Application of Taguchi Method in Design of Surface Eddy Current Probes for Diagnostics of Power Equipment

Halchenko V. Ya., Trembovetska R.V., Tychkov V.V.
Cherkasy State Technological University,
Cherkasy, Ukraine

Abstract. The article's aim is to create a method of reducing the influence on the surface eddy current probes output signal of a number of interfering parameters without their elimination, to ensure its stability, which is achieved as a result of computer search of design and operating values of probes Taguchi-parameters at the stage of their design. To achieve the goal the following tasks were carried out: software for calculating the output signal of surface probes, which is based on the electrodynamic model of the measurement process for the test object in the form of a conductive plate of infinite overall dimensions and finite thickness; using the Taguchi method, a special design of experiments with the use of orthogonal arrays is constructed, the fulfillment of which makes it possible to determine the influence of each parameter and their complex nonlinear interaction on the output signal of the probe; by integrating the Taguchi method with computer numerical simulation, the optimal controllable parameters of the probe were determined, minimizing the signal changes caused by noise factors. The most important research result is the method creation of providing the signals probes stability and reducing the influence of noise parameters on them simultaneously without their elimination. The method effectiveness is demonstrated on the example of designing a thickness gauge, which allowed computer search for a set of its optimal parameters to maximize the signal-to-noise ratio, thereby reducing the signal variability. The significance of the obtained results lies in the creation of theoretical and practical approaches to the design of surface eddy current probes with new properties of interfering factors suppression, which provide the best conditions for reliable diagnostics of power equipment objects.
***Keywords*:** Taguchi method, computer modeling, eddy current probe, noise suppression, design of experiment, orthogonal arrays, signal-to-noise ratio.

DOI: https://doi.org/10.52254/1857-0070.2024.4-64.02
UDC: 681.518.5+621.318+519.242

Aplicarea metodei Taguchi în proiectarea traductoarelor de curent turbionar montate pe patch pentru diagnosticarea echipamentelor de putere

Halicenko V.Y., Trembovețka R.V., Tycikov V.V.
Universitatea Tehnologică de Stat Cerkasy, Cerkasy, Ucraina
***Rezumat*.** Este propusă o metodă pentru reducerea influenței unui număr de parametri de zgomot simultani asupra semnalului de ieșire al sondelor de suprafață de curent turbionar. Acest lucru asigură stabilitatea sondelor de semnal cu proprietăți nou dobândite, reducând variabilitatea acestuia. Măsurile corespunzătoare sunt luate în etapa de proiect prin căutarea computerului atât a parametrilor Taguchi de proiectare, cât și de operare ai sondelor. În acest scop, se propune utilizarea integrării metodei Taguchi cu modelarea computerizată numerică. A fost creat software-ul corespunzător pentru calcularea semnalelor de ieșire ale sondelor de suprafață, care se bazează pe modelul electrodinamic al procesului de măsurare a unui obiect de testare sub formă de dimensiuni infinite și grosime finită a unei plăci conductoare. Modelul matematic, într-o formă analitică, conectează toți parametrii influenți cu un singur raport. Metoda lui Taguchi se bazează pe un design special al experimentului, a cărui implementare ne permite să determinăm efectul fiecărui parametru și interacțiunea complexă a acestora asupra semnalului de ieșire al sondei. Designul este construit folosind rețele ortogonale, ceea ce îl face mai eficient. În urma experimentelor cu procesare statistică adecvată, s-au obținut valorile parametrilor optimi ai sondei, care minimizează modificările semnalului cauzate de parametrii de zgomot. Valorile lor sunt estimate ținând cont de proprietatea „mai mare este mai bine” pentru caracteristica statistică sub forma raportului semnal-zgomot introdus de Taguchi în acest scop. Cele mai importante rezultate ale cercetării sunt crearea unei metode care să asigure, deja în faza de proiectare, stabilitatea semnalelor de ieșire ale convertoarelor și slăbirea influenței asupra acestora simultan a întregului set de parametri de zgomot fără a le suprima efectiv.
Cuvinte-cheie: metoda Taguchi, modelare computerizată, traductor de curenți turbionari, suprimarea zgomotului, proiectare experimentală, rețele ortogonale.

Применение метода Тагучи при проектировании накладных вихретоковых преобразователей для диагностики энергетического оборудования

Гальченко В.Я., Трембовецкая Р.В., Тичков В.В.
Черкасский государственный технологический университет, Черкассы, Украина

Аннотация. Цель статьи заключается в создании метода ослабления влияния на выходной сигнал ряда препятствующих измерениям накладными вихретоковыми преобразователями параметров без их физического устранения, обеспечения его стабильности, что достигается в результате компьютерного поиска конструктивных и режимных значений Тагучи-параметров преобразователей на этапе их проектирования. Для достижения поставленной цели выполнялись следующие задачи: создано программное обеспечение для расчета выходного сигнала накладных преобразователей, в основе которого заложена электродинамическая модель процесса измерений для объекта контроля в виде токопроводящей пластины бесконечных габаритных размеров и конечной толщины; с использованием метода Тагучи построен специальный план экспериментов с применением ортогональных массивов, выполнение которого позволяет определить влияние каждого параметра и их сложного нелинейного взаимодействия на выходной сигнал преобразователя; интеграцией метода Тагучи с компьютерным численным моделированием определены оптимальные контролируемые параметры преобразователя, сводящие к минимуму изменения сигнала, вызванные шумовыми факторами. Оценка оптимальных значений продуктивных параметров проектирования выполняется с учетом свойства «larger is better» для статистической характеристики в виде отношения сигнал/шум, введенной для этого. Важнейшими результатами исследований является создание метода обеспечения уже на этапе проектирования устойчивости выходных сигналов преобразователей и ослабление влияния на них одновременно всей совокупности шумовых параметров без их фактического устранения. Продемонстрирована эффективность предложенного метода на примере проектирования вихретокового толщиномера, что позволило компьютерным поиском совокупности его оптимальных конструктивных и режимных параметров максимизировать отношение сигнал/шум, тем самым уменьшив вариабельность сигнала и его зависимость от помех. Значимость полученных результатов заключается в создании теоретических и практических подходов к проектированию накладных вихретоковых преобразователей с новыми свойствами подавления мешающих факторов, которые обеспечивают наилучшие условия для надежной диагностики объектов энергетического оборудования.

