq S_2 ,$$

where S_1, S_2 is a square under the intersection of two different metals to be compared, ΔS is an estimated value of the difference between metals.

And the difference between the bands is according to the formula:

$$F_n = \left| \frac{f_{n1} - f_{n2}}{f_{n1}} \right| \cdot 100\% , \quad f_{n1} \geq f_{n2} ,$$

$$F_v = \left| \frac{f_{v1} - f_{v2}}{f_{v1}} \right| \cdot 100\% , \quad f_{v1} \geq f_{v2} ,$$

$$\Delta f = \frac{\Delta_n + \Delta_v}{2} ,$$

where $f_{n1}, f_{n2}, f_{v1}, f_{v2}$ are the lower and upper bands of the spectrum [21–23] of the two metals that to be compared, Δf is a difference in spectrum width by level -40dB [24, 25].

Table 5 – Percentage difference in parameters between copper and some other metals

Comparable metals	The difference in the areas under the bypass	The difference in the bands
Silver vs copper	7.8%	4.48%
Gold vs copper	5.6%	1.67%
Copper vs titanium	15.8%	11.96%
Copper vs lead	2.5%	1.99%
Copper vs aluminum	8.927%	7.8%

The results of identification of the metal are shown in table 6 on the example of duralumin.

Table 4 – Spectral characteristics of some investigated materials

Metal	Spectrum width by level -40dB (Hz)	S under the bypass spectrum (dB·Hz)
Steel 20	3.84 ± 0.12...23.05 ± 0.25	444.50±3.62
Copper	6.72 ± 0.08...27.48 ± 0.16	575.88±3.12
Steel and copper together	7.51 ± 0.19...26.00 ± 0.22	485.50± 4.23
Gold 90.0% pure	6.50 ± 0.15...27.99 ± 0.32	545.0 ± 4.39
Бісмут	4.89 ± 0.11... 28.46 ± 0.86	580.6 ± 10.8
Silver 99.99% pure	6.64 ± 0.10...27.00 ± 0.14	544.36 ± 3.55
Silver 90.0% pure 1 Ruble 1896y.	6.72 ± 0.04...27.55 ± 0.29	556.87 ± 4.74
Silver 90.0% pure 50 kopeck 1912y.	6.75± 0.05... 27.50±0.17	552.81+ 3.88
Silver 88.5% pure Thaler 1665y.	6.67 ± 0.09... 26.84 ± 0.19	541.30 ± 3.34
Silver 75.0% pure Thaler 1648y.	6.66 ± 0.08...27.02 ± 0.21	544.43 ± 3.00
Silver 68.3% pure 1618y.	7.09 ± 0.13...28.27 ± 0.23	553.04 ± 4.34
Nickel	9.56 ± 0.11... 26.77 ± 0.18	495.00 ± 4.50
Titanium	7.44 ± 0.29... 27.84 ± 0.36	537.66 ± 5.15

Table 6 – Results of identification of the metal

Metal benchmark	Metal new: duralumin					% similar to the standard	
	Difference %, for each of informative parameters					Spectrum. method	Time method
	1	2	3	4	5		
Metal	Polarity	S	Fn	Fv	K%		
Steel	100	21.111	44.779	20.099	72.300		
Copper	0	2.516	3.363	4.743	12.211		
Gold 90,0% pure	0	3.274	6.527	2.975	13.748		
Bismuth	100	2.853	29.679	1.346	7.681		
Silver 99,99% pure	0	3.452	4.514	6.407	16.602		
Silver 90,0% pure	0	1.322	3.363	4.501	10.754		
Nickel	100	12.148	26.491	7.204	24.385		
Titanium	100	4.694	6.533	3.495	24.385		
Duralum	0	1.156	2.246	2.489	1.475	98,29%	98,52%

The decision on the similarity of an unknown metal to an existing one is based on the matrix of differences (columns 1–5 of Table 6). The line with the largest number of minimum differences is selected (the selected positions **in bold are highlighted** in Table 6) and for this position, the percentage similarity is calculated, by averaging only the minimum values.

The number of cases of correct identification duraluminium: 45 times out of 50, the probability of 0.90.

The researches carried out on the developed experimental RS confirmed the possibility of accumulation of signals of groups of different metals and the creation of images of objects, which can be different metals.

6 DISCUSSION

The experimental studies confirmed the hypothesis about the possibility of using the eddy-current method for the identification of metals. The proposed model with a sufficient probability allows us to link the signal form at the output of the FD with the parameters of the metal from which the OK is made, as can be seen from the comparison of the calculated and experimentally taken signals.

As can be seen objects made of different materials can be identified by the difference between the two highest positive peaks in the signal FD. To do this, the processing of the signal uses a graphical-digital method, which, by the amplitudes of the maxima and their time placement, allows identification of objects of control by the type of metal from which they are made.

CONCLUSIONS

Thus, the actual task of identifying metal objects is solved by new information features detected in the form of a signal at the output of the ECD, its transformation into a graphical-digital image of a metal object, its analysis and comparison with images recorded in the memory of the eddy current radio system. The signal processing technique and the radio engineering system that implements it are developed.

