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Robust parameter design of eddy current meters for the electrical conductivity of materials and products of considerable thickness

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ABSTRACT

A method for increasing the signal-to-noise ratio SNR of surface eddy current conductivity meters for moving planar metal nonmagnetic (dia-, paramagnetic) and weakly magnetic test objects is proposed. This was achieved because of Taguchi's robust parameter design of probes with rectangular orthogonal coils, which helped determine their optimal modifications using the design of experiments theory. The given specific examples demonstrate the effectiveness of the method, which, in addition to increasing the SNR, also simultaneously reduces the variance of the output signal. To create a Taguchi design of experiments, a magnetodynamic model of the probe over a moving test object was used, along with the use of orthogonal arrays. The reliability of the found optimal modifications of eddy-current probes is proved by confirming computer numerical calculations. The hierarchy of the degree of influence of the design and operating parameters of probes on their signal characteristics was established by means of variance ANOVA analysis. On this basis, the technical requirements for the accuracy of manufacturing their structures and the conditions for maintaining the stability of the probe's operating modes are formulated.

1. Introduction

The structural condition of materials and products is crucial for their effective use in industry, as its analysis allows us to collect comprehensive information about them, including assessing the quality of mechanical and heat treatment operations, determining the presence of internal mechanical stresses, their strength and hardness, chemical purity, etc. Data on the structural features of conductive materials can be collected by measuring their structurally sensitive characteristics, such as electrical conductivity and magnetic permeability. A widespread non-contact method of such measurements is eddy current, which uses the effect of penetration of the generated primary electromagnetic field into the product, which creates a secondary field of eddy currents in the object. The distribution of eddy currents changes with depth due to the attenuation of the primary field in the controllable environment, allowing the inspection of object properties mainly in the subsurface layers of its material. The degree of penetration of the primary field can vary due to changes in its frequency, magnetic permeability, and electrical conductivity of the observation object. In summary, the resulting field, because of the interaction of the primary and secondary fields, is a carrier of information about the structurally sensitive characteristics of the object. However, they are not the only informative factors that influence the formation of a useful signal.

It is known that the factors that contribute to the uncertainty of these measurements include [1] curvature and roughness of the surface objects, variations in their thickness, the influence of edges, temperature, the presence of material discontinuities, heterogeneity of their electrophysical properties, and, most importantly, the lift-off changes. The situation becomes much more complicated when measurements need to be made on moving objects, which is typical, for example, when automated lines are used in the technological process. In modern electromagnetic structural spectroscopy, certain trends in the conduct of these measurements have emerged, according to which non-ferromagnetic objects are characterized by the eddy current method of determining electrical conductivity, and ferromagnets are characterized by measuring the coercive force using magnetic structural spectroscopy. At

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the same time, it is known [1] that the eddy current method can be used to testing electrically conductive weakly magnetic materials with a relative magnetic permeability $\mu_r = 1 \ldots 10$. The effects on the informative signal of magnetic permeability and electrical conductivity on magnetic samples cannot be separated, unless at very low excitation frequencies [2,3], which makes measurements challenging. Therefore, the development of methods for such measurements of electrical conductivity with noise effects on the results of variations in magnetic permeability attracts the attention of many researchers, but the approaches they propose are not ideal in implementation and require further improvement. Non-destructive eddy current testing (ECT), among other things, includes measuring the electrophysical properties of materials and products. This is done, in particular, using eddy current electrical conductivity meters, which are based on eddy current probes (ECP).

In this study, we will limit ourselves to measurements of surface transformer ECPs with rectangular orthogonal coils of conductivity planar metal nonmagnetic (dia-, paramagnetic) and weakly magnetic objects of considerable thickness that are moving.

When measuring the electrical conductivity of objects by the eddy current method, one of the central tasks to be performed to ensure their required accuracy is to completely or at least partially suppress the influence of all the previously mentioned interfering factors that affect the signal formation of probes. So, let us look at the current state of the art in approaches to addressing this issue. In the framework of this research, we will focus on eliminating such interference as lift-off variations, which are significant for magnetic and nonmagnetic objects at the same time. It is possible to reduce the influence of this factor within certain limits by using several schemes and methods of processing probe signals, in particular, resonant [4], amplitude-phase, and phase methods. The most widespread at present are phase conductivity meters [5], which, due to the insensitivity of phase characteristics, demonstrate certain acceptable results in terms of accuracy. In [6], a linear relationship was found between the lift-off probe and the coefficient of change in the inductance of the dual-frequency eddy current. On its basis, an algorithm has been proposed for reconstructing the value of the lift-off probe to the test object (TO). The reconstructed lift-off value is then used to further numerically obtain the electrical conductivity of the material at low frequency using an iterative inverse solver. A similar approach based on the use of the dual-frequency technique was proposed in [7] for the simultaneous determination of thickness and conductivity, where the result is achieved by exploring an inverse algorithm to investigate the relationship between the thickness and the perpendicular component of the magnetic flux density for different conductivities of the object. In [8], the method of eddy current measurements of the conductivity of solid metal rods was investigated. A simplified theoretical model for the coil surrounding a cylindrical sample was also obtained, and it was found that the real part of the change in its impedance at high frequency is related to the inverse of the root of the rod conductivity. Based on the relationship between the change in impedance and the conductivity of the rod, a simple and effective measurement method has been created. In [9], a simplified analytical solution was obtained based on the classical Dodd-Deeds analytical solution, according to which it was proved that the conductivity of the sample is inversely proportional to the value of the crossover frequency with phase equal to $-3\pi/4$. Consequently, the conductivity of samples can be estimated based on their characteristics. The method described in [10] aims at simultaneously estimating the conductivity and diameter of metal rods using eddy current testing with sweep-frequency excitation. It is based on the statement that the peak frequency of the imaginary part of the self-inductance variation has an inverse relationship with conductivity. At the same time, the peak frequency is also affected by the diameter of the rod. However, to separate the effects, it is shown that the real part of the change in self-induction is related at high frequencies only to the diameter of the metal rod. The research proved that by combining the peak frequency and the real part of the change in self-induction at high frequency, it is possible to simultaneously determine the conductivity and radius. In [11], a modified analytical solution for square metal plates of finite size was investigated based on the Dodd-Deeds method, and a modified analytical expansion of the eigenfunction in the truncated region was also constructed. As a result, based on the modified analytical solution, the results of conductivity and side length measurements of square metal plates with finite dimensions have been presented. In [12], a novel eddy current method based on a sweep-frequency strategy was proposed for the accurate measurement of the conductivity of metal plates. Again, the method uses a simplified theoretical model for conductivity measurement, which is derived from the classical analytical solution of Dodd-Deeds. According to the analytical solution, the real and imaginary parts of the mutual inductance signal have an intersection in the frequency domain. In the mathematical model, the corresponding frequency of the intersection, i.e., the crossover frequency is inversely proportional to the conductivity of the sample.