Ключевые слова: метод Тагучи, компьютерное моделирование, вихретоковый преобразователь, подавление шумов, план экспериментов, ортогональные массивы.

INTRODUCTION

The operational safety, reliability, and durability of power equipment largely depend on timely and reliable monitoring and diagnostics of the condition of its components [1-3]. Technical diagnostics of energy facilities are usually carried out by non-destructive testing methods, one of which is eddy current, which is realized as a result of the interaction of an external electromagnetic excitation field and a secondary field of eddy currents induced in the test object (TO) [4-6]. In this case, changes in the condition of power equipment are recorded by eddy current probes (ECPs), in particular, surface.

The demand for eddy current testing in the energy sector proves by a set of modern publications, in particular, those devoted to the diagnostics of certain elements of NPP steam generators [7, 8]. The output signal of the ECP, i.e., the EMF, is a carrier of information on a number of TO parameters and other factors of influence, which can be conditionally divided into controllable productive and interfering, i.e., noise, factors according to their usefulness in its formation. Moreover, depending on the parameter measured by the ECP, the influencing factors may move from one of these groups to another. Thus, avoiding the influence of noise factors on the formation of the probe signal or at least its significant reduction is a very important problem in the practical implementation of eddy current testing [9].

Effective testing of a certain measured parameter is possible if the sensitivity of the probe to it is significantly lower than to other parameters that are not currently measurable. In the case of only one noise factor, the problem is solved by selecting the operating point of the ECP on the complex plane, which is performed as a result of a deep analysis of the complex dependencies of the output signal on the measured and noise parameters under harmonic excitation of the probe [10, 11]. In multi-parameter cases when there are more than two noise factors, which is almost always the case, the task becomes much more complicated and requires the use of cumbersome mathematical calculation methods along with measurements either at different excitation frequencies [12] or with a set of pick-up coils of different radii or with their placement at different heights above the TO. Thus, solving this problem requires finding new, more advanced and easy-to-use ways to mitigate the impact of measurement noise parameters.

It should be noted that this aim can be achieved at the design stage of the ECP using the Taguchi method, which has been widely used and proven effective in many technical applications, including non-destructive testing [13, 14]. However, the authors did not find any information on its involvement in the design of the ECP in scientific sources. Whereas the method can control the variability of the ECP output signal by optimizing the input parameters, i.e., it makes it possible to obtain a stable signal even in the presence of factors that affect its variation. The method is based on a special design of experiments, the implementation of which allows us to determine the effect of each parameter and, most importantly, their complex interaction of the output signal of the ECP. As a result of the experiments, the values of Taguchi-parameters are obtained, i.e., the optimal controllable parameters of the probe that minimize signal changes caused by noise parameters. It is also important to minimize the number of experiments within the design of the experiments, which is ensured by using some types of orthogonal arrays to create them, which are most adapted to the designed specific version of the ECP design. In general, this is determined by the number of controllable productive and noise parameters, as well as the number of graded levels of their representation in the designs of the relevant experiments. The results obtained using orthogonal arrays are almost as good as those obtained using full-factor experiments. This is possible due to their fundamental property by providing a balanced and fair comparison of levels for any parameters. Therefore, the Taguchi method implements a statistical approach that allows you to gain important knowledge about a complex multivariate measurement process. The method was created as an experimental one, but to determine the output signal of the ECP, the values obtained by computer calculations according to the corresponding mathematical model of the measurement process can be included in the design of experiments. That is, the Taguchi method is integrated with computer numerical modeling. The method involves the use of a certain loss function, i.e., the fitness-function *Fitness*, which is interpreted as the deviation of the characteristic under study from its desired target and which is calculated from the responses to the data set contained in the experiment design table. Subsequently, its values are transformed in accordance with [15, 16] into the signal-to-noise ratio used for optimization, i.e., finding such a combination of the set of values of the controllable productive parameters of a particular grading level to have the largest average response:

$$S/N = -10\log_{10}(Fitness) \quad (1)$$

Where $Fitness = \frac{1}{n}\cdot\sum_{i=1}^{n}\frac{1}{y_i^2}$, y_i is the output signal of the probe.

The verification of the truth of the found Taguchi-parameters of the ECP design is carried out by conducting a test experiment to ensure that the found values improve the value of the S/N ratio compared to its analogues at the initial values of the corresponding parameters.

Therefore, taking into account all of the above, the purpose of the article is to create a method for mitigating the effect on the output signal of a number of parameters that noise with measurements by surface ECPs without their physical elimination and ensuring its stability, which is achieved as a result of a computer search for both design and operating values of the Taguchi-parameters of probes at the design stage.

