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ROBUST PARAMETER DESIGN OF SURFACE EDDY CURRENT PROBES. THE CASE OF MEASURING GEOMETRIC ANOMALIES IN A STATIONARY TEST OBJECT

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The aim of the paper is to develop a method for increasing the signal-to-noise ratio of eddy current measurement of geometric anomalies in static planar objects without actually eliminating the inherent effects of noise factors. This is achieved by means of Taguchi's robust parameter design of rectangular frame surface probes, which allows determining the optimal configuration of their constructions. On a specific example, a robust configuration construction of the eddy current probe design is found, i.e., its technical variant that ensures a reduction of the output signal variance near its average value, i.e., resistance to noise disturbances, due only to the appropriate determination of the values of the controllable design and operating parameters of the probe without eliminating uncontrollable interference inherent in the test objects. For the robust design of a number of eddy current meters with different functionalities, a universal magnetodynamic model of the probe was used, which, together with the application of orthogonal arrays, allows the creation and implementation of Taguchi-design of experiments. The software that implements this model has been verified, including by comparing it with the results of calculations on test's examples performed using the finite element method. The accuracy achieved in this case allows us to assert the adequacy of the created computer program. The data obtained as part of the Taguchi-design of experiment were used to evaluate design options using the "larger is better" quality loss function and the signal-to-noise ratios calculated on its basis, which made it possible to select the optimal combination of design and operating parameters of the eddy current probe. The reliability of the found optimal configuration of the eddy current probe design was proved by confirmatory calculations. The research results were also experimentally verified on a prototype. References 21, figures 6, tables 9.

Keywords: robust parameter design, measuring geometric anomalies, rectangle surface eddy current probe, noise suppression, universal magnetodynamic model of the probe, Taguchi's experimental design, quality loss function, signal-to-noise ratio.

Introduction. The latest conceptual capabilities of modern methods of designing measuring probes often make it possible to completely change their conventional consumer properties. This trend is also characteristic of eddy current probes (ECP), which is confirmed by the creation of uniform ECPs [1, 2, 3], Smart ECPs, in particular, multi-element probes with flexible parameterization by electronic switching [4], etc. It is developing rapidly and is being widely implemented in engineering activities.

Among the known ones, ECPs are distinguished by a significant information content of the selected signal. This is a consequence of the dependence of the output signals of the ECP on a significant number of factors at the same time, which can be considered both their significant advantage and a significant disadvantage. This information capability of the ECP allows for the separate measurement of a number of parameters in the test object (TO), but other influencing factors are already becoming interferences to establishing the actual values of the measured factor. The research and study of techniques for separate control of the effects of a factor or their joint aggregates on the process of forming ECP signals during eddy current measurements of specific parameters is of considerable practical interest.

The main factors affecting the ECP signal include the presence of continuity violations, changes lift-off, local changes in the magnetic permeability of the TO material and its electrical conductivity, certain features of the TO geometry, in particular, surface curvature, its roughness, etc. Thus, it is important to keep

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the impeding factors at a constant level in ECP measurements, which is almost always practically impossible. When more than one factor simultaneously affects the output signal of a probe, it becomes quite difficult to separate the influence of the measured factor from the influence of interfering factors. Moreover, the ECP is characterized by influences that are inherent in the TO and cannot be controlled.

For these reasons, there is a need to find effective ways to separate the effects of factors, which are usually focused on certain approaches to processing information selected from the ECP. There are phase, multi-frequency, amplitude-phase, projection, and other methods. These methods are mostly based on the analysis of hodographs of signal changes on a complex plane under certain measurement conditions related to the choice of the frequency of the electromagnetic sensing field.

When conducting eddy current measurements, it is advisable to use the concept of signal-to-noise ratio (SNR), where noise is considered any possible signal that has no relationship with the measured parameter. At the same time, depending on the functionality of the measuring instrument being designed, each signal can be considered both measurable, i.e. useful, and noise that needs to be suppressed. Noise always masks the definition of the measured parameter, so it is important to increase the signal-to-noise ratio. This aim can be achieved by various methods, among which the most common are the choice of an effective sensing frequency, parameter combination of signals of several different frequencies during testing, and the choice of probe design.