We would like to focus our attention on publications [13,14], which discussed methods of conductivity measurements for ferromagnetic samples and moving objects, respectively. In the first case, the measurement uncertainty increases due to possible fluctuations in magnetic permeability along with lift-off variations. Overcoming a similar problem was discussed in [6]. The second distinguishing feature is the need to take into account the speed of the sample movement in the measurement results, since this parameter can also be considered interfering if it changes uncontrollably. Thus, in [13], a sweep-frequency eddy current method was proposed to achieve simultaneous conductivity and permeability measurements, which is insensitive to lift-off changes. The relations between eddy current testing signals of different frequencies and electromagnetic parameters of magnetic materials have been found. That is, the real part of the mutual inductance at low frequencies is mainly related to permeability. The zero crossover frequency at high frequencies is proportional to the ratio of permeability and conductivity. Consequently, the conductivity and permeability of a material can be estimated simultaneously by combining the information obtained from the tests. To eliminate the lift-off interference, a compensation technique is used with the introduction of an additional pick-up coil into the probe. In [14], a method of measuring conductivity based on the use of the field of eddy currents of a moving conductor is presented, which can be used for conductive objects of arbitrary finite size. The essence of the measurement method is to first determine the density of eddy currents in the moving conductor and then consider it as an excitation source to determine the induced voltage in the pick-up coil. The conductivity of an object is directly calculated using the measured values of the induced voltage and the parameters of the conductor, including size, spatial position, speed, and coils and excitation current parameters. In fact, using this method, the conductivity can be calculated directly from the analytical expression.

Review [15] emphasizes the advantages of measuring electrical conductivity with the Pulsed Eddy Current (PEC) method, particularly highlighting the ability to determine it alongside other characteristics [3,16,17] using various inversion models. This can be achieved, as shown, for ferromagnetic and non-ferromagnetic materials, unlike the traditional single-frequency method of eddy current testing with sinusoidal excitation. This effect results from a broader frequency spectrum of the excitation signal of the PEC testing, which includes multiple frequency components in the response. Therefore, this excitation option can be considered a “simplified” implementation of multi-frequency excitation with its inherent positive properties. Because of the skin-layer depth associated with each frequency, the signal obtained from the probe carries more information about the measurement object. Thus, PEC has significant potential for use in tasks involving the reconstruction of subsurface profiles of electrical conductivity of materials, which largely determines its characteristic area of application. In addition, the broadband output signal adds efficiency in suppressing interference, since the response of each frequency has the ability to compensate for it

[18]. However, the method is not free from the disadvantages that are inherent in the entire group under consideration.

Thus, the literature review shows the main directions of modern research on solving this problem, which are mainly concentrated on processing selected probe signals, i.e., all the methods analyzed above have a common drawback, namely, insufficient attention to obtaining signals that are informatively “clean” from uncontrollable influences that interfere with measurements at the stage of their formation.

For example, PEC, as the most competitive of the methods under consideration, implies for determining conductivity a mandatory solution by one of the methods of a certain inverse problem. This [3,16,17], in turn, requires either linearization of the ferromagnets magnetization curve and elimination of the influence of the pulsed excitation magnetic field on it, or an increase in the signal-to-noise ratio, which significantly affects the accuracy of determining the area under the transient eddy current signal, etc., which, even with minor inaccuracies, lead to relatively significant errors in the inversion results. The method of solving the inverse problem, which is often characterized by the properties of ill-posed problems, is also not trivial. This should be considered a disadvantage of the PEC method.

The method proposed in [19] for PEC implementation is free from these drawbacks. It involves determining a specific similar point to the Lift-Off intersection (LOI), which is obtained from the geometric configuration of the PEC probe. The point is found because of the intersection of signals from the transient response belonging to two internal probes that are components of the ECP. The peculiar parameters of this point allow the electrical conductivity of the measurement object to be evaluated. A single measurement is sufficient to determine them. The disadvantage of this method is that it prevents changes in the lift-off from affecting the measurement results. In addition, the correctness of the point parameters determination depends on the similar characteristics of the internal probes for reception. The method is already applied at the measurement stage and requires signal processing.

One method to overcome these obstacles is the robust parameter design of eddy current conductivity meters using Taguchi optimization based on orthogonal arrays. Thanks to this approach, it is possible to find such optimal design and operating parameters of the probes that allow for increasing the signal-to-noise ratio (SNR) and simultaneously reducing the level of variations of their output signals caused by uncontrollable interfering factors. It should be noted that signals improved in this way at the generation stage can be further processed using the above methods. The authors were unable to find relevant studies on this problem other than those they own [20,21]. They obtained encouraging results for eddy current probes designed to measure other quantities. Therefore, it is advisable to transfer the experience gained to the design of electrical conductivity meters for materials and products.

Thus, the **aim** of this study is to create a method of robust parameter design of eddy current conductivity meters for planar metal nonmagnetic (dia-, paramagnetic) and weakly magnetic moving objects of considerable thickness based on Taguchi‘s optimization, which provides an increase in the SNR of surface transformer probes with rectangular orthogonal coils and reduces the variation of their signal‘s characteristics due to uncontrollable interfering factors.

2. Models and methods

2.1. Statement of the research

The conceptual formulation of the research problem is presented as follows: at the design stage of a transformer surface eddy current probe with rectangular orthogonal coils, i.e., a means of measuring the electrical conductivity of a moving planar nonmagnetic or weakly magnetic object of considerable thickness, it is necessary to find, using the Taguchi‘s robust parameter design method, such a combination of its design and operating parameters that realizes the maximum signal-to-noise ratio, while ensuring low variability of the output signal‘s characteristics without actually eliminating the effects of uncontrollable noise factors.

