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METHOD AND DEVICE FOR THREE-PARAMETER EDDY CURRENT CONTROL OF METAL RODS

The article analyzes known non-contact one-parameter and two-parameter eddy current methods and devices for controlling the geometric magnetic and electrical parameters of metal cylindrical products. ***The subject*** *of the study is the development of a non-contact method and device, based on a transformer eddy current transducer, for the joint determination of three parameters of a metal cylindrical product, namely: diameter, magnetic permeability, and electrical conductivity.* ***The aim*** *of this work is to increase the sensitivity of three-parameter eddy current quality control of metal cylindrical products and develop a device scheme for their rejection. To achieve the aim, the following* ***tasks*** *were solved: to develop the theoretical foundations of a control method based on finding the frequency of the electromagnetic field of a transformer transducer with a rod under study, which corresponds to the extremum of the transformation function; to develop a device scheme and an algorithm for implementing the developed method; to conduct experimental studies in order to compare the results obtained by the developed method with control methods.* ***Results obtained****: the main mathematical expressions were found that link the measured parameters of the primary transducer signal with the information geometric, magnetic and electrical parameters of the controlled metal product; a device and an algorithm for implementing the proposed method were developed, based on finding the frequency of the field of the electromagnetic transducer with a rod, which corresponds to the extremum of its conversion function in the case of compensating for the influence of the air gap between the transducer and the rod; the use of extreme points of the sensor conversion functions with the product when implementing measurements allows achieving the highest sensitivity to the parameters being measured; the developed method and device allow increasing the resolution of the transducer to geometric magnetic and electrical parameters, which are 2%, 5% and 8%, respectively.* ***Conclusion:*** *the developed method and device are of great importance for the further development of multiparameter methods for quality control of metal products, in particular when conducting express analysis of material blanks, quality control of the technological process of manufacturing products, as well as selective control of reliability of operation during their operation.*

Keywords: *eddy current converter; extremum of the conversion function; metal rod.*

1. Introduction

Currently, the problem of quality control of industrial products is an urgent task. About 75% of metal structures in various industries have completed their design service life. At the same time, the aging of metal structures and equipment significantly accelerates the pace of technical equipment. Ensuring the necessary reliability of objects during operation is impossible without the use of non-destructive testing methods [1].

1.1. Motivation

The development of non-destructive testing methods for product quality, which are established by international and state standards, is an important factor for product competitiveness. Continuous quality control of materials at the supply stage, during technological operations in the manufacture of parts, as well as during their further operation ensures reliability and safety.

Compared to unproductive and expensive destructive testing methods, electromagnetic non-destructive testing is the most effective method for studying metal products. The advantages of electromagneticnon-destructive testing methods, such as high productivity, speed, multi-parameter, electrical form of the output signal, and weak dependence on ambient temperature, pressure, humidity, and contamination of the surface of the examined control objects, open up wide possibilities of its application in systems of non-contact quality control of materials and products. Primary electromagnetic transducers (EMT) are used as sensitive elements (sensors) [2].

Most often, it is necessary to determine the chemical composition of the material, recognize the steel grade, assess the hardness, strength, depth, and quality of mechanical, thermal, and chemical-thermal treatments, determine the degree of mechanical stress, control the quality of surface layers, detect intercrystalline corrosion, heterogeneity of the control objects structure, and

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determine the parameters of defects and geometric dimensions, especially in the case of environmental contamination, elevated temperatures, mechanical vibrations, and other obstacles to conducting high-quality non-contact control [3].

Important for practice was the development of methods for solving inverse electromagnetic control problems related to determining product parameters from the measured parameters of the output signal of the primary converter.

1.2. State of the art

In theoretical and practical terms, one- and two-parameter electromagnetic control methods for metal product parameters have been studied extensively. An analysis of known works has shown that a significant part of the authors focused on the development of theoretical models for simplified specific control cases or two-dimensional idealizations of the electromagnetic field using approximate calculation methods. A single approach to solving a wide range of electromagnetic control problems for various field and control object configurations has not been identified at present [4].

The use of simplified mathematical models did not allow us to fully determine the quantitative relationships between the geometric and electromagnetic characteristics of control objects because the theory of the electromagnetic method of controlling products of finite dimensions is based mainly on empirical laws. This is a significant obstacle to the use of known methods to increase the reliability of multi-parameter control.

An analysis of the available literature shows that when simultaneously determining three or more parameters of the object under study, a larger number of independent equations is necessary. This means that it is necessary to measure a larger number of electrical parameters for the converter. Such parameters can be determined in a converter operating on the basis of a method based on several fixed frequencies [5].

However, the use of this method in practice is complicated by the difficulty of synchronization in the exciting field and the separation of the output electrical parameters from the resulting signal of the converter.

An analytical solution to the nonlinear electrodynamics problem in regions with discontinuous coefficients and local anisotropy is hardly possible. In this regard, the modeling of electromagnetic processes in the implementation of electromagnetic non-destructive testing is carried out on the basis of numerical methods. As the experience of many researchers has shown, this problem cannot be solved by a simple mechanical increase in the number of selected nodes without any restrictions. The fact is that with an increase in the number of selected nodes, not only the calculation time and the rounding error increase sharply.

One of the main directions for developing non-destructive testing methods is structural analysis. The subject of non-destructive structural analysis can be changes in the state of a material caused by inhomogeneous mechanical forces. For example, as a result of hardening or any other mechanical treatment, as well as processes in metals associated with thermal, chemical-thermal treatments or hardening by high-frequency currents. The main task of electromagnetic structureoscopy is to detect differences in the structure, chemical composition, or hardness of a controlled sample according to changes in the electromagnetic characteristics [4, 6].