In this study, we will focus on the implementation of the latter as the most promising in terms of ease of implementation using the technique of robust parameter design based on the Taguchi`s method when searching for an optimal configuration of the probes design. Moreover, it is also possible to further apply other methods of separating the information influences of the factors mentioned earlier to probes with their improved configuration. In the following, we will understand the robasterization of the ECP to mean, in accordance with Taguchi's concept, the search for such an optimal technical option in terms of the design configuration that allows to ensure the stability of the output signal to noise interferences, namely, the reduction of variations of the output signal around its average, due only to the appropriate determination of the values of the controllable design and operating parameters of the probes without eliminating uncontrollable interference inherent in the TO. Moreover, it is recommended to consider and calculate the signal-to-noise ratio as a certain performance statistic to measure the effect of noise factors on the output signal for each ECP design configuration to be analyzed and to find the option that corresponds to the maximum value.

The Taguchi method has been widely used in industry to optimize the performance of various technical products and processes and has become even more popular in modern conditions than at the beginning of its appearance. This is evidenced by the analysis of the latest research by scientists, for example, publication [5] and review [6], some of which are devoted to its application in non-destructive testing methods [7, 8, 9]. However, the authors' attempts to find information on the use of robust design to improve the characteristics of the ECP were unsuccessful, except for publications by the authors themselves [10, 11]. It conducted a study on increasing the signal-to-noise ratio of an eddy current thickness gauge of metal plates based on a surface encircle probe, where encouraging positive results were achieved. Thus, it makes sense to scale the gained research experience to other types of measurements of TO parameters with surface ECP.

Therefore, **the aim of the article** is to create a method for increasing the signal-to-noise ratio of eddy current geometric anomaly measurement with frame surface probes by means of Taguchi`s robust parameter design, which allows determining the optimal configurations of their structures for testing static planar objects without actually eliminating the effects of their inherent noise factors.

Problem statement. Let us formulate the research problem: at the stage of designing an eddy current measurement with a frame surface transformer probe, i.e., a means of measuring geometric anomalies of a static planar TO in the form of violations of material continuity, curvature of its surface, its roughness, etc., it is necessary to find, using the Taguchi`s robust parameter design method, such a configuration of the probe design, namely, its operating and design parameters, which ensures low variability, and thus stability, of the ECP output signal without actually eliminating the effects of uncontrollable noise factors and realizes the maximum signal-to-noise ratio.

The general methodology for implementing Taguchi's robust parameter design is described in detail in numerous thorough monographs, for example, in [12], and recent publications [13, 14], which discuss modern approaches to its application. The methodology adapted to the design of eddy current probes was discussed in detail by the authors in their studies [10, 11]. For the above reasons, this article provides only brief information necessary for further understanding of the material on the use of such methodology, with an accent on the existing specific differences.

Thus, the main stages of the Taguchi`s method necessary for the design of the ECP, i.e., the research objectives, are as follows: to distinguish the TO characteristic measured by the probe, which is recorded by its output signal; to identify the controllable parameters of the ECP, as well as possible levels of their gradation when varying; to determine the noise factors and their gradation levels; to assign intervals of changes in the controllable and noise factors; to select orthogonal arrays that are appropriate to the characteristics of both groups of factors; to create a design of experiments and conduct them, using computer modeling to calculate the output signal of the ECP according to the proposed universal magnetodynamic model; on the basis of ANOVA analysis (Analysis of Variance) of the influence of factors on the induced EMF of the probe and the values of the signal-to-noise ratio calculated for each test based on the Taguchi's quality loss function, select the optimal configuration of the ECP design according to the appropriate combination of gradation levels of controllable factors that maximizes the SNR; to conduct confirmatory numerical experiments to verify the found optimal parameters of the ECP design configuration.

In the following, we will illustrate all these stages of robust ECP design in detail with the above examples.

Universal magnetodynamic model of the ECP. Robust parameter design by the Taguchi`s method in the classical sense refers to experimental methods for determining the desired combination of controllable factors of ECPs that identify the configuration of their design. However, we accept that in this study, the output signal of the probe is determined as a result of calculations using a certain mathematical expression, i.e., computer numerical modeling. Therefore, for this purpose, we chose an analytical mathematical model of the surface ECP [15] with correction according to [16], which can be considered universal for almost all practical measurement applications. It was created under the following assumptions: the TO medium is linear, isotropic, and homogeneous. However, there are certain limitations to its use: possible boundary effects, deviations of the ECP axis from the perpendicular position to the surface of the TO were not taken into account, although their influence on measurements exists in reality.