A detailed description of Taguchi’s optimization method is contained in numerous publications, including recent ones [22–25]. Information on the adaptation of the method for applied problems of eddy-current measurements similar to those mentioned in this study is given in the authors’ articles [20,21].

2.2. Magnetodynamic model of the measurement process

Determining the values of the output signals of probes with different variants of design and operating parameters is a necessary condition for finding the optimal combination of them, which will ensure the highest possible SNR and reduce the signal‘s characteristics variations caused by uncontrollable interfering factors. Surface transformer probes with rectangular coils are capable of creating a uniform distribution of eddy currents in the test object area with greater efficiency than circular ones [26–29], which gives them advantages.

Currently, there are known types of probes that vary in the design of the excitation system, specifically with an excitation coil placed parallel to the surface of the object and a perpendicular variant of its placement, such as a tangential meter. Depending on the shape and orientation of the pick-up coils relative to the excitation coil, the following probe designs are considered: parallel coils and orthogonal coils. The choice of one design or another is primarily determined by the ability of the excitation system to create a uniform distribution of eddy currents in the test zone, which significantly improves measurement conditions, and by the relative orientation of the pick-up coil within the meter. It is well known that tangential excitation systems generate uniform eddy currents in a conductive medium. However, research [29] shows that for coils with a small height, the zone of homogeneity is small. Increasing it requires the use of coils with significant dimensions in height, which preserves the advantages of the excitation system. However, even in such cases, the dimensions of the uniformity zone constitute a relatively insignificant part of the specified parameter. Therefore, to ensure the effective use of the overall dimensions of the excitation coil in terms of maximizing the uniformity zone of eddy currents with a priori given normalized homogeneity indicators, it is necessary to solve the corresponding inverse problem, i.e., perform optimal synthesis of the source of the exciting electromagnetic field. Practically the same can be said about the excitation system with a coil parallel to the object, as proven by research [26].

The design of probes with a coil configuration perpendicular to the surface of the object [30,31] can be considered promising, which is a type of tangential probe with all the advantages and disadvantages mentioned above. This design is characterized by the parallel arrangement of rectangular coils. Perpendicular coils placed above the conductor generate distinct eddy current distributions, offering distinct characteristics. This has enabled the creation of an effective new method of measuring conductivity based on the discovered frequency property.

Based on the above, it is advisable to combine an innovative approach with Taguchi optimization to create a modernized design of a meter with coils perpendicular to the conductor and to implement the measurement method proposed in [31] using it, which requires rather cumbersome research.

Therefore, at this stage, the authors of the article have chosen to study the structure of a transformer conductivity meter with a pair of orthogonal coils. Currently, the conventional version in the form of a parametric probe with a circular coil is more widely used. However, according to certain studies, the latter is characterized by relatively insignificant changes in the induced signal due to interaction with the measuring object, in particular, amplitudes of 3–10 % and phases of 1–3 degrees, which still need to be selected against the excitation signal. In the chosen structure of the meter, a rectangular excitation coil induces eddy currents similar to homogeneous in the object, and the pick-up coil records the electrical signal associated with the perpendicular component of the resulting electromagnetic field. Therefore, the prerogatives of probes of this structure are their self-differentiation, self-nulling, which is ensured by the compensating properties of the structure. At the same time, in the presence of a moving object, it is possible to measure the conductive properties of the material, which is further demonstrated by the results of numerical modeling.

Probe's structures with such properties have become a modern trend in measuring technology, as evidenced by the large number of publications devoted to their use in a number of studies, including [32–37], which propose various designs with and without cores. Therefore, we will focus on studying the structure of the coils of eddy current meters, after first explaining how they work. Let us assume that the pick-up coil consists of two identical segments that are symmetrical about the Oz axis (Fig. 1). If the pick-up coil is placed along the Oy axis, i.e., the distance c = 0, and the measurement object is stationary v = 0, then the EMFs induced by eddy currents in the segments are compensated each other. This is true due to the self-differentiating property of the design, under conditions of homogeneous distribution of eddy currents in the object, uniformity of the electrophysical properties of its material, its defectlessness, and significant thickness. The resulting EMF of the meter is zero in this case. If the measured object is moving, i.e., v ≠ 0, there is a redistribution of eddy currents under the segments of the pick-up coil and their higher concentration under one segment [27].In this case, the balance of the EMFs of the segments is disturbed and, accordingly, a differential signal is formed, which is proportional to their difference.

A general view of the design of this type of probe and its geometric characteristics is illustrated in Fig. 1, which also shows the structure of a moving observation object consisting of two layers of material.

This model of the sample is generalized, but its simplified partial version will be used in the following. In order to bring the model of Fig. 1 in line with the conditions defined in the research regarding the test object, in further model computer calculations, we will consider the first layers with a thickness d_1 to be absent, i.e., $d_1 = 0$. Therefore, the second layer, due to the assumed condition of a significant thickness d_2 of the sample, will be assumed to be infinitely thick $d_2 = \infty$. Its electrophysical properties, in particular, the electrical conductivity σ_2 and magnetic permeability μ_2, will be considered characteristic of the object as a whole, i.e., $\sigma = \sigma_2$ and $\mu = \mu_2$. We also assume that the object is of infinite width and length and moves with a velocity v along the Oy axis.

The excitation coil is placed parallel to the sample plane, while the pick-up coil is orthogonal to it. The rectangular excitation coil is characterized by geometric dimensions $2a_1 \times 2b_1$ and cross-section $w_1 \times h_1$. It has the number of turns N_1. The coil is located at a height z_1 above the sample surface. The current law of the multi-turn excitation coil is sinusoidal $I \cdot e^{j\omega t}$ with an angular frequency ω. The pick-up coil with dimensions $2a_2 \times 2b_2$ and height z_2 is characterized by a cross-section $w_2 \times h_2$. It has N_2 turns. The coil is displaced from the Oz axis in the direction of the Ox axis by a distance c. To model the measurement process, we chose an analytical mathematical model from [38], along with some of its refinements in accordance with [39], obtained for a two-layer object, but which can be used virtually unchanged, taking into account the above features.