I. PROBLEM STATEMENT

To implement the method, the design environment of performance and noise parameters is first determined, which is identified by a list of variables, intervals of their possible values, and accepted levels of their gradation. For each of the possible vectors of $\mathbf{PF}^{\mathrm{T}}$ productive parameters, numerical experiments with different levels of noise determined by the $\mathbf{NF}^{\mathrm{T}}$ vectors are performed to obtain an array of probe EMF values, i.e., its modulus $\mathrm{mod}(E_i)$ (Fig. 1).

This array is used to calculate the output statistics $\left(S/N\right)_j$, where $j = 1,...,9$, defined in the form (1). This statistic is used as a criterion for comparing vectors of productive parameters.

Instead of studying the project environment as a whole, it is advisable to use statistical methods of designing experiments to move to the appropriate subset of it in the form of a matrix of controllable productive parameters.

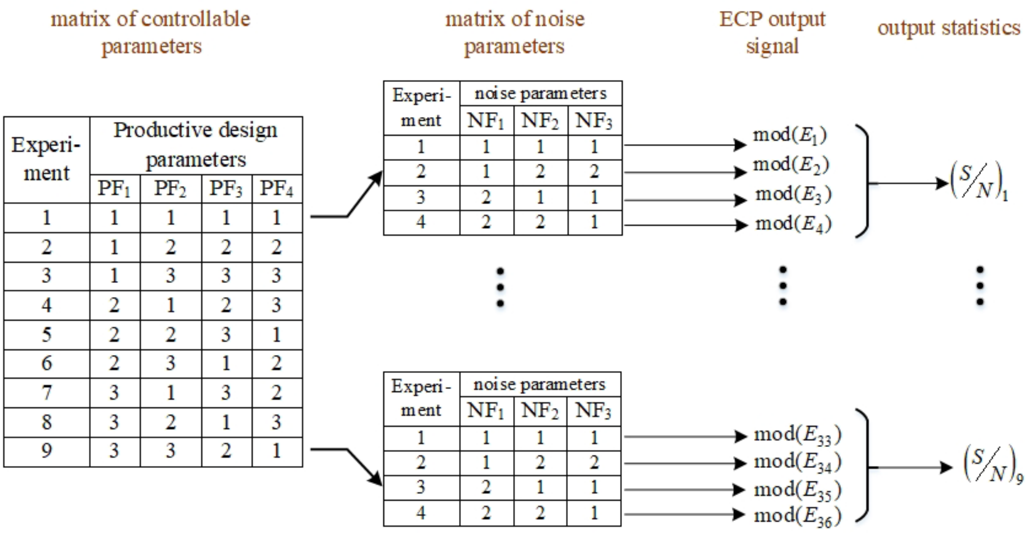

Fig. 1. Scheme of the formation of a hypothetical simplified general design of Taguchi experiments in the presence of 4 productive parameters and 3 noise parameters with three and two levels of gradation, respectively.

As a result, the output statistics are estimated for all vectors of the controllable parameter matrix and all vectors of the noise parameter matrix.

It is necessary to find such a vector among other possible productive parameters in the environment that maximizes the average output statistics by gradation levels:

$$\left(\overline{S/N}\right)^{prod} = -10 \cdot \log_{10} \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{1}{\left(\mathrm{mod}\left(E_i\right)\right)^2} \to \max \quad (2)$$

Where n is the number of noise parameters vectors, E is the amplitude of the output signal of the ECP.

Thus, the best gradation levels for each of the productive parameters are searched, so that the probe signal has the lowest variability, i.e., is insensitive to noise factors. According to the Taguchi method, this combination of levels (Taguchi-parameters) is considered optimal, and minimizing the effect of noise on the ECP signal is equivalent to minimizing the standard deviation. Therefore, to find the optimum, we use methods of designing experiments rather than numerical optimization algorithms.

II. DESCRIPTION OF RESEARCH METHOD

At the initial stage of designing surface ECPs with new properties, to draw up a design of experiment using the integration approach by combining the Taguchi method and computer numerical modeling of the measurement process, it is necessary to determine the structure of the design table and the corresponding mathematical model for calculating the probe output signal.

The electrodynamic model of the process of measuring the ECP for a TO in the form of a plate in the analytical form in the cylindrical coordinate system is represented by the relation [17], which, to determine the EMF E, relates a number of parameters, including the design and operating parameters of the probe, electrophysical and geometric characteristics of the TO:

$$E = -j \cdot \omega \cdot w_{mes} \cdot \oint_{Lc} \dot{A}(P) dl_p \quad (3)$$

Where $\dot{A} = \left[\frac{1}{(R2-R1)\cdot(h2-h1)}\right] \int_{h1}^{h2} \int_{R1}^{R2} \dot{A}_1 dR dh$,

$$\dot{A}_1 = \frac{\mu_0 \cdot R \cdot \dot{I}}{2} \left[\int_0^\infty J_1(\lambda R) \cdot J_1(\lambda \rho) \cdot e^{-\lambda|z-h|} d\lambda + \int_0^\infty J_1(\lambda R) \cdot J_1(\lambda \rho) \cdot \varphi_1 \cdot e^{-\lambda(z+h)} d\lambda \right], \ \dot{I} = I \cdot e^{j\omega t},$$

$$\varphi_1 = \frac{(\lambda \cdot \mu_2 - q_2) \cdot (\mu_3 \cdot q_2 + \mu_2 \cdot q_3) \cdot e^{d \cdot q_2} - (\lambda \cdot \mu_2 + q_2) \cdot (\mu_2 \cdot q_3 - \mu_3 \cdot q_2) \cdot e^{-d \cdot q_2}}{\Lambda},$$