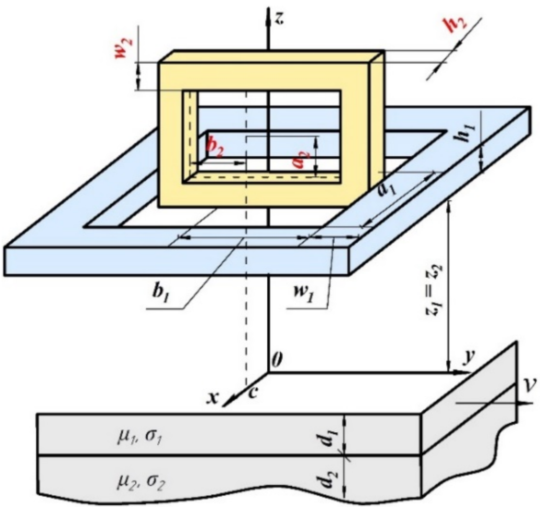


Fig. 1

The TO is assumed to be a two-layer of infinite width and length with thickness d_i and electrophysical properties of materials σ_i and μ_i (i = 1, 2), where σ and μ are the electrical conductivity and relative magnetic permeability, respectively. The TO moves with velocity v. The current of a rectangular multi-turn excitation coil with the number of turns N_1 varies according to a harmonic law $Ie^{j\omega t}$ with an angular frequency ω. The pick-up coil of the ECP has N_2 turns. The geometric model of the ECP above the TO is shown in Fig. 1.

When solving the problem in [15], the entire space was divided into three regions: Region 0 $(z > 0)$, Region 1 $(-d_1 < z < 0)$ and Region 2 $(z < -d_1)$. Provided that the depth of penetration of the electromagnetic field is less than the thickness of the TO ($d_1 + d_2$), the mathematical model of the ECP was created assuming that the TO is considered as a half-space, i.e., $d_2 = \infty$.

Induced by the secondary electromagnetic field generated by eddy currents in the TO, the EMF of the surface probe over a moving object is calculated according to expression (1). It relates the design and operating parameters of the probe, the electrophysical and geometric characteristics of the TO, and also takes into account the location of the pick-up coil in Region 0, which is shown in Fig. 1, i.e., when the EMF is induced by the x-component of the magnetic induction of the secondary field:

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

where $\kappa = \dfrac{\left(\dfrac{\gamma_1}{\varsigma} - \dfrac{\mu_1}{\mu_0}\right)\cdot\left(\dfrac{\gamma_2}{\gamma_1} + \dfrac{\mu_2}{\mu_1}\right) + \left(\dfrac{\gamma_1}{\varsigma} + \dfrac{\mu_1}{\mu_0}\right)\cdot\left(\dfrac{\gamma_2}{\gamma_1} - \dfrac{\mu_2}{\mu_1}\right)\cdot e^{-2\gamma_1 d_1}}{\left(\dfrac{\gamma_1}{\varsigma} + \dfrac{\mu_1}{\mu_0}\right)\cdot\left(\dfrac{\gamma_2}{\gamma_1} + \dfrac{\mu_2}{\mu_1}\right) + \left(\dfrac{\gamma_1}{\varsigma} - \dfrac{\mu_1}{\mu_0}\right)\cdot\left(\dfrac{\gamma_2}{\gamma_1} - \dfrac{\mu_2}{\mu_1}\right)\cdot e^{-2\gamma_1 d_1}}$, $\gamma_1 = \sqrt{\xi^2 + \eta^2 - j\sigma_1\mu_1 v\eta + j\omega\sigma_1\mu_1}$,

$\gamma_2 = \sqrt{\xi^2 + \eta^2 - j\sigma_2\mu_2 v\eta + j\omega\sigma_2\mu_2}$, $\varsigma = \sqrt{\xi^2 + \eta^2}$, 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,