The problems solved by electromagnetic structureoscopy include: determining the degree of chemical purity of materials and alloys; sorting by grades, chemical composition, and other characteristics that affect the electromagnetic properties of the material; detecting parts that were processed in modes that do not meet the requirements; detecting areas of inhomogeneous structure and decarburized areas, both in the process of manufacturing parts and during their operation; detecting areas of possible destruction, assessing the susceptibility of the material to corrosion, corrosion cracking, and determining the residual strength and operating time of the part before destruction [7].

Work is being carried out to modernize low-frequency structureoscopes to expand the range of controlled material grades and their geometric dimensions, increase their reliability, and increase the average service life.

The “Förster Institute” supplies several types of structureoscopes in which the movement of sensors along the controlled surface is carried out using electric motors controlled by a computer according to a program that takes into account the shape of the part [8].

In addition, insufficient attention is paid to single-parameter methods that compensate for part of the converter signal caused by changes in an uncontrolled parameter. These methods include amplitude–phase, amplitude-phase and resonance methods [5,9].

The amplitude method, in which the informative parameter is the amplitude of the output signal of the converter, consists in the fact that the signal of a certain frequency, which is removed from the measuring winding of the converter, is rectified in amplitude, and the phase compensator reduces the influence of the phase on the control results.

The phase method, the influence of the change in the air gap between the converter and the controlled object is eliminated. The necessary direction of the amplitude vector to reduce the interfering influence factor is carried out using phase compensation devices at the output of which an informative parameter is obtained.

In the amplitude-phase method, a compensation converter with a standard sample is used along with the working converter. This method is characterized by high sensitivity and discrimination due to the determination of the change in the parameters of the controlled object compared with the parameters of the standard sample.

The above methods are based on the fact that the lines that characterize the change in parameter values on the complex plane have different directions.

Although widely used, single-parameter methods have a significant drawback: they do not allow us to obtain complete information about the control object. A diverse range of products with different physicochemical properties and geometric parameters requires the development of two- or multi-parameter control methods and devices that implement them [10,11].There are two-frequency amplitude and amplitude-phase methods of controlling one parameter, which allow reducing the influence of interfering parameters at the same time. Moreover, one of the frequencies of the probing field is used to determine the controlled parameter, and the other, usually higher, is used to compensate for the influence of the uncontrolled interfering parameter.

The most fully developed two-parameter methods are variable-frequency and fixed-frequency. The variable-frequency method consists of the need to maintain a fixed value of the generalized parameter, which combines the geometric and electromagnetic parameters of the product and the frequency of the magnetizing field. In the case of non-magnetic materials, it is necessary to maintain a fixed value of the phase of the introduced EMF of the converter at any value of the diameter of the object under study. The informative parameter is frequency.

The fixed-frequency method aims to maintain a fixed frequency value when studying controlled products with different diameters. The informative parameter in this case is the phase of the introduced EMF, by the value of which the generalized parameter is found and, together with the obtained values of the EMF (introduced or total), the necessary characteristics of the product are calculated [10].

Low-frequency structurescopes most often operate at an industrial frequency of 50 Hz and allow visual or automatic analysis of the shape of the electromagnetic transducer signal curve. To control the above characteristics, as well as to sort ferromagnetic steels by grade, devices of type VR-10P and its subsequent varieties are used. High-frequency structurescopes control the quality of ferromagnetic materials during their surface hardening, as well as the hardness of the sheet material. The carbon content in the surface layer of the product significantly changes its electromagnetic parameters in the cross-section. Abroad, structurescopes have been created that have high characteristics, and most of them are multipurpose, for example, “Magnatest” (“Förster Institute”, Germany). Universal eddy current devices with microprocessors and micro-computers enable various non-destructive testing tasks in the fields of flaw detection, structureoscopy, and thickness measurement. Devices and devices of this type are usually multi-parameter devices that allow simultaneous measurement of several parameters of control objects [12].

Eddy current methods also allow us to successfully control the geometric parameters of an object, which are required to determine other physical characteristics. This is usually the diameter of cylindrical products, the thickness of the pipe walls with one-sided access to the object, and the thickness of the layer of multilayer structures, within wide limits determined by the dimensions of the measuring coil of the converter.

In the amplitude-frequency method, to reduce the impact of the gap change, the properties of resonant circuits, including the converter coil, are also used. In this case, the circuit itself is an oscillator element [13].

Multiparameter methods are based on determining informative parameters of sensor signals and identifying their functional relationships with the electromagnetic and geometric characteristics of control objects. Such a statement of the problem requires, in the process of determining the control parameters, the mandatory use of computer technology [14].

1.3. Objectives and approach

This research aimed at developing a contactless method and device based on a transformer eddy current transducer for the joint determination of three parameters of a metal cylindrical product: diameter, magnetic permeability, and electrical conductivity.

The main tasks and stages of this research are as follows:

– stage 1. Development of a physical and mathematical model of an electromagnetic transducer, the operation of which is based on the extremum of the transformation function;

– stage 2. Calculation of the relations describing the operation of transformer-type electromagnetic transducers when determining three parameters of a cylindrical product;

– stage 3. Normalized transducer parameters that link the output signals with the characteristics of the controlled product;

– stage 4. Development of a multi-parameter control device based on the use of transformer transducers to control the magnetic permeability, specific electrical conductivity, and diameter of cylindrical products;

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– stage 5. We conducted a comparative analysis of the obtained results of controlling the parameters of the studied products using the developed method with the results of control methods;

– stage 6. Develop a device diagram and algorithm for implementing the developed method;

– stage 7. Experimental studies were conducted to compare the results obtained by the developed method with control methods;

– stage 8. Discussion of the results and formulation of recommendations for the practical use of the developed device in control systems for various technological processes of controlling product parameters during manufacture and operation.