$$\Lambda = (\lambda \cdot \mu_2 + q_2) \cdot (\mu_2 \cdot q_3 + \mu_3 \cdot q_2) \cdot e^{d \cdot q_2} - (\lambda \cdot \mu_2 - q_2) \cdot (\mu_2 \cdot q_3 - \mu_3 \cdot q_2) \cdot e^{-d \cdot q_2},$$

$$q_2 = \sqrt{\lambda^2 - k_2^2} = \sqrt{\lambda^2 + j \cdot \omega \cdot \sigma_2 \cdot \mu_0 \cdot \mu_2}, \; q_3 = \sqrt{\lambda^2 - k_3^2} = \sqrt{\lambda^2 + j \cdot \omega \cdot \sigma_3 \cdot \mu_0 \cdot \mu_3}, \; \mu_3 = 1, \; \sigma_3 = 0,$$

$$k^2 = -j \cdot \mu_0 \cdot \mu \cdot \sigma$$

J1() is a first-order Bessel function of the first kind; $\dot{A}$ is the azimuthal component of the magnetic vector potential, Wb/m; $\dot{I}$ is an alternating sinusoidal current of angular frequency ω, A; *R* is the radius of the turn of the ECP excitation coil with an insignificantly small cross section, m; *h* is the height of the coil location above the surface of the TO, m; *d* is the thickness of the plate, m; *ρ*, *z* are the coordinates, m; $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$, H/m is the magnetic constant in vacuum; *μ* is the relative magnetic permeability of the environment; *σ* is the electrical conductivity of the environment, S/m; $(R2 - R1) \times (h2 - h1)$ is the cross-section of the probe excitation coil, m^2; w_{mes} the number of turns of the pick-up coil of the ECP; *P* is an observation point with coordinates *(ρ, z)* belonging to the contour *Lc* of the pick-up coil of the ECP.

The mathematical model of the measurement process was obtained under the following assumptions: the probe field is considered quasi-stationary; wave processes in the air are neglected; bias currents in a conductive medium are also neglected.

The model contains a non-proprietary integral of the first kind, for the calculation of which it is advisable to use the Gauss-Laguerre quadrature formula and the truncation method. Formula (3) allows us to calculate the amplitude and phase of the output signal of a transformer surface ECP, the pick-up coil of which is located in the lift-off and the lower plane of the excitation coil.

The structure of the general table of the design of experiments is determined by the number of influential productive and noise parameters.

For certainty, we will assume that an eddy current thickness gauge with inherent new properties is being designed, for which the signal measured parameter is the thickness of the TO *d*; productive design parameters - the inner radius of the excitation coil *R1*, the outer radius of the excitation coil *R2*, 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 *h2*, and the operating parameters - the excitation frequency *f*, the excitation current *I*; noise parameters - the magnetic permeability of the TO *μ*, its electrical conductivity *σ*, and the lift-off *h1*. Accordingly, we will have 7 productive controllable parameters and 3 noise ones. If we determine the levels of gradation of their presentation in separate tables of design of experiments for each of these two groups, it is possible to select suitable types of orthogonal arrays in L-format from the relevant catalogs, in particular $L_9(3^4)$, $L_{18}(2^1,3^7)$, etc., which automatically determine the number of experiments required to implement both designs.

It is worth noting an important property of orthogonal arrays that allows you to remove a certain number of columns from them, if necessary, that is, to reduce the number of parameters that appear in their typical version. In this case, the modified array will still be orthogonal. Thus, it is possible to customize standard arrays to one's needs. After preparing two separate design of experiments, it is necessary to combine them into a common design according to the following scheme (Fig. 1). The next stage of research involves calculating the values of the fitness function and the signal-to-noise ratio using formula (1).

The calculated values of signal-to-noise ratios for all experiments, individual parameters, and average *S/N* values of each parameter for all gradation levels are used to further evaluate the optimal values of the productive parameters of the ECP design, taking into account the "larger is better" property [18]. The aim of optimization design is to find a combination of performance parameters that minimizes the impact of noise parameters. Verification of the obtained estimate is carried out by conducting a test numerical experiment, which should confirm the correctness of the Taguchi-parameters.

III. NUMERICAL EXPERIMENTS

According to the mathematical model (3), the software was developed, the adequacy of which was determined in the COMSOL Multiphysics environment by the finite element method. The test numerical modeling was performed for the case of representing the probe excitation system by a turn with the following initial data:

(ρ, z)=($10\cdot10^{-3}$, $1\cdot10^{-3}$) m; *f*=2 kHz; *d*=$5\cdot10^{-3}$ m; *R*=$20\cdot10^{-3}$ m; *h*=$2\cdot10^{-3}$ m; *I*=1 A; *σ*=$3.77\cdot10^{7}$ S/m, *μ*=1. A comparative analysis of the results of calculations of the magnetic vector potential values obtained in two different software environments shows that the calculated values coincide with a fairly high accuracy of 0.039 %.

In order to determine the lower and higher limits of changes in each influential parameter, additional studies of the sensitivity of the ECP to them were previously conducted.

Thus, using formula (3), a number of numerical experiments were conducted to determine the dependence of the output signal of the ECP on the influencing parameters, provided that the parameter under analysis varied within certain specified limits, and all other parameters remained unchanged.

The initial data for this analysis are as follows: *R1*=$20\cdot10^{-3}$ m, *R2*=$21\cdot10^{-3}$ m, *h1*=$2\cdot10^{-3}$ m, *h2*=$3\cdot10^{-3}$ m, *z*=$1\cdot10^{-3}$ m, *r*=$13\cdot10^{-3}$ m, *d*=$3\cdot10^{-3}$ m, *f*=1.5 kHz, *I*=1 A, *σ*=$6.99\cdot10^{6}$ S/m, *μ*=20.