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

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

Thus, we have a mathematical model of the ECP, which is in fact universal, since it can be used in a number of cases of eddy current measurements, namely test of planar static electrically conductive products of considerable thickness ($\delta << (d_1 + d_2)$, $v = 0$, $\mu_1 = \mu_2$, $\sigma_1 = \sigma_2$, where δ is the depth of penetration of the electromagnetic field, $\delta = \sqrt{2/(\omega\mu\mu_0\sigma)}$); inspection of planar moving electrically conductive products of considerable thickness ($\delta << (d_1 + d_2)$, $v \neq 0$, $\mu_1 = \mu_2$, $\sigma_1 = \sigma_2$); inspection of planar static two-layer electrically conductive products ($v = 0$, $\mu_1 \neq \mu_2$, $\sigma_1 \neq \sigma_2$); inspection of planar moving two-layer electrically conductive products ($v \neq 0$, $\mu_1 \neq \mu_2$, $\sigma_1 \neq \sigma_2$); inspection of dielectric coatings on a static electrically conductive basis ($v = 0$, $\mu_1 = 1$, $\sigma_1 = 0$, $z_1 = 0$); inspection of electrically conductive coatings on a static electrically conductive basis ($v = 0$, $\mu_1 \neq \mu_2$, $\sigma_1 \neq \sigma_2$). Therefore, within the framework of using a single magnetodynamic model of the ECP, it is possible to consider a number of similar studies.

To calculate the EMF of the probes, we created software, the adequacy of which was confirmed by verification on numerical calculations with the following design parameters of the excitation coil $a_1 = 12$ mm, $b_1 = 12$ mm, $z_1 = 1$ mm, $w_1 = 2$ mm, $h_1 = 8$ mm, $N_1 = 500$ and the pick-up coil – $a_2 = 3$ mm, $b_2 = 5$ mm, $z_2 = 1$ mm, $w_2 = 5$ mm, $h_2 = 2$ mm, $c = 6$ mm, $N_2 = 300$. The electrophysical parameters of the TO were set as follows: $\sigma_1 = 3.8 \cdot 10^7$ S/m, $\mu_1 = 1$, $\sigma_2 = 5.8 \cdot 10^7$ S/m, $\mu_2 = 1$. Fig. 3 shows the values of the x-component of the magnetic induction vector obtained by formula (2) from [15] in the space between the excitation coil and the conductive plate at x = - 16, ..., 16 mm, y = 0 mm, z = 5 mm, d_1 = 200 µm, f = 2 kHz:

$$B_{rx} = \frac{j\mu_0 I N_1}{2\pi^2 w_1 h_1}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\kappa\cdot k_1}{\eta\varsigma}\cdot\left[e^{-\varsigma(z+z_1)} - e^{-\varsigma(z+z_1+h_1)}\right]\cdot e^{-j(x\xi + y\eta)}d\xi d\eta. \quad (2)$$

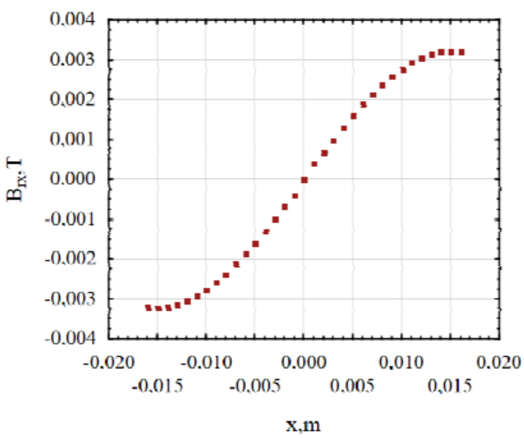


Fig. 2

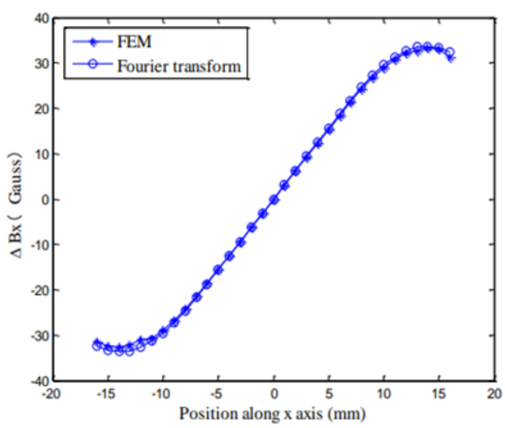


Fig. 3 [14]