Thus, the solution of these tasks allows, on the basis of the created multi-parameter methods and means, to obtain the most complete information about cylindrical products of various assortments by electromagnetic and geometric parameters using the same electromagnetic converter. Since electromagnetic parameters are informative, having determined them using the developed methods and devices, it is possible to solve further applied technical tasks using the correlation of these parameters with characteristics such as strength, hardness, chemical composition, temperature, and others.

Paper structure. Section 1, “Introduction”, consists of three subsections that define the motivation, current state of the problem, goal, and main stages of the research. Subsection 1.1, “Motivation”, describes the problem of quality control of industrial products, in particular metal structures in operation, using non-destructive testing methods.

In subsection 1.2, “State of the art”, we consider existing research on one-, two-, and three-parameter electromagnetic control methods for the parameters of metal products, focusing on the impossibility of using simplified mathematical models or analytical solutions to nonlinear electrodynamics problems. The direction of development of non-destructive testing methods is considered in electromagnetic spectroscopy.

In section 1.3, “Objectives and Approach”, the paper outlines specific goals for the development of a non-contact method and device, based on a transformer eddy current transducer, for the joint determination of three parameters of a metal cylindrical product, thus defining the main tasks and stages of the research.

Section 2, “Materials and Methods,” describes in detail the eddy current control methods used to determine the three characteristics (d, μ_r, σ) of the rods using indirect measurements based on the results of direct measurements of the signal parameters of a through-type transformer eddy current converter (TECC) at certain frequencies f* of its alternating magnetic field, which correspond to the extrema of its conversion functions. A method for compensating the TECC air gap was also investigated.

Section 3, “Results and Discussions”, presents the results of the experiments, mainly focusing on reducing errors compared to known methods when using the time and spatial harmonics of the exciting field and simplifying the measurement automation process.

The document ends with the section “Conclusions”, which summarizes the research results.

2. Materials and method of research

2.1. Analysis of known eddy current control methods

Known methods for determining the three characteristics (d, μ_r, σ) of rods are based on indirect measurements from direct measurements of the signal parameters of TECC of the through-type at certain frequencies f* of its alternating magnetic field, which correspond to the extrema of its conversion functions. The theoretical basis is the presence of an extrema of the dependence of the imaginary part $\mathrm{Im}\,\dot{K}$ of the complex parameter $\dot{K}$ on the generalized parameter X, and in previous studies [14, 15] various values of its X* (from 2.5 to 2.515) were given. Since the values of the extrema parameters of this function are used as constants in the formulas for calculating the controlled parameters (d, μ_r, σ) of rods, the inaccuracy of determining the value X* leads to a chain of systematic errors in their indirect measurements. Therefore, it is necessary to refine the value X*.

Experimental studies of these methods revealed a drawback associated with the significant influence of the air gap between the secondary winding of the through-hole TECC and the rod on the accuracy of the control results. This phenomenon is particularly observed when the diameter d_v of the secondary winding of the TECC exceeds the diameter d of the controlled ferromagnetic rods. In [16], a device scheme with a variometer for artificial compensation of the air gap, measuring instruments, and analog functional converters was proposed. Most of the procedures require manual work by the operator, which limits the control to only the selective type and laboratory conditions. Therefore, it is necessary to develop a device scheme that can significantly reduce manual operations and automate the control process under industrial conditions.

The important factors in the development of devices for the implementation of such control methods are the speed and accuracy of the measurement results. In many respects, they depend on the choice of the optimal method for searching for the extrema of the TECC transformation functions and accordingly the frequency f*, according to these criteria. In previous studies [14,15], a combination of the uniform search and “golden” section methods was used. Laboratory tests of metal rods made of different alloys and with different electrophysical properties showed that the disadvantages of such an algorithm are a fairly large number of iterations (tens) and relatively significant errors in determining the frequency f*. Therefore, additional studies are required to determine the optimal method.

2.2. Theoretical foundations of the method with air gap compensation of TECC

The eddy current method of simultaneous measurements of controlled parameters (d, μ_r, σ) of metal rods is based on the solution of a system of three independent equations [10, 11]

$$\begin{cases} \left(\mathrm{Im}\,\dot{K}\right)^{*} = \left(\dfrac{\mathrm{Im}\dot{E}}{E_0}\right)^{*} \cdot \dfrac{1}{\eta\mu_r} \\ X^{*} = \dfrac{d}{2}\sqrt{2\pi\mu_0\mu_r\sigma f^{*}} \\ \dot{K}^{*} = \dot{E}_f^{*}/\left(E_0^{*}\eta\mu_r\right) \end{cases}, \tag{1}$$

where $\mathrm{Im}\dot{E}$ – imaginary part of the normalized complex electromotive force (EMF) $\dot{E}$ at the terminals of the secondary winding of the TECC with a rod;

E_0 – EMF of an empty TECC, caused by the magnetic flux in the air;

η – coefficient of filling the cross-sectional area of the cavity of the secondary winding of the TECC with the cross-sectional area of the rod;

μ_0 – magnetic constant, $\mu_0 = 4\pi \cdot 10^{-7}$ Hn/m;

$\dot{E}_f$ – EMF due to magnetic flux in the body of the rod.