The finalized values of the limits for changing the influential parameters are shown in Table 1.

The orthogonal array $L_{18}(2^1,3^7)$ was chosen for the productive parameters (Table 2), and the array $L_9(3^4)$ was chosen for the noise parameters with three levels of gradation for both types (Table 3) [19].

Table 1

Influencing parameters on the output signal of the ECP when TO`s thickness measuring

Limits of change of influencing parameters	Lower bound	Upper bound	Factor symbol
Inner radius of the excitation coil *R1*, m	0.0184	0.0208	A
Outer radius of the excitation coil *R2*, m	0.020916	0.02352	B
Radius of the pick-up coil *ρ*, m	0.01118	0.0195	C
Distance to the top edge of the excitation coil *h2*, m	$2.76\cdot10^{-3}$	$3.24\cdot10^{-3}$	D
Height of the pick-up coil *z*, m	$9\cdot10^{-4}$	$1.1\cdot10^{-3}$	E
Excitation frequency *f*, kHz	1.125	1.875	F
Excitation current *I*, A	0.75	1.25	G
Magnetic permeability *μ*	18.4	21.6	H
Electrical conductivity *σ*, S/m	$6.431\cdot10^{6}$	$7.549\cdot10^{6}$	J
Lift-off *h1*, m	$1.84\cdot10^{-3}$	$2.16\cdot10^{-3}$	K

Table 2

Modified orthogonal arrays $L_{18}(2^1,3^7)$ for productive parameters

№	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	2	2	2	2	2	2
3	1	3	3	3	3	3	3
4	2	1	1	2	2	3	3
5	2	2	2	3	3	1	1
6	2	3	3	1	1	2	2
7	3	1	2	1	3	2	3
8	3	2	3	2	1	3	1
9	3	3	1	3	2	1	2
10	1	1	3	3	2	2	1
11	1	2	1	1	3	3	2
12	1	3	2	2	1	1	3
13	2	1	2	3	1	3	2
14	2	2	3	1	2	1	3
15	2	3	1	2	3	2	1
16	3	1	3	2	3	1	2
17	3	2	1	3	1	2	3
18	3	3	2	1	2	3	1

Table 3

Modified orthogonal arrays $L_9(3^4)$ for noise parameters

№	1	2	3	4	5	6	7	8	9
H	1	1	1	2	2	2	3	3	3
J	1	2	3	1	2	3	1	2	3
K	1	2	3	1	2	3	2	3	1

Since these arrays have a larger number of factors than required for this study, they were further modernized, namely, one factor was removed, in particular, a factor with two gradations was removed from $L_{18}(2^1,3^7)$, and one redundant factor was removed from $L_9(3^4)$. The values of the parameters in the selected orthogonal arrays are converted into units of real physical quantities (Table 4, Table 5), corresponding to low, medium, and high levels of their gradation. By combining the selected arrays, the total number of computational experiments to be performed under this design is 162. Thus, a general design of experiments has been created, the quality of which determines the effectiveness of further research [20-22]. Subsequently, according to the design, the next stage of research is carried out, namely, for each experiment, the EMF of the probe is determined at the specified settings for all levels of factors and the S/N value is calculated for each of them (Table 5). At the same time, for the entire set of experimental data, the minimum EMF value is 0.008719 V, and the maximum is 0.0999 V.

The next stage involves the selection of rational combinations of the design and operating parameters of the probe according to the criterion of maximizing S/N.

Table 4

Design of experiments for noise parameters

№	H	J	K
1	18.4	6431000	0.00184
2	18.4	6990000	0.002
3	18.4	7549000	0.00216
4	20	6431000	0.002
5	20	6990000	0.00216
6	20	7549000	0.00184
7	21.6	6431000	0.00216
8	21.6	6990000	0.00184
9	21.6	7549000	0.002

Table 5

Design of experiments for productive parameters

№	A	B	C	D	E	F	G	S/N
1	0.0184	0.020916	0.01118	0.00276	0.0009	1125	0.75	-40.8927
2	0.0184	0.022218	0.01534	0.003	0.001	1500	1	-29.4873
3	0.0184	0.02352	0.0195	0.00324	0.0011	1875	1.25	-20.2394
4	0.0196	0.020916	0.01118	0.003	0.001	1875	1.25	-33.5477
5	0.0196	0.022218	0.01534	0.00324	0.0011	1125	0.75	-34.6718
6	0.0196	0.02352	0.0195	0.00276	0.0009	1500	1	-23.9131
7	0.0208	0.020916	0.01534	0.00276	0.0011	1500	1.25	-28.1325
8	0.0208	0.022218	0.0195	0.003	0.0009	1875	0.75	-24.8341
9	0.0208	0.02352	0.01118	0.00324	0.001	1125	1	-40.3505
10	0.0184	0.020916	0.0195	0.00324	0.001	1500	0.75	-25.6035
11	0.0184	0.022218	0.01118	0.00276	0.0011	1875	1	-35.4354
12	0.0184	0.02352	0.01534	0.003	0.0009	1125	1.25	-30.1614
13	0.0196	0.020916	0.01534	0.00324	0.0009	1875	1	-28.0298
14	0.0196	0.022218	0.0195	0.00276	0.001	1125	1.25	-23.4327
15	0.0196	0.02352	0.01118	0.003	0.0011	1500	0.75	-40.4383
16	0.0208	0.020916	0.0195	0.003	0.0011	1125	1	-25.3630
17	0.0208	0.022218	0.01118	0.00324	0.0009	1500	1.25	-36.0704
18	0.0208	0.02352	0.01534	0.00276	0.001	1875	0.75	-32.2822

To do this, we performed a statistical analysis for each productive parameter at all levels of its gradation, namely, we calculated the average values $\left(\overline{S/N}\right)^{prod}$; the absolute error of the average value $\Delta = \left(\overline{S/N}\right) - \left(\overline{S/N}\right)^{prod}$, where $\left(\overline{S/N}\right)$ is the average value of the signal-to-noise ratio of all productive parameters, which is -30.716 dB; standard deviation *St.Dev*, the results of which are shown in Table 6. The obtained values make it possible to find the Taguchi-parameters of the ECP that provide the maximum *S/N* ratio, i.e., their optimal values (Table 7).