At the location of the pick-up coil shown in Fig. 1, the EMF is induced by the x-component of the magnetic induction of the field.

$$E = \frac{2\omega\mu_0 I N_1 N_2}{\pi^2 w_1 h_1 w_2 h_2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\kappa k_1 k_2}{\eta^2\xi\varsigma^2}\sin\left(\frac{h_2\xi}{2}\right)e^{-j\xi c}\times\left[e^{-(2z_1+w_2+a_2)\varsigma} - e^{-(2z_1+w_2+a_2+h_1)\varsigma}\right]d\xi d\eta, \quad (1)$$

$$\kappa = \frac{\left(\frac{\gamma_1}{\varsigma}-\frac{\mu_1}{\mu_0}\right)\cdot\left(\frac{\gamma_2}{\gamma_1}+\frac{\mu_2}{\mu_1}\right)+\left(\frac{\gamma_1}{\varsigma}+\frac{\mu_1}{\mu_0}\right)\cdot\left(\frac{\gamma_2}{\gamma_1}-\frac{\mu_2}{\mu_1}\right)\cdot e^{-2\gamma_1 d_1}}{\left(\frac{\gamma_1}{\varsigma}+\frac{\mu_1}{\mu_0}\right)\cdot\left(\frac{\gamma_2}{\gamma_1}+\frac{\mu_2}{\mu_1}\right)+\left(\frac{\gamma_1}{\varsigma}-\frac{\mu_1}{\mu_0}\right)\cdot\left(\frac{\gamma_2}{\gamma_1}-\frac{\mu_2}{\mu_1}\right)\cdot e^{-2\gamma_1 d_1}},$$

$$k_1 = \frac{\sin[a_1\xi - b_1\eta + (\xi-\eta)w_1] - \sin(a_1\xi - b_1\eta)}{2(\xi-\eta)} + \frac{\sin(a_1\xi + b_1\eta) - \sin[a_1\xi + b_1\eta + (\xi+\eta)w_1]}{2(\xi+\eta)}$$

$$k_2 = \frac{\varsigma\sin\eta(b_2+w_2)\left[e^{\varsigma(w_2+a_2)}+e^{-\varsigma(w_2+a_2)}\right] - \eta\cos\eta(b_2+w_2)\left[e^{\varsigma(w_2+a_2)}+e^{-\varsigma(w_2+a_2)}\right]}{\eta^2+\varsigma^2} + \frac{\eta\cos(\eta b_2)[e^{\varsigma a_2}-e^{-\varsigma a_2}] - \varsigma\sin(\eta b_2)[e^{\varsigma a_2}+e^{-\varsigma a_2}]}{\eta^2+\varsigma^2}$$

$\gamma_1 = \sqrt{\xi^2+\eta^2 - j\sigma_1\mu_1\nu\eta + j\omega\sigma_1\mu_1}$,

$\gamma_2 = \sqrt{\xi^2+\eta^2 - j\sigma_2\mu_2\nu\eta + j\omega\sigma_2\mu_2}$, $\varsigma = \sqrt{\xi^2+\eta^2}$, ξ and η are the integration variables of the Fourier transform, $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ H/m is the magnetic constant in vacuum.

Calculations using formula (1) require numerical computer calculations of improper integrals of the first kind. The mathematical model (1) was verified by the authors of [38] by comparing the results of calculations obtained both with its use and the finite element method, which was recognized as adequate and demonstrated a fairly high accuracy. Similar results were obtained using the software created within the framework of these studies using formula (1) with the same initial data

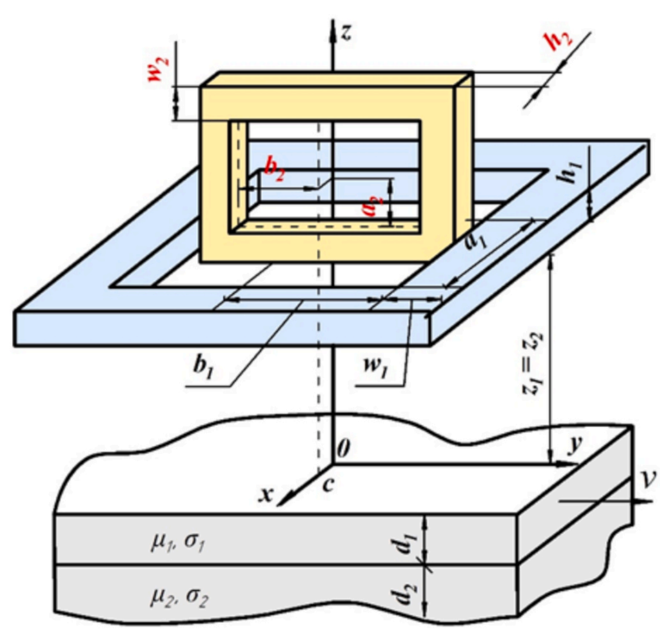

Fig. 1. Geometric model of a moving sample conductivity meter.

as in [38], and also prove its reliability.

2.3. Taguchi optimization

Optimization by the Taguchi method is performed by means of the theory of design of experiments, which involves the creation of an appropriate design known as the Taguchi design. To build it, a pair of orthogonal arrays is used, one of which determines the changes in the controllable parameters in the generated probe modifications, and the other – possible combinations of interfering factors that distort the output signals of the previously obtained probe modifications. The creation of the Taguchi design continues with the calculation values of the EMF E for each of them using formula (1). The next step is to determine the SNR values, which is performed by taking into account the "larger is better" property and using the Taguchi quality loss function [20].

The collected information on the values of the signal-to-noise ratio SNR allows you to determine the best values of the controllable parameters from their discretized set.

3. Numerical simulation results

In the following, we will consider all the stages of Taguchi's robust parameter design of the eddy current conductivity meter for two types of materials of the test object – nonmagnetic and weakly magnetic. In this case, we will consider two types of eddy current probe structures, namely, those with rectangular orthogonal coils and, additionally, the traditional one with circular coils. This is how the Taguchi design of experiments was initially created, taking into account that the controllable design parameters are all the geometric dimensions of the excitation and pick-up coils and the center distance between them, and the operating parameter is the excitation frequency. In this case, the noise factors, i.e., uncontrollable parameters, are the magnetic permeability of the material (for a weakly magnetic sample), the lift-off, and the instability of the probe speed.