The filling factor η is calculated as

$$\eta = d^{\,2}/d_m^2\,, \tag{2}$$

where d_m – diameter of the measuring winding of the converter.

In the equations of system (1), the parameters corresponding to the extrema of the generalized function (3) or the transformation functions of the TECC with a metal rod (4)

$$\mathrm{Im}\,\dot{K} = F(X) \tag{3}$$

$$\frac{\mathrm{Im}\dot{E}}{E_0\,\eta\mu_r} = F(f). \tag{4}$$

The value of the imaginary part of the complex EMF quantity $\dot{E}$ is equal to (Fig.1)

$$\left|\mathrm{Im}\dot{E}\right| = E\sin\varphi_0, \tag{5}$$

where E is the measured value of the EMF at the terminals of the measuring winding of the TECC with a rod; φ_0 is the measured value of the phase shift angle between the EMF $\dot{E}$ and E_0. The distribution of the EMF vectors and other parameters of the TECC signals with a controlled rod is illustrated by the diagram (Fig. 1).

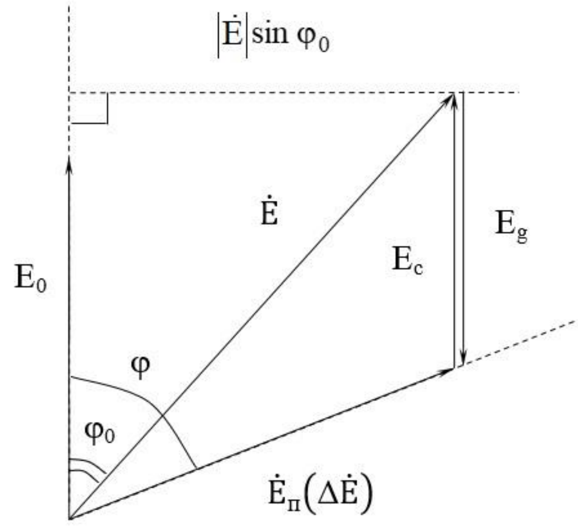

Fig. 1. Vector diagram of the EMF of a converter with a rod

Note that the first equation of system (1) is a condition for the agreement of the extrema of functions (3) and (4), which allows the correct application of the second and third equations of this system with the previously calculated values of the parameters X* and $\left|\dot{K}^{*}\right|$. Then it becomes possible to solve this system with respect to the characteristics of the controlled rod (d, μ_r, σ).

However, for this purpose, it is still necessary to measure the parameters of the TECC signal at the frequency f* of its field. Therefore, the first equation of system (1) is also the condition for its definition when its value corresponds to the value of the generalized parameter X* for a rod with specific valuesd, μ_r, σ.

To increase the accuracy of the auto-frame measurements, the extremum of the generalized transformation function was refined $\left|\mathrm{Im}\,\dot{K}\right| = F(X)$ by calculating the values of its parameters (X, module $\left|\dot{K}\right|$ and its phase angle φ), given in the table 1.

Experimental determination of frequency f^{*}. The field of the controlled rod TECC means that it is possible to immediately obtain the numerical values of the generalized parameter X^{*}=2,514999 and related quantities (Table 1) in the left-hand sides of the equations of system (1).

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Table 1

Fragment of the parameter values of the generalized transformation function $|\mathrm{Im}\,\dot{K}|=F(X)$ in the zone of its extremum

X	$\lvert\dot{K}\rvert$	φ, degree	$\lvert\mathrm{Im}\dot{K}\rvert$
2.514996	0.7236277775973	31.4403392231	0.3774518085562
2.514997	0.7236275371579	31.4403508622	0.3774518085567
2.514998	0.7236272967185	31.4403625013	0.3774518085569
2.514999	**0.7236270562792**	**31.4403741403**	**0.3774518085570**
2.515000	0.7236268158399	31.4403857794	0.3774518085569
2.515001	0.7236265754006	31.4403974184	0.3774518085566
2.515002	0.7236263349615	31.4404090574	0.3774518085561

The search was performed by searching for the extremum of the TECC transformation function

$$\left(\frac{E\sin\varphi_0}{E_0\,\eta\mu_r}\right)^{*}=F\left(f^{*}\right). \qquad (6)$$

The implementation of known methods for eddy current control of several rod parameters was carried out by two-section TECC [11,14].

In them, an alternating current I of a certain frequency *f* is passed through the primary windings to create a magnetic field for the TECC. At the terminals of the secondary windings of the first (working) section, in the cavity of which the rod is placed, an EMF arises $\dot{E}$, and the empty second (reference) section – EMF E_0, which is also the reference signal of the VSP for measuring the phase angle φ_0 (Fig. 1).

Note that the values of the coefficient η and the magnetic permeability μ_r of the rod are unchanged when the frequency f of the TECC field changes. However, they affect the steepness of the peak of the transformation functions (4) in the zone of their extrema depending on the specific values of the diameter d and the permeability μ_r of the current controlled rod, which in turn affects the accuracy of determining the frequency value f^*.

Laboratory studies of a TECC with a secondary winding diameter d_v=18.54 mm and a field strength of 46 A/m allowed us to construct its transformation functions (4) (Fig. 2) with bars made of steel grade 20 of different diameters d′, but with the same values of their electromagnetic characteristics μ_r' i σ′ which are indicated in Table 2.