The obtained Taguchi-parameters were verified by conducting a test numerical experiment. Thus, with the determined optimal parameters of the ECP (Table 7), we have a predicted value of *S/N*= - 19.1149 dB, which is bigger than any value obtained in Table 5 of the design of experiments. At the same time, the EMF of the probe signal is from 0.102 V to 0.11 V, i.e. the signal variation from its average value is ± 3.5%.

Table 6

The results of statistical calculation of productive parameters

№	Level	$\left(\frac{S}{N}\right)^{prod}$	Δ	*St.Dev*
A	0.0184	-30.3033	0.41259	7.246097
	0.0196	-30.6722	0.04365	6.704024
	0.0208	-31.1721	-0.45623	6.206812
B	0.020916	-30.2616	0.45434	5.983752
	0.022218	-30.6553	0.06061	5.580716
	0.02352	-31.2308	-0.51495	8.301248
C	0.01118	-37.7892	-7.07328	3.152597
	0.01534	-30.4608	0.25504	2.585253
	0.0195	-23.8976	6.81824	1.976516
D	0.00276	-30.6815	0.03444	6.845206
	0.003	-30.6386	0.07724	5.789202
	0.00324	-30.8276	-0.11168	7.485683
E	0.0009	-30.6503	0.06563	6.642403
	0.001	-30.7840	-0.06809	6.065658
	0.0011	-30.7134	0.00247	7.450253
F	1125	-32.4787	-1.76279	7.421627
	1500	-30.6075	0.10836	6.383146
	1875	-29.0615	1.65443	5.794657
G	0.75	-33.1204	-2.40454	6.960412
	1	-30.4299	0.28601	6.297032
	1.25	-28.5974	2.11853	5.992380

Table 7

The Taguchi-parameters of the probe

Parameter	*R1*, m	*R2*, m	*r*, m	*h2*, m	*z*, m	*f*, Hz	*I*, A
Value	0.0184	0.020916	0.0195	0.003	0.0009	1875	1.25
$\left(\frac{S}{N}\right)^{opt}$, dB	-30.3033	-30.2616	-23.8976	-30.6386	-30.6503	-29.0615	-28.5974

All of this confirms the correctness of the found productive parameters of the designed ECP.

In addition, an ANOVA analysis of variance of the parameters was performed [23], the results of which indicate their statistical significance except D and E (Table 8) at a degree of freedom of 2. Where *SS* is the sum of the squares of the variance component, *MS* is the mean square of the variance component, *F* is the variance ratio, and *p* is the significance level.

For the residuals, similar parameters are $SS_{residual}$=0.0917, $MS_{residual}$=0.0306 at the degree of freedom 3.

For a more stable estimate of the variance of the residuals, the non-significant parameters are combined into one error group, which gives $MS_{residual}$ = 0.0376.

In this case, there are no significant differences in the EMF signal of the probe, i.e., all relevant parameters have been taken into account correctly, and there are no unexpected interactions between them.

Table 8

Results of the ANOVA analysis

№	*SS*	*MS*	*F*	*p*
A	2.281	1.140	37.33	0.0075
B	2.851	1.425	46.66	0.0055
C	579.5	289.75	9482.7	0.000002
D	0.117	0.058	1.92	0.2896
E	0.053	0.026	0.87	0.501
F	35.138	17.569	574.97	0.0001
G	62.111	31.055	1016.3	0.000057