The factor of material inhomogeneity of the object should also be included in the noise factor. Its influence on the meter signal is quite significant, and it is desirable to suppress it or separate it from other similar ones. However, the main idea of Taguchi's optimization method is to use complex nonlinear relationships of factors influencing the formation of the primary signal of the meter in such a way as to select the best combination of them, in which those factors that have been previously identified as harmful have the least impact on this process. In other words, the Taguchi method does not provide for the separation of the effects of harmful factors, but is tuned to a specific interference situation that occurs. Consequently, due to its uncertainty, it is not possible to take into account the inhomogeneity of the material when measuring with a probe designed using the proposed method. In the following, the article first presents a step-by-step example of designing an eddy current probe with orthogonal rectangular coils, and then, for comparison, the corresponding optimization of a transformer probe with circular coils.

Table 1
Influential parameters in electrical conductivity measurements.

Parameters	Variation range	
Excitation coil width a_1 [mm]	10–20	
Excitation coil length b_1 [mm]	16–24	
Cross-section height of the excitation coil h_1 [mm]	4–8	
Cross-section width of the excitation coil w_1 [mm]	1–4	
Pick-up coil width a_2 [mm]	3–5	
Pick-up coil length b_2 [mm]	10–14	
Cross-section height of the pick-up coil h_2 [mm]	1–2	
Cross-section width of the pick-up coil w_2 [mm]	1–2	
Inter-axial distance c [mm]	2–9	
Moving speed v [m/s]	10–30	
Excitation frequency f [kHz]	10–25	
Lift-off z_1 [mm]	0.5–1.5	
Magnetic permeability of the test object μ	nonmagnetic	weakly magnetic
	≈ 1	1–5

Table 1 shows the parameters affecting the output signal of the eddy current conductivity meter and the limits of their changes.

Thus, we have two groups of parameters: controllable and uncontrollable. Based on considerations of the number of parameters for each of the groups, it is possible to select the following acceptable orthogonal arrays $L_{32}(2^1, 4^9)$, $L_{12}(2^{12})$, $L_{50}(2^1, 5^{11})$ from the catalogs [40,41] for the first group and $L_9(4^3)$, $L_{16}(4^5)$ for the second. In addition, considering the number of gradation levels of parameters in the specified sets of orthogonal arrays, such of them, which have a larger number of them along with the provided number of experiments, are selected for further studies. In further experiments, the controllable parameters will be considered at five levels of gradation on the orthogonal array $L_{50}(2^1, 5^{11})$, and the uncontrollable parameters will be considered at four levels of gradation $L_{16}(4^5)$, respectively. However, in this study, the number of controllable and uncontrollable parameters is less than the initially specified in the selected arrays, so they were modified to the required number, i.e., two extra factors were removed from each, resulting in $L_{50}(5^{10})$ with 50 variants of probe modifications (Table 2) and $L_{16}(4^3)$, which provides 16 combinations of interfering factors (Table 3). This was done in accordance with the properties of orthogonal arrays [41]. Then, finally, the Taguchi design of experiments is obtained by combining the selected modified orthogonal arrays. It should be noted that for weakly magnetic and nonmagnetic materials, the scheme will be similar, but for the second case, it is necessary to take into account the absence of the noise parameter μ, i.e., a modified orthogonal array $L_{16}(4^2)$ is used.

Subsequently, the design of the experiment is recalculated into units of real physical quantities, and for each variant of probe modification, its output signal EMF E is determined under various variations of the influence of uncontrollable noise parameters, and the SNR value is calculated for each of them. Table 2 shows the results of these calculations for the case of a weakly magnetic sample material, taking into account the interferences listed in Table 3. To calculate the EMF according to formula (1), in addition to the design, operating, and noise parameters given in Table 1, the following initial data were set: electrical conductivity of the material $\sigma = 1.45 \cdot 10^6$ S/m, excitation current $I = 0.3$ A, number of turns $N_1 = 250$, $N_2 = 50$.

Based on the calculated values of the SNR coefficients for each of the planned experiments, taking into account the "larger is better" property, the optimal controllable parameters of the eddy current probe were determined.

Table 4 for the case of a weakly magnetic sample shows the average SNR values for each controllable parameter at all levels of its gradations and the absolute errors of its average $\Delta = (\overline{SNR}) - (\overline{SNR})^{cont}$, where $(\overline{SNR})$ is the average value of the signal-to-noise ratio of all controllable parameters, which is − 8.26 dB. At the same time, similar results were obtained for a non-magnetic sample with similar numerical SNR values.

Taking these statistical indicators into account, the optimal parameters of the probe are further searched for, which provide the highest possible SNR ratio. As a result, we found the optimal ECP designs for the cases of measuring the conductivity of both non-magnetic and weakly magnetic samples, which are identical. The design and operating parameters of the optimal meter design for both types of materials are given in Table 5.

Using a similar algorithm, the authors investigated an eddy current probe with circular excitation and pick-up coils arranged coaxially. In this case, an analytical mathematical model from [20] for a static object was used to model the measurement process, i.e., to determine the probe's EMF. In this case, the initial data were set to be as conditionally comparable as possible to the structure of the probe, which was

Table 2
Taguchi's design of experiments.

№	controllable parameters							results [V]					SNR [dB]
	a_1 [mm]	b_1 [mm]	h_1 [mm]	…	w_2 [mm]	c [mm]	f [kHz]	1	2	…	15	16	
1	10	16	4	…	1.00	2.00	10.00	0.1087	0.0807	…	0.0734	0.0775	–22.51
2	10	18	5	…	1.25	3.75	13.75	0.3502	0.2645	…	0.2362	0.2403	−12.37
3	10	20	6	…	1.50	5.50	17.50	0.7480	0.5777	…	0.5160	0.5169	−5.61
…	…	…	…	…	…	…	…	…	…	…	…	…	…
48	20	20	5	…	1.00	2.00	25.00	0.2721	0.2345	…	0.2186	0.2180	−13.14
49	20	22	6	…	1.25	3.75	10.00	0.1970	0.1633	…	0.1483	0.1450	−16.38
50	20	24	7	…	1.50	5.50	13.75	0.3728	0.3060	…	0.2774	0.2721	−10.96

Table 3
Noise variances.