Table 2

Physical characteristics of steel bars 20

Sample, №	μ_r'	σ′, MSm/m	d′, mm	η
1	81.0	2.46	5.0	0.073
2	81.0	2.46	7.0	0.143
3	81.0	2.46	10.0	0.291

These characteristics were determined using appropriate control methods. Thus, the diameter d′ was measured with a micrometer, the magnetic permeability μ_r' was determined using a F5063 ferrometer, and the specific electrical conductivity σ' – according to the P329 double DC bridge circuit. The TECC transformation functions obtained with these rods are presented in Fig. 2.

It can be seen that the nature of the change in the transformation function of sample № 1 with the smallest coefficient η (or diameter d) is very slow with a rather "blurred" zone of its extremum. However, increasing the value of η only by 2 times (for sample № 2) allows us to more accurately identify the region of its extremum, and by 4 times (for sample № 3) to significantly narrow it. At the same time, the last value of η was only 0.291, which is much less than 1 when applying the measuring winding directly to the sample. Therefore, the sharper the peak of the transformation function in the region of its extremum becomes, the more accurate and reliable the results of determining the frequency f* and the corresponding parameters of the TECC signals, and ultimately – the controlled characteristics of the rods. Therefore, another way to increase the accuracy of measurements of many parameters is to artificially increase the value of η as close as possible to 1, regardless of the diameters of the controlled rods when using the same TECC with a fixed diameter value d_v.

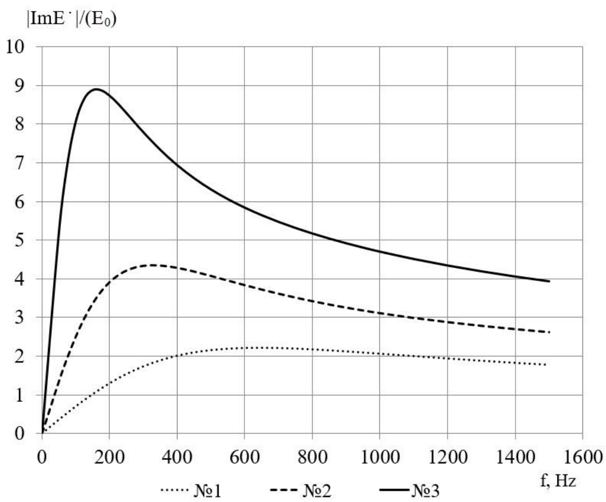

Fig. 2. Transformation functions of TECC with rods of different diameters

Research has also shown that a decrease in the magnetic permeability μ_r at stable values of d and σ of the rods leads to a flat character for the transformation functions of the TECC with them. However, unlike the coefficient η, its value at a constant magnetic field strength H cannot be artificially changed. It should be borne in mind that the value μ_r of the controlled rod can change when the strength H changes because the induction curves B=F(H) of ferromagnetic materials of the rods are generally nonlinear, with the exception of the initial section and the saturation zone [2]. Eddy current control is usually carried out at field strength values $H \leq 50$ A/m, which correspond to the initial linear section of the induction curves for most ferromagnetic steels. Therefore, during the control process, it is necessary to maintain the permissible (for the section $H \leq 50$ A/m) actual value of the alternating current I in the primary winding of the TECC, which is calculated in advance using the following formula:

$$I = H \cdot l / (\sqrt{2} W_1), \tag{7}$$

where l and W_1 are the length and number of turns of the primary windings, respectively, of each TECC section.

Let us note a characteristic feature of the transformation functions of TECC with metal rods, which is manifested in the shift of the frequency f* of the “peaks” of their extrema toward its increase with a decrease in the values of η, μ_r or σ.

The analysis of the influence of changing the parameters of metal rods on the degree of steepness of peaks in the region of extrema of the transformation functions of the TECC with them showed that the only adjustable parameter that can change the steepness of peaks is the filling factor η. Indeed, a factor influencing the accuracy of control results, especially for rods made of ferromagnetic alloys, is the presence of an air gap between the turns of the TECC secondary winding and the controlled rod. This occurs when the diameter d_v of the TECC secondary winding exceeds the diameter d of the rods and is especially evident in the case of $\eta \ll 1$.

The maximum steepness of the peaks of functions (4) is achieved when the condition $\eta=1$ is met. It can be achieved by selecting a TECC with a diameter d_v that is as close as possible to the diameter d of the controlled rod, or by artificially increasing the value η as close as possible to 1. The first approach is acceptable only for controlling rods of the same (or close) diameters, which limits the use of TECC for a specific diameter d_v.

The second way is more universal [11] and can be implemented by introducing into the two-section circuit of the TECC with working (WS) and reference (RS) sections an additional compensation section (CS) with an adjustable number of secondary turns (Fig. 3).

This allows artificially bringing the measuring winding WS (Fig. 3) closer to the diameter of the rod, thus compensating for the influence of the air gap in the TECC on the control results. At the CS terminals, it is possible to obtain the EMF of the air gap compensation $\dot{E}_c$ and direct it in the direction opposite to the EMF $\dot{E}_g$, which is caused by the magnetic flux in the air gap between the TECC winding and the rod (Fig. 1).