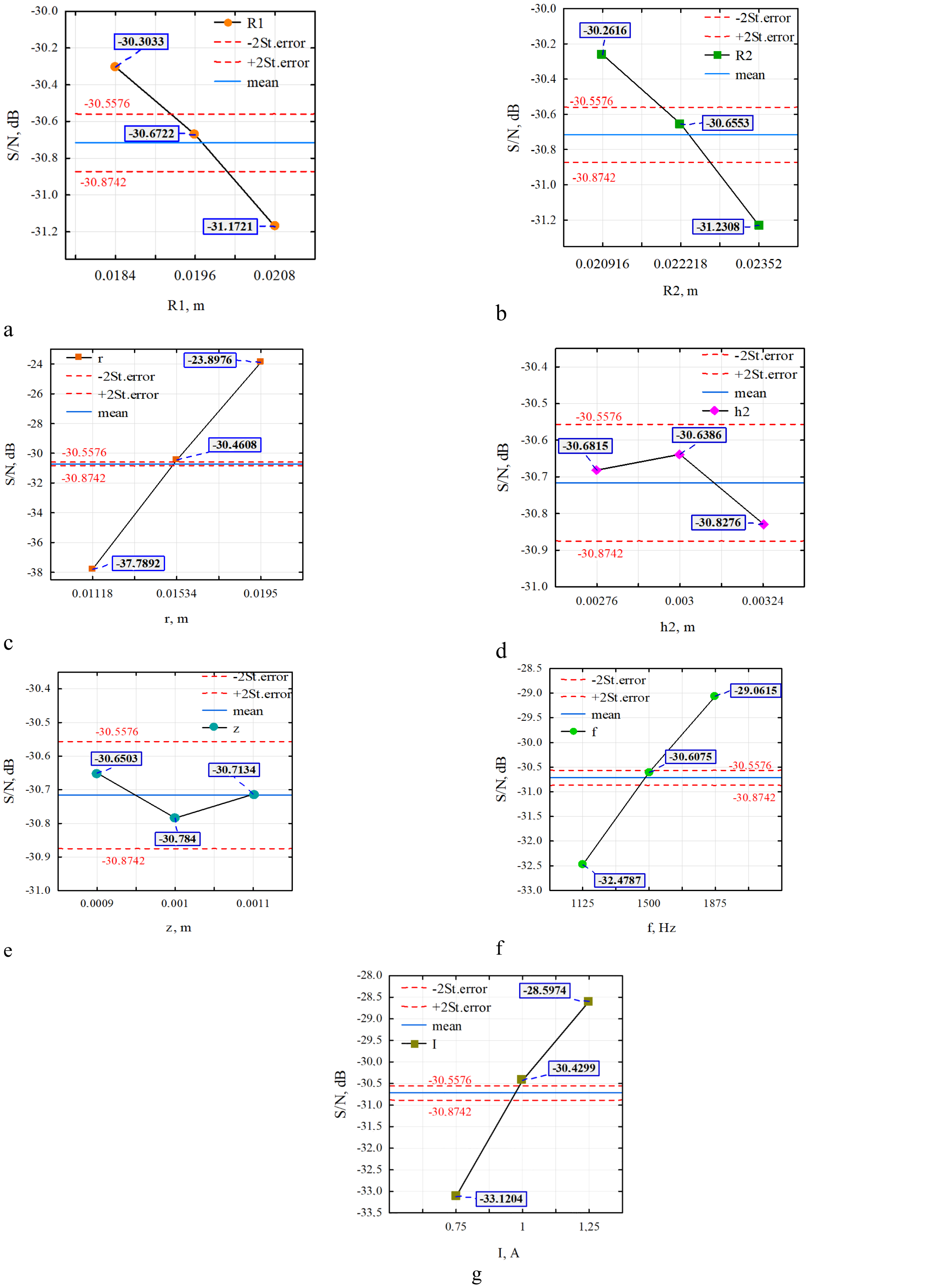

Fig. 2. $\left(S/N\right)^{prod}$ **by levels for the controllable productive parameters: a - internal radius of the excitation coil** ***R1*****; b - external radius of the excitation coil** ***R2*****; c - pick-up coil radius** ***r*****; d - distance to the top edge of the excitation coil** ***h2*****; e - height of the pick-up coil location** ***z*****; f - excitation frequency** ***f*****; g - excitation current** ***I*****.**

DISCUSSION AND CONCLUSIONS

Thus, to visually assess the best settings for each productive parameter, we graphically analyzed the average S/N values and indicated the two-fold limits of the standard error *St.error* around its mean (Fig. 2).

The graphs clearly demonstrate the correctness of the conclusions about finding the Taguchi-parameters of the probe.

It should also be noted that the study quite effectively used the proposed method of reducing the impact of noise parameters on the output signal of the ECP, which is implemented at the design stage. To implement this method, the software for calculating the output signals of the ECP based on the electrodynamic model of the process of measuring the TO in the form of a conductive plate of infinite dimensions and finite thickness was created and verified in COMSOL Multiphysics.

Design of experiments for controllable productive and noise parameters using orthogonal arrays that take into account the influence of each parameter and their nonlinear interaction with each other on the output signal of the probe is constructed. On their basis, an effective general design of experiments was created to establish the Taguchi-parameters of the ECP.

Thus, as a result of the numerical experiments with their statistical processing, the design and operating optimal parameters of the ECP were found, which ensure signal stability with *S/N*=-19.115 dB and its variability from the average within ± 3.5 % caused by noises.

References

[1] Ida N., Meyendorf N. (Eds.). *Handbook of advanced nondestructive evaluation*. Cham, Switzerland: Springer International Publishing, 2019, vol. 10, 1626 p. doi:10.1007/978-3-319-26553-7

[2] Sabbagh H.A., Murphy R.K., Sabbagh E.H., Aldrin J.C., Knopp J.S. *Computational electromagnetics and model-based inversion*. New York, NY, USA: Springer-Verlag, 2013, 448 p. doi: 10.1007/978-1-4419-8429-6

[3] Li S., Li J. Condition monitoring and diagnosis of power equipment: review and prospective. *High Voltage*, 2017, vol. 2, no. 2, pp. 82-91. doi:10.1049/hve.2017.0026

[4] Arnold W., Goebbels K., Kumar A. *Non-destructive Materials Characterization and Evaluation*. Springer, 2023, 317 p. doi:10.1007/978-3-662-66489-6

[5] García-Martín J., Gómez-Gil J., Vázquez-Sánchez E. Non-destructive techniques based on eddy current testing. *Sensors*, 2011, vol. 11. no. 3, pp. 2525-2565. doi:10.3390/s110302525

[6] Lüthi T. *Non-Destructive Evaluation Methods.* EMPA—Swiss Federal Laboratories for Materials Science and Technology; Self-Published: Dübendorf, Switzerland, 2013.