The scientific novelty of the obtained results are to derive new information criteria in the output signal of the eddy current converter that characterize the metal type. It is proposed to identify metals to compare graphically-digital images of a signal obtained from an unknown metal with images recorded in a database of known metals, which allows them to be identified within the subsets of non-ferrous (non-magnetic) and ferrous (magnetic) metals. To improve the accuracy of the obtained results, it is proposed to use the spectral identification method simultaneously with the graphical-digital method.

The practical significance of the obtained results are to explain the causes of differences in the form of signals received from different metals, to create a database of graphical-digital images and to develop a layout of a radio-technical identification system, which allows to distinguish metals within the subgroups of non-ferrous and ferrous metals.

Prospects for further research is the creation of mathematical support for the implementation of spectral and graphical-digital methods of identification, development of new and effectively operating units of the radio engineering system.

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РАДІОТЕХНІЧНА СИСТЕМА ІДЕНТИФІКАЦІЇ МЕТАЛІВ НА ОСНОВІ ВИХРОСТРУМОВИХ ПЕРЕТВОРЮВАЧІВ

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АНОТАЦІЯ

Актуальність. Розглянуто задачу створення радіотехнічної системи (РС) ідентифікації металів в середині підгруп магнітних та немагнітних металів на основі вихрострумів перетворювачів (ВСП). Об'єктом дослідження є радіотехнічна система ідентифікації металів.

Метод. Розробка радіотехнічної системи, яка дозволяє розширити можливості ВСП шляхом ідентифікації металу в підмножині немагнітних (мідь, золото, срібло і інших) і магнітних (сталь, нікель) матеріалів.

Запропонована структурна схема РС, яка базується на обробці сигналів ВСП в часовій та спектральній областях, яка надає можливість ідентифікації типу металу в межах підмножини немагнітних і магнітних матеріалів, що дозволяє підвищити ймовірність виявлення прихованих в діелектричному середовищі об'єктів контролю (ОК), виготовлених з кольорових та чорних металів.

Результати. Достовірність отриманих результатів перевірки роботи методики перевірялась на лабораторному макеті РС, який складається з аналогової вихрострумової частини та мікроконтролера із АЦП для передачі даних на ноутбук, що програмно реалізує методи обробки сигналу. В статті запропонована гіпотеза виникнення інформативного параметру та математична модель, яка пояснює причини виникнення сигналу та його форму. Експериментально підтверджена можливість використання РС для ідентифікації металів в рамках підмножини немагнітних і магнітних матеріалів.

Висновки. Проведені експериментальні дослідження підтвердили працездатність запропонованої РС та методів обробки сигналів вихрострумів перетворювачів, програмного забезпечення, що його реалізує. Результати роботи дозволяють рекомендувати структуру радіотехнічної системи для розробки приладів ідентифікації металу, з якого виготовлений об'єкт контролю. Перспективи подальших досліджень полягають в адаптації математичного і програмного забезпечення не лише бази образів металів, а і для створення складних об'єктів, що дозволить ідентифікувати об'єкт, і тим самим, розширити їх функціональні можливості.

КЛЮЧОВІ СЛОВА: вихрострумів перетворювач, металеві об'єкти контролю, ідентифікація металів.

УДК 621.39

РАДИОТЕХНИЧЕСКАЯ СИСТЕМА ИДЕНТИФИКАЦИИ МЕТАЛЛОВ НА ОСНОВЕ ВИХРЕТОКОВЫХ ПРЕОБРАЗОВАТЕЛЕЙ

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АННОТАЦИЯ

Актуальность. Рассмотрена задача создания радиотехнической системы (РС) идентификации металлов в середине подгрупп магнитных и немагнитных металлов на основе вихретоковых преобразователей (ВТП). Объектом исследования является радиотехническая система идентификации.

Метод. Разработка радиотехнической системы, которая позволяет расширить возможности ВТП путем идентификации металла в подмножестве немагнитных (медь, золото, серебро и другое) и магнитных (сталь, никель) материалов.

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Предложена структурная схема РС, которая использует обработку сигналов ВТП во временной и спектральной областях. РС позволяет идентифицировать тип металла, из которого выполнен объект контроля (ОК), в рамках подмножеств немагнитных и магнитных материалов, что позволяет повысить вероятность выявления скрытых в диэлектрической среде ОК, изготовленных из цветных, драгоценных или черных металлов.

Результаты. Достоверность полученных результатов проверки работы методики проверялась на лабораторном макете РС, который состоит из аналоговой вихретоковой части и микроконтроллера с АЦП для передачи данных на ноутбук, который программно реализует методы обработки сигнала. В статье предложена гипотеза возникновения информативного параметра и математическая модель, которая объясняет причины возникновения сигнала и его форму. Экспериментально подтверждена возможность использования компьютеров для решения задачи идентификации металлов в рамках подмножества немагнитных и магнитных материалов.

Выводы. Проведенные экспериментальные исследования подтвердили работоспособность предложенной РС и методов обработки сигналов ВТП, программного обеспечения, которое его реализует, что позволяет рекомендовать ее для разработки приборов идентификации металла, из которого изготовленный объект контроля. Перспективы дальнейших исследований состоят в адаптации математического и программного обеспечения не только базы образов металлов, но и создания образов сложных объектов, что позволит идентифицировать скрытый металлический объект и тем самым расширить ее возможности.

КЛЮЧЕВЫЕ СЛОВА: вихретоковый преобразователь, металлические объекты контроля, идентификация металлов.

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