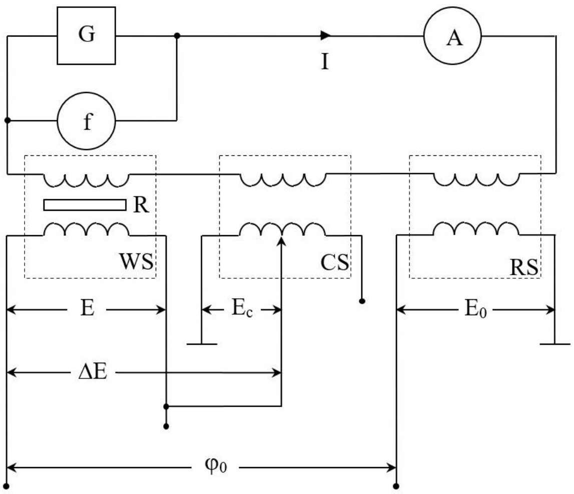

Fig. 3. Three-section TECC and its signals

Fulfilling the condition $\eta=1$ allows us to compose a system of equations in which the equality of the TECC signal parameters become valid:

$$\begin{cases} |\dot{E}_g| = |\dot{E}_c| \\ \varphi_0 = \varphi = 31.44° \\ |\dot{E}| = |\dot{E}_f| = |\Delta\dot{E}| \\ |\dot{E}^*_{0c}| = |\dot{E}_0| - |\dot{E}_c| \end{cases}, \tag{8}$$

where φ – phase angle of shift between EMF$\dot{E}_f$ and $\dot{E}_0$ (Fig. 1); $\Delta\dot{E}$ – EMF of the converter with a rod after compensation (Fig. 1, 3);

$\dot{E}^*_{0c}$ – EMF of an empty TECC, caused by the magnetic flux in the air on the size of the cross-sectional area of the controlled rod after compensation (at $\eta=1$).

It makes sense to comment on the physical essence of the equations of system (8) using a diagram (Fig. 1). The first equation corresponds to the end of the compensation of EMF $\dot{E}_g$ with the signal $\dot{E}_c$, additionally created in the opposite direction to it.

Because gap compensation occurs at the set frequency f*, at the moment of its execution the phase shift angles $\varphi_0 = \varphi$ are equal (the second equation of system (8)). However, the phase angle φ is simultaneously the angle of the complex parameter $\dot{K}$, and therefore, for the extremum of function (6), its value is 31.44° (Table 1).

The value of the EMF $\dot{E}_f$ can be measured only when the winding is applied directly to the rod.

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Therefore, when using the TECC, this operation is replaced, for example, by measuring the value of the EMF $\Delta\dot{E}$ at the terminals of the counter-connected secondary windings of its working and compensation sections (Fig. 3) after compensation, i.e., fulfilling the condition η=1. At the moment of compensation, all EMF values in the third equation of system (8) are equal. After gap compensation, the cross-sectional area of the empty TECC, through which the magnetic flux penetrates, conditionally decreased to that of the controlled rod. Accordingly, the EMF E_0 is also reduced by the value of the EMF E_c to the value of the conditional EMF E^*_{0c}, which is reflected by the fourth equation of system (8).

The value of EMF $\dot{E}_g$is usually calculated using the following formula:

$$\dot{E}_g = E_0\left(1 - \frac{d^2}{d_m^2}\right). \tag{9}$$

Considering that when compensating $|\dot{E}_g| = |\dot{E}_c|$, we obtain the ratio for calculating the diameter of the controlled rod as

$$d = d_m\sqrt{1 - \frac{E_c}{E_0}}. \tag{10}$$

From the first (or third) equation of system (1), considering the relations of system (8) and the known constants $(\mathrm{Im}\dot{K})^*$ (or $\dot{K}^*$ (Table 1), we obtain the formula for determining the magnetic permeability of the rod

$$\mu_r = 1.381927 \cdot \Delta E/(E_0 - E_c). \tag{11}$$

From the second equation of system (1)), considering formulas (10) and (11), we obtain the expression for calculating the specific electrical conductivity σ of the controlled rod as

$$\sigma = 2318786.1 \cdot E_0/\left(d_m^2 \Delta E f^*\right). \tag{12}$$

It can be seen that the formulas for calculating the controlled characteristics of the bars relate them only to the measured parameters of the TECC signal (E_c, E_0, ΔE and f*) and known constants, which significantly simplifies the control algorithm.

Select a frequency search method f^*. The search for this frequency is based on the search for the extremum of the transformation function (4), from which, taking into account (5), it is clear that when changing the frequency of the TECC field, it is necessary to measure a combination of its signal parameters: EMF E and E_0, and the phase angle φ_0 between them (Fig. 3). The accuracy of determining the frequency f* is very important, because the accuracy of measuring the parameters of the rods ultimately depends on it. Therefore, when choosing an algorithm for its determination from a number of one-dimensional search methods [17-20], the goal was to minimize the number of search iterations with a given accuracy of its determination.

Research on the simplest methods for finding the extrema of transformation functions (8) TECC, which are close to polynomials (Fig. 2), showed that the method of quadratic interpolation with three points [21] is optimal in terms of speed and accuracy of determining the frequency f*. The implementation is based on the localization of the extremum region of function (4) by the selected limiting values of the frequency of the TECC field and the task of accuracy (absolute error Δf) of determining the frequency f*. The proposed method also allows us to detect extrema of functions even outside the specified frequency interval of the search, which can be the case when there is a lack of a priori information for its determination.

If at least approximate data on the parameters are known d, μ_r, σ bars (alloy grade, magnetic properties, diameter etc.) or samples of the same type of serial production are subject to control, then it is possible to empirically significantly narrow the frequency interval for searching for the extremum, the approximate average value of which f_i is calculated by the formula

$$f_i = 3204399.284/(d^2\mu_r\sigma). \tag{13}$$

In these cases, the number of iterations can be significantly reduced to 2-3. It should be noted that the choice of the accuracy level of frequency determination f* (by setting the value of its error Δf) must be previously coordinated with the metrological characteristics of the measuring instruments of the parameters of the TECC signals, such as sensitivity, the price of the smallest digit of digital devices or the price of the division of analog instruments, measurement limits, accuracy classes (normalized errors) etc. Too small a selected value of Δf can lead to a weak change in the parameters of the TECC signals within the insensitivity zones of the corresponding measuring instruments.