Experiments	υ [m/s]	μ	z_1 [mm]
1	10	1.00	0.500
2	10	2.33	0.833
…	…	…	…
15	30	3.66	0.833
16	30	5.00	0.500

discussed above. Although this does not allow for a correct comparison of meters with different structures, it does allow for at least a general evaluation of the effectiveness of their application. Then, for this case of the ECP structure, the controllable design parameters are: the inner radius of the excitation coil R_1, the outer radius of the excitation coil R_2, the radius of the pick-up coil ρ, the height of the pick-up coil z′, the distance to the upper surface of the excitation coil g_2, and the operating parameter is the excitation frequency f; the noise parameters are the magnetic permeability of the test object μ and the lift-off z_1 [20]. The values of which varied in the range: $R_1 = 16$–17 mm, $R_2 = 17.5$–20 mm, ρ = 15–20 mm, z′ = 0.5 mm, $g_2 = 4.5$–8.5 mm, and such parameters as f, μ, σ, I, z_1 and the number of turns of the pick-up coil of the ECP were taken as for the previous probe.

Then, for the design of the experiments, we used similar orthogonal arrays and determined the output signal at various variations of the influence of noise uncontrollable parameters for the weakly magnetic material of the object. As a result, we found the optimal parameters of the probe that provide the highest possible SNR ratio (Table 6).

4. Numerical confirmation experiments and ANOVA analysis

Due to the complexity of physical experiments related to research on moving samples, the reliability of the design results was confirmed numerically. The confirmation experiments of this research are: first, to determine the maximum possible SNR value provided by the obtained optimal design, and second, to evaluate the effect of various

Table 4
Information on SNR.

Factor	a_1 [mm]					b_1 [mm]				
Level	10.00	12.50	15.00	17.50	20.00	16.00	18.00	20.00	22.00	24.00
$(\overline{SNR})^{cont}$	−7.590	−7.400	−7.714	−8.600	−9.990	−8.823	−8.394	−8.197	−8.020	−7.874
Δ	0.670	0.856	0.547	−0.338	−1.735	−0.560	−0.132	0.063	0.242	0.387
Factor	h_1 [mm]					w_1 [mm]				
Level	4.00	5.00	6.00	7.00	8.00	1.00	1.75	2.50	3.25	4.00
$(\overline{SNR})^{cont}$	−7.436	−7.858	−8.236	−8.700	−9.070	−8.064	−8.204	−8.253	−8.380	−8.040
Δ	0.825	0.403	0.024	−0.439	−0.814	0.197	0.056	0.008	−0.119	−0.144
Factor	a_2 [mm]					b_2 [mm]				
Level	3.00	3.50	4.00	4.50	5.00	10.00	11.00	12.00	13.00	14.00
$(\overline{SNR})^{cont}$	−9.317	−8.810	−8.237	−7.766	−7.177	−9.545	−8.807	−8.305	−7.575	−7.075
Δ	−1.0550	−0.5480	0.0246	0.4950	1.0840	−1.2830	−0.5460	−0.0440	0.6860	1.1870
Factor	h_2 [mm]					w_2 [mm]				
Level	1.00	1.25	1.50	1.75	2.00	1.00	1.25	1.50	1.75	2.00
$(\overline{SNR})^{cont}$	−8.243	−8.260	−8.291	−8.166	−8.347	−8.504	−8.395	−8.124	−8.242	−8.043
Δ	0.0184	0.0013	−0.0290	0.0958	−0.0860	−0.2420	−0.1330	0.1380	0.0195	0.2180
Factor	c [mm]					f [kHz]				
Level	2.00	3.75	5.50	7.25	9.00	10.00	13.75	17.50	21.25	25.00
$(\overline{SNR})^{cont}$	−15.570	−10.170	−7.096	−4.999	−3.473	−13.835	−10.315	−7.573	−5.561	−4.023
Δ	−7.308	−1.909	1.165	3.262	4.789	−5.573	−2.053	0.688	2.700	4.238

Table 5
Taguchi's parameters of the optimal design of the ECP.

Parameters	a_1 [mm]	b_1 [mm]	h_1 [mm]	w_1 [mm]	a_2 [mm]	b_2 [mm]	h_2 [mm]	w_2 [mm]	c [mm]	f [kHz]
Value	12.50	24.00	4.00	1.00	5.00	14.00	1.75	2.00	9.00	25.00

Table 6
Parameters of the optimal design of the ECP with circular coils.

Taguchi's parameters	R_1, [mm]	R_2, [mm]	ρ, [mm]	h_2, [mm]	f, [kHz]
Value	16	17.5	18.75	4.5	25

combinations of noise factors on the output signal of the probe by the Monte-Carlo method. Thus, for the first part of this experiment, for the obtained optimal parameters of the probe design, the EMF values were determined at the same variations of the influence of noise uncontrollable parameters as for the main Taguchi's experiment, and a signal-to-noise ratio of 5.33 dB was obtained. At the same time, various unoptimized ECP designs, which are represented by 50 variants of modifications in Table 2, have a much lower SNR ratio, which reaches a value from − 22.5 to 3.25 dB (Fig. 2).

For the obtained optimal structure of the eddy current probe with circular coaxial coils, the signal-to-noise ratio is − 28.7 dB. At the same time, various unoptimized designs of such a structure have an SNR ratio that reaches a value from − 29.19 to − 39.23 dB. The obtained results convincingly show the advantage of the structure of the probe with rectangular orthogonal coils, which has a much better SNR.

The second part of the confirmatory numerical experiments was conducted for a weakly magnetic sample and consisted of determining the output signals of the optimal ECP design and one of the unoptimized designs when they are subjected to noise parameters, in particular, the lift-off z_1 and magnetic permeability μ, both separately and both together.