[7] Vigneron A., Demaldent E., Decitre J.M., Sollier T. Modelling the Influence of the Tube Support Plate on the Eddy Current Testing of the Steam Generator: Numerical Tools. *In NDE in Nuclear*, 2023, vol. 28. NDT.net. HAL Id: ea-04487893 version 1, doi:10.58286/28669

[8] Vigneron A., Demaldent E., Decitre J.M., Sollier T. Modelling of wear defects under Anti Vibration Bars in U-bend for the Eddy Current inspection of Steam Generator tube. Les journées cofrend/ cofrend days, France, Marseille, 06 - 08 June 2023. *e-Journal of Nondestructive Testing*, 2023, vol. 28, no. 9. doi:10.58286/28500

[9] Technical Manual - *Nondestructive Inspection Methods*. NAVAIR 01-1A-16. T.O. 33B-1-1. TM 1-1500-335-23, dated 15 may 2014. https://www.tinker.af.mil/Portals/106/Documents/Technical%20Orders/AFD-101516-33B-1-1.pdf

[10] Fan M., Cao B., Sunny A. I., Li W., Tian G., Ye B. Pulsed eddy current thickness measurement using phase features immune to liftoff effect. *Ndt & E International*, 2017, vol. 86, pp. 123-131. doi:10.1016/j.ndteint.2016.12.003

[11] Tian G. Y., Li Y., Mandache C. Study of lift-off invariance for pulsed eddy-current signals. *IEEE transactions on magnetics*, 2009, vol. 45, no. 1, pp. 184-191. doi:10.1109/TMAG.2008.2006246

[12] Xu H., Lu M., Avila J. R., Zhao Q., Zhou F., Meng X., Yin W. Imaging a weld cross-section using a novel frequency feature in multi-frequency eddy current testing. *Insight-Non-Destructive Testing and Condition Monitoring*, 2019, vol. 61, no. 12, pp. 738-743. doi:10.1784/insi.2019.61.12.738

[13] Xie J., Qiao Y., Qi Y., Xu Q., Shemtov-Yona K., Chen P., Rittel D. Application of the Taguchi method to areal roughness-based surface topography control by waterjet treatments. *Applied Surface Science Advances*, 2024, vol. 19, 100548. doi:10.1016/j.apsadv.2023.100548

[14] Puška A., Stojanović I. Application of Taguchi Method in Optimization of the Extraction Procedure of Sheet Metal, *Advanced Engineering Letters*, 2024, vol. 3, no. 1, pp. 13-20. doi:10.46793/adeletters.2024.3.1.2.

[15] Krishnaiah K., Shahabudeen P. *Applied design of experiments and Taguchi methods*. PHI Learning Pvt. Ltd., 2012, 371 p.

[16] Reddy A. C. S., Rajesham S., Reddy P. R., Kumar T. P., Goverdhan J. An experimental study on effect of process parameters in deep drawing using Taguchi technique. *International Journal of Engineering, Science and Technology*, 2015, vol. 7, no. 1, pp. 21-32. doi:10.4314/ijest.v7i1.3
[17] Sobolev V.S., Shkarlet Y.M. *Nakladnye i jekrannye datchiki (dlja kontrolja metodom vihrevyh tokov)*. [Surface and screen sensors (for eddy current monitoring)]. 1967. 144 p.
[18] Taguchi G. *System of experimental design: engineering methods to optimize quality and minimize costs.* 1st Edition, American Suppliers Institute, Dearborn, 1987. 1189 p.
[19] Wu F.C. Simultaneous Optimization of Robust Design with Quantitative and Ordinal Data. *International Journal of Industrial Engineering: Theory, Applications and Practice*, 2022, vol. 15, no. 2, pp. 231–238. doi:10.23055/ijietap.2008.15.2.124
[20] Koshevoy N.D., Dergachov V.A., Pavlik A.V., Siroklyn V.P., Koshevaya I.I., Hrytsai O.A. Modified Gray Codes for the Value (Time) Optimization of a Multifactor Experiment Plans. In: Nechyporuk M., Pavlikov V., Kritskiy D. (eds) Integrated Computer Technologies in Mechanical Engineering - 2021. ICTM 2021. *Lecture Notes in Networks and Systems*, 2022, vol 367, Springer, Cham. doi:10.1007/978-3-030-94259-5_29
[21] Koshevoy N.D., Muratov V.V., Kirichenko A.L., Borisenko S.A. Application of the “jumping frogs” algorithm for research and optimization of the technological process. *Radio Electronics, Computer Science*, Control, 2021, no. 1. pp. 57-65. doi:10.15588/1607-3274-2021-1-6
[22] Taback N. *Design and Analysis of Experiments and Observational Studies Using R.* Chapman and Hall/CRC. 2022.
[23] Aslett L. J., Coolen F., De Bock J. *Uncertainty in Engineering: Introduction to Methods and Applications.* Springer Nature. 2022.

Information about authors.

Volodymyr Yakovych Halchenko, Professor at Cherkasy State Technological University, Cherkasy, Ukraine. His current research interests include non-destructive testing, mathematical modelling, optimization and intellectual data analysis.
E-mail: v.halchenko@chdtu.edu.ua

Ruslana Volodymyrivna Trembovetska, Professor at Cherkasy State Technological University, Cherkasy, Ukraine. Her current research interests include non-destructive testing, mathematical modelling, optimization and intellectual data analysis.
E-mail: r.trembovetska@chdtu.edu.ua

Volodymyr Volodymyrovych Tychkov, Associate Professor at Cherkasy State Technological University, Cherkasy, Ukraine. His current research interests include non-destructive testing, mathematical modelling, optimization and intellectual data analysis.
E-mail: v.tychkov@chdtu.edu.ua