Algorithm to implement the control method. The algorithm can be divided into 3 stages of measuring the parameters of the TECC signals with a rod: searching for the frequency value f*, compensating for the influence of the air gap, and determining the controlled parameters of the rod. The first two are cyclic. In the third stage, the procedure for rejecting rods can be implemented. To search for frequency f*, the quadratic interpolation algorithm with three points [21] was selected. For its implementation, 2 limit frequency values (f_a and f_b) of the uncertainty interval of the extremum of the studied function

(4) and the value f_i inside it are set, usually the average

$$f_i = \frac{(f_a + f_b)}{2}. \quad (14)$$

At these frequencies, at a stable value of the current strength I (7), the values of the EMF E and E_0 and the angle φ_0 are measured. Next, the values of the corresponding functions $F(f)=(E\sin\varphi_0)/E_0$ are calculated, they are stored, and the next i-th value f_i is determined using the method given in [21]. If its difference with the previous value f_i does not exceed the specified error of frequency determination Δf, then it is accepted as the value f* that was sought and stored. Otherwise, the cycle is repeated, but the uncertainty interval.

The compensation of the air gap effect is carried out at fixed values of the frequency f* and the field strength H of the TECC by adjusting the number of secondary turns of its compensation section (Fig. 3) until the angle φ_0=31.44° is equal (the second equation of the system (8)). Then, the values of the EMF E_k, E_0, ΔE are measured, and the controlled parameters of the rod are calculated according to formulas (10-12), the numerical coefficients, and the values of the diameter d_v of which are previously entered into the memory device.

3. Results and discussion

The experimental study of known eddy current control methods revealed a drawback associated with the significant influence of the air gap between the secondary winding of the through-hole TECC and the rod on the accuracy of the control results. An analysis of the literature on the implementation of a device for artificial compensation of air gaps by measuring instruments and analog functional converters allowed us to identify a number of complexities, features, and shortcomings of the scheme. This confirmed the relevance of the research and laid the foundation for the development of a device scheme that significantly reduced manual operations and allowed us to automate the control process under industrial conditions.

The developed method allows us to determine the geometric, magnetic, and electrical characteristics of products independently of each other by measuring the measured values of the sensor signal only at one field frequency determined for a specific product. The latter leads to a significant reduction in errors compared to known methods when using the time and spatial harmonics of the exciting field. This allows us to significantly simplify the process of measurement automation and reduces the time of computational operations.

The appearance of the primary processing device for the TECC output signals with the cylindrical product is shown in Fig. 4. After primary processing, the information from the device is sent via the USB channel to a personal computer, where it is processed to obtain and display numerical values of the informative parameters of the sample under study (d, μ_r, σ).

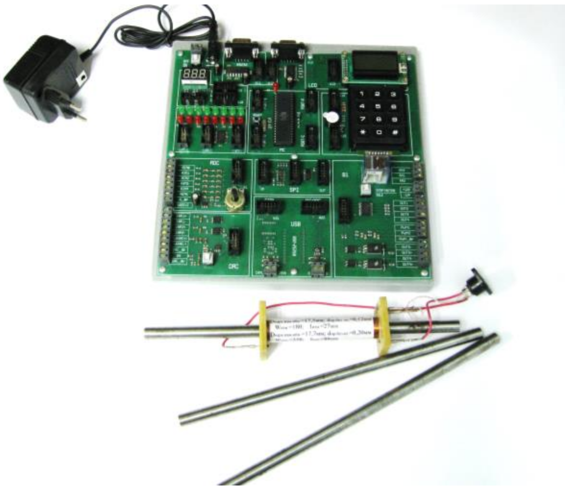

Fig. 4. Appearance of the TECC output signal primary processing board with the samples

It should be noted that the choice of the accuracy level for determining the frequency f* (by setting the value of Δf) must be coordinated with the metrological characteristics of the measuring instruments for the TECC signal parameters. Too small a value of Δf can lead to weak changes in the parameters of the TECC signals within the insensitivity zone of the measuring instruments.

The use of extreme points of the transformation functions of the sensor with the product to implement measurements allows us to achieve the highest sensitivity to the measured parameters.

Taking the full differential with respect to the generalized parameter x for expressions (10)-(12), we obtain the functional dependences of the relative sensitivities S_d = f(x), $S_{\mu r}$ = f(x) and S_σ = f(x). These dependencies over various changes in the parameter x are shown in Fig. 5.

The analysis shows that for each sample these sensitivities will be different, but by changing the current frequency, it is possible, for different combinations of parameters d, μ_r and σ of the studied sample, to obtain the value x at which the joint determination of the three parameters of the sample will be performed with the maximum relative sensitivity for each of them, which respectively have the values S_d = 0.52, $S_{\mu r}$ = 0.4 and S_σ = 0.17.

The results of determining the values of μ_r, σ and d of samples using the proposed method are in good agreement with the data of control methods (micrometric, ballistic and bridge). The proposed method also has important practical applications because it allows us to

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obtain the most complete information about the geometric, physical, and mechanical parameters of a product, such as its tensile strength, temperature, chemical composition, and grade.