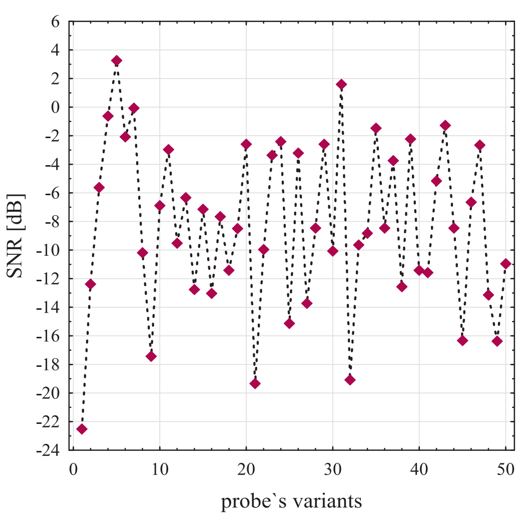

Fig. 2. SNR values for probe design variants.

Table 7
Noise factors.

№	Experiment 1	Experiment 2	Experiment 3	
	z_1 [mm]	μ	z_1 [mm]	μ
1	1.001	3.482	0.500	2.978
2	0.527	4.218	0.693	3.963
3	1.073	3.304	1.085	3.482
4	1.031	4.646	0.850	4.218
5	1.343	3.910	1.323	3.304
…	…	…	…	…
21	1.043	2.200	1.376	4.306
22	0.937	1.508	1.456	1.317
23	1.196	4.139	1.040	2.200
24	0.940	3.439	0.962	4.140
25	1.078	1.289	1.362	1.510

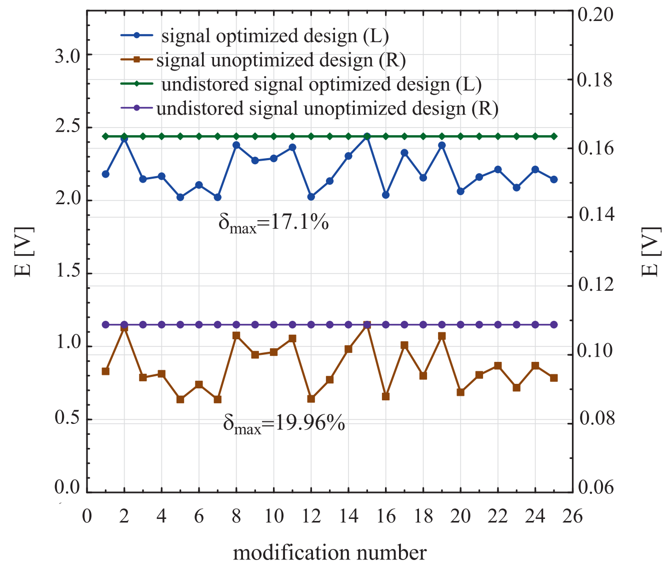

Fig. 3. Dependences of the ECP output signals on variations of lift-off z_1.

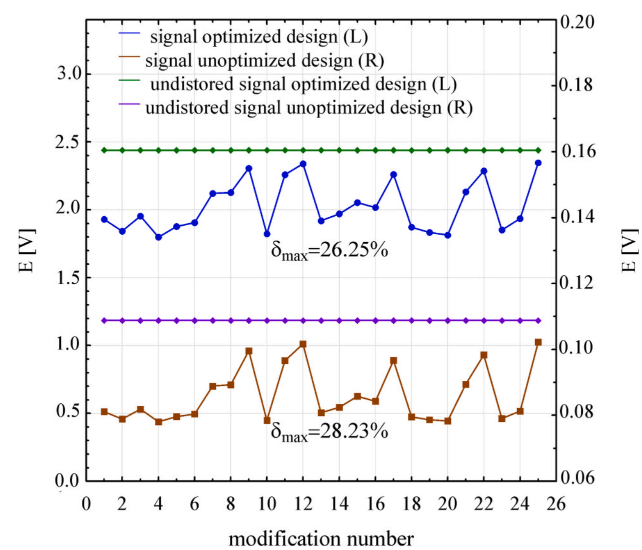

Fig. 4. Dependences of the ECP output signals on variations of magnetic permeability μ.

The signal variations around its noiseless case were determined by the Monte-Carlo method. The noise factor, the effect of which was studied, varied according to a uniform distribution law within the limits indicated in Table 1 for 25 realizations. The second noise parameter was fixed. Thus, in Experiment 1 (Table 7), the values z_1 = var, μ = 2 were used, and in Experiment 2, μ = var, z_1 = 0.5 mm. Whereas in Experiment 3, both parameters were varied simultaneously. Table 7 shows some values of the noise parameters at which these numerical experiments were performed. Figs. 3–5 shows the dependence of the output signals of the probes of the optimized and unoptimized designs on changes in the z_1 (Fig. 3), magnetic permeability μ (Fig. 4), and their combined simultaneous effect (Fig. 5).

Variance ANOVA analysis [42] is the final stage of the study, on the basis of which the statistical significance of the influence of design parameters on the resultant feature in the form of ECP signal was evaluated by Fisher's criterion. As a rule, a prerequisite for applying this analysis is to check a number of conditions, one of which is that the distribution of the initial data follows a normal law. Therefore, the output data in the form of ECP output signals for each probe variant were checked for

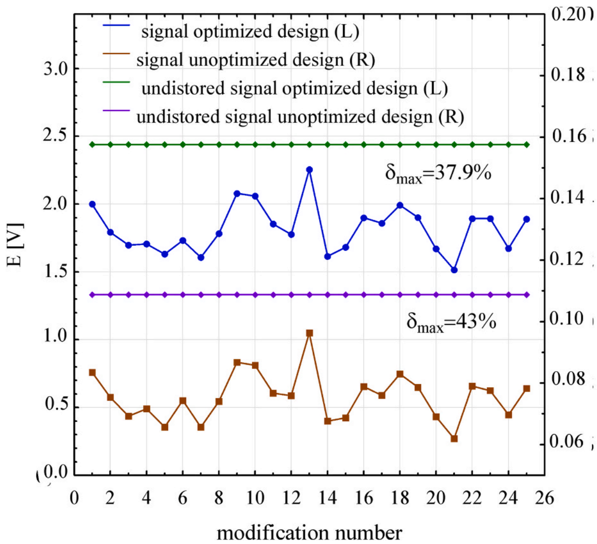

Fig. 5. Dependences of the ECP output signals on variations of the simultaneous influence of both factors z_1 and μ.

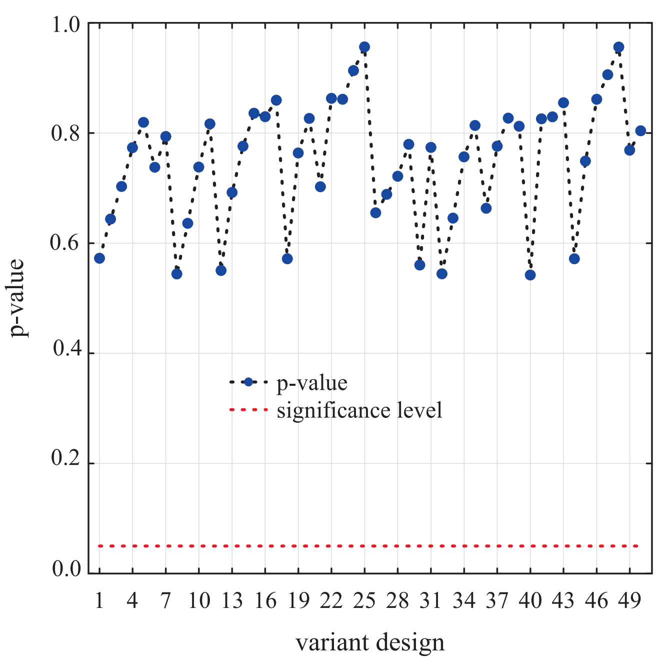

Fig. 6. Checking the normality of the distribution law of the studied data according to the p-value chart.

Table 8
Results of ANOVA-analysis.

Parameter	SS	MS	F^{exp}	p	G %
a_1	46.0871	11.5218	436.9320	0.000001	2.760
b_1	5.4590	1.3647	51.7540	0.000003	0.330
h_1	17.0025	4.2506	161.1930	0.000001	1.020
w_1	0.7699	0.1925	7.2990	0.006643	0.046
a_2	28.3547	7.0887	268.8190	0.000001	1.700
b_2	38.2551	9.5638	362.6800	0.000001	2.290
h_2	0.1779	0.0445	1.6860	0.236261	0.010
w_2	1.4354	0.3589	13.6080	0.000742	0.085
c	919.8338	229.9585	8720.5420	0.000001	55.160
f	610.0276	152.5069	5783.4050	0.000001	36.580
residual	0.2373	0.0264			

compliance with this law using the Shapiro-Wilk criterion with a significance level of α = 5 %, which is the most effective method for solving such a problem for small samples. To test the criterion, the experimental probability p-value is calculated for all variants of the ECP designs, provided that the null hypothesis is correct and is shown in Fig. 6. Obtained p-values for all fifty cases of the ECP designs significantly exceed the established level of significance, that indicates that the distribution of the studied data follows the normal law.

Subsequently, a number of statistical indicators were obtained for all controllable parameters (Table 8), such as: SS – sum of squares of the variance component and residuals, MS – mean square of the variance component and residuals, F^{exp} – variance ratio at the degree of freedom $q_1 = 4$, p – probability of random influence of the factor on the resultant trait, G – percentage contribution of each factor.

The statistical significance of the influence of each factor on the signal-to-noise ratio of the ECP is assessed by checking the condition $F^{exp} > F_{\alpha,q_1,q_2}$, where α is the accepted significance level equal to 0.05, q_1 is the number of degrees of freedom of the corresponding factor, and q_2 is the number of degrees of freedom of all random factors. If the condition is met, then the influence of the evaluated factor on the performance feature is significant, otherwise, it is insignificant. For this study, the critical value of Fisher's criterion is $F_{0.05,4,9} = 3.63$. Then, checking the condition for each factor, the insignificance of the h_2 parameter was found (Table 8). Thus, the information obtained on the degree of influence of the design and operating parameters of probes on their signal allows us to take it into account in the future when formulating requirements for the accuracy of manufacturing structures and conditions for maintaining the operation of probes.

5. Discussion and conclusion

In the study, using the examples of surfaces with rectangular orthogonal coils of eddy current conductivity meters, a computer robust design using Taguchi method was carried out, which was implemented on the basis of combining the theory of design of experiments with numerical modeling of test processes. To implement the proposed method, the software was created and verified by test calculations using the finite element method by comparing the results of calculating changes in the amplitudes of induced EMFs when varying the excitation frequency. The parameters influencing the measurement of electrical conductivity by the eddy current method have been determined and used to form a Taguchi design of experiments using modified orthogonal arrays, namely $L_{50}(5^{10})$ for controllable and $L_{16}(4^3)$ for uncontrollable ones. As a result of computer experiments, it was found that the proposed approach of robust design of the electrical conductivity meter can be applied not only to non-magnetic materials, as is usually the case in practice, but also to test objects with weakly magnetic material properties. The optimal setting of the design and operating parameters of the meters, which minimizes the influence of uncontrollable noise factors at the stage of signal formation, is determined. This is proved by comparative calculations of signal-to-noise ratios for the optimal designs of the ECP for both types of materials. It was found that the optimal design is the same and provides the maximum possible signal-to-noise ratio of 6.8 dB when the test object is nonmagnetic and 5.33 dB for the case of weakly magnetic. The reliability of the found optimal configurations of ECP designs is illustrated by confirmatory numerical experiments by comparing them with the SNR values for their unoptimized designs. In addition, by the Monte-Carlo method, experiments were performed on the effect of various noises, both individually and together, on the ECP signals of the optimal designs with an estimation of variations around their noiseless variants. For the obtained optimal designs, a decrease in the variations of the output signals is observed. For the case of a weakly magnetic sample, they ranged from 2 to 5 % compared to one of the unoptimized design variants.

And finally, the ANOVA analysis allows us to establish the hierarchy of the influence of the controllable parameters on the output signal of the probes and to formulate requirements for the accuracy of their manufacture and maintenance of the stability of the frequency mode of tests.

Additionally, the advantage of the probe‘s structure with rectangular orthogonal coils over the structure of a traditional transformer meter with a pair of circular coils is shown.

CRediT authorship contribution statement

Volodymyr Ya. Halchenko: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Ruslana Trembovetska:** Writing – review & editing, Visualization, Validation, Software, Investigation, Data curation. **Volodymyr Tychkov:** Visualization, Investigation, Formal analysis. **Viacheslav Kovtun:** Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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