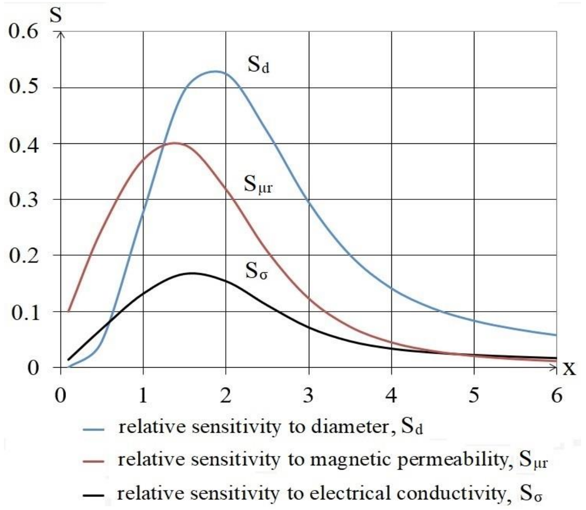

Fig. 5. Dependences of relative sensitivities on the generalized parameter x

4. Conclusions

This study considers the problem of quality control of metal products via non-destructive testing, namely, by the electromagnetic method using a transformer eddy current transducer. An analysis of the existing methods was conducted, and their main limitations were identified, in particular, the impossibility of using simplified mathematical models to accurately determine the parameters of the control objects.

A new approach to determining three parameters of a metal cylindrical product was developed: diameter, magnetic permeability, and electrical conductivity (d, μ_r, σ) with compensation for the influence of the air gap of the TECC with the rod on the measurement results. A physical and mathematical model based on the extremum of the transformation function and a method for introducing normalized parameters that allow more accurate determination of the characteristics of a controlled object are proposed.

The formulas for calculating the controlled characteristics of the rods are obtained and are associated only with the measured parameters of the TECC signal and known constants.

Based on the proposed approach, a multi-parameter control device was developed that provides high accuracy for measuring the electromagnetic and geometric parameters of products. Experimental studies were conducted, and the results confirmed the effectiveness of the developed method. A comparison with traditional control methods was conducted, which demonstrated the advantages of using a transformer eddy current transducer, in particular its non-contact nature, speed, and high sensitivity.

Thus, the proposed method and device can be widely used in production processes to ensure quality control of metal products. Further research can be aimed at improving signal processing algorithms, optimizing the design of the converter, and integrating the developed method into automated control systems for industrial production, which will contribute to increasing the efficiency and reliability of technological processes.

Contributions of authors: conceptualization, methodology – **Mykola Sirenko;** formulation of tasks, analysis **– Boris Gorkunov, Serhii Lvov;** development of method of research and device **– Mykola Sirenko, Boris Gorkunov;** analysis of results, visualization **– Boris Gorkunov, Serhii Lvov, Tetiana Drozdova;** writing – original draft preparation, writing – review and editing **– Tetiana Drozdova.**

Conflict of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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This study was conducted without financial support.

Data Availability

The work has associated data in the data repository.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods in their work.

All the authors have read and agreed to the published version of this manuscript.

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СПОСІБ І ПРИСТРІЙ ТРЬОХПАРАМЕТРОВОГО ВИХОРОСТРУМОВОГО КОНТРОЛЮ МЕТАЛЕВИХ ПРУТКІВ

М. М. Сіренко, Б. М. Горкунов, С. Г. Львов, Т. В. Дроздова

В статті проведений аналіз відомих безконтактних однопараметрових та двохпараметрових вихорострумових способів та пристроїв контролю геометричних магнітних та електричних параметрів металевих циліндричних виробів. **Предметом** дослідження є розробка безконтактного методу та пристрою, на основі трансформаторного вихрострумового перетворювача, для спільного визначення трьох параметрів металевого циліндричного виробу, а саме: діаметру, магнітної проникності та електропровідності. **Метою** даної роботи є підвищення чутливості трьохпараметрового вихорострумового контролю якості металевих циліндричних виробів і розробка схеми пристрою для їх розбракування. Для досягнення мети вирішено наступні завдання: розробити теоретичні основи способу контролю, заснованого на пошуку частоти електромагнітного поля трансформаторного перетворювача з досліджуваним прутком, яка відповідає екстремуму функції перетворення; розробити схему пристрою і алгоритм реалізації розробленого способу; провести експериментальні дослідження з метою порівняння отриманих результатів розробленим методом з контрольними методами. **Отримані результати**: знайдено основні математичні вирази, що пов’язують вимірювані параметри сигналу первинного перетворювача з інформаційними геометричними, магнітними та електричними параметрами контрольованого металевого виробу; розроблено пристрій і алгоритм реалізації цього способу, заснований на пошуку частоти поля електромагнітного перетворювача з прутком, яка відповідає екстремуму його функції перетворення в разі компенсації впливу повітряного зазору між перетворювачем та прутком; використання екстремальних точок функцій перетворення датчика з виробом при реалізації вимірювань дозволяє досягти найвищої чутливості до параметрів, які вимірюються; розроблений метод та пристрій дозволяють підвищити розрізнювальну здатність перетворювача до геометричних магнітних та електричних параметрів, які становлять 2%, 5% і 8% відповідно. **Висновок**: розроблений метод та пристрій має важливе значення для подальшого розвитку багатопараметрових методів контролю якості металевих виробів, зокрема при проведені експрес аналізу заготівок матеріалу, контролю якості технологічного процесу виготовлення виробів, а також вибірковий контроль надійності роботи при їх експлуатації.

Ключові слова: вихорострумовий перетворювач; екстремум функції перетворення; металевий пруток.

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