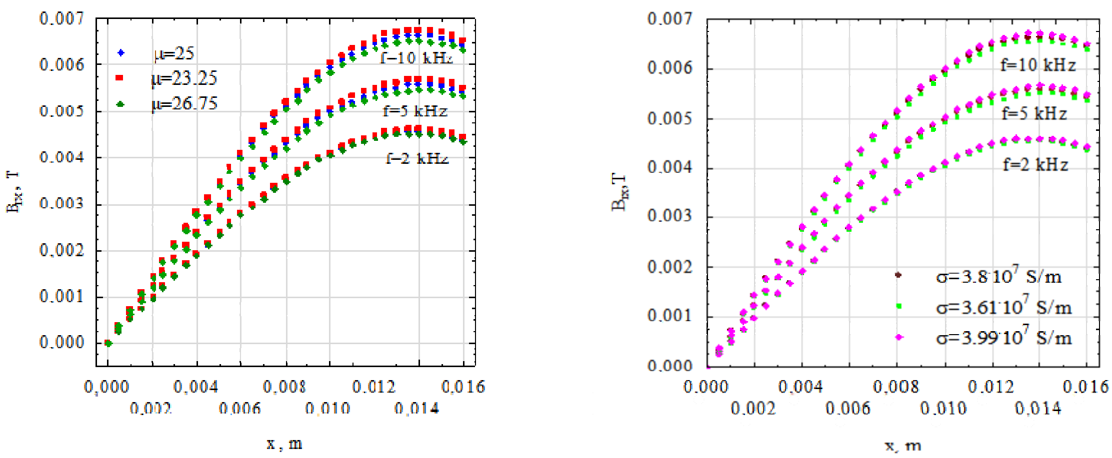
The results of verification of the values of the x-component of the magnetic induction vector of the secondary field are shown in Fig. 2 and Fig. 3, where Fig. 3 contains the results of calculations by the finite element method (FEM) [15], and Fig. 2 – by the created software. The induction values are consistent both in terms of the type of functional dependence and numerical values. Similar results with acceptable accuracy were obtained when comparing the output signals of the ECP calculated by the FEM and by formula (1).

The selection of orthogonal arrays for the controllable and noisy group's factors. To create a design of experiment based on the Taguchi`s method, it is first necessary to identify all influencing factors and classify them as either controllable or noise. For an eddy current measurement, the controllable constructive parameters are all geometric dimensions of the excitation and pick-up coils and the center distance between them, while the operational parameters are the excitation`s frequency and current. In this case, the noise factors are the electrophysical properties of the TO material and the lift-off between the probe and the TO.

To determine the range of variation of each influencing parameter, additional studies of the sensitivity of the ECP to them were performed. In other words, numerical experiments were conducted to determine the dependence the EMF of probe on all the influencing parameters. In this case, the parameter under analysis was varied within certain specified limits, and all other parameters were unchanged. The basic initial data for analyzing the sensitivity of the ECP to the influencing factors are as follows: $a_1 = 12$ mm, $b_1 = 14$ mm, $h_1 = 8$ mm, $w_1 = 3$ mm, $a_2 = 3.5$ mm, $b_2 = 5$ mm, $h_2 = 3.5$ mm, $w_2 = 2.5$ mm, $c = 3$ mm, $d_1 = 4.4$ mm, $f = 2.75$ kHz, $I = 1$ A, $\sigma = \sigma_1 = \sigma_2 = 0.12 \cdot 10^7$ S/m, $\mu = \mu_1 = \mu_2 = 2$. Finally, Table 1 summarizes the parameters affecting the output signal of the eddy current measurement and the limits of their change. Fig. 4 shows graphs of the change in the electromagnetic field induction modulus depending on the electrophysical parameters of the TO, namely magnetic permeability (Fig. 4, *a*) and electrical conductivity (Fig. 4, *b*), at different excitation frequencies.

Table 1

Factors	Variation range
Excitation coil width a_1, mm	8-16
Length of the excitation coil b_1, mm	12-16
Excitation coil cross-sectional height h_1, mm	6-10
Cross-sectional width of the excitation coil w_1, mm	1-5
Width of the pick-up coil a_2, mm	1-6
Length of the pick-up coil b_2, mm	2-8
Cross-sectional height of the pick-up coil h_2, mm	1-6
Cross-sectional width of the pick-up coil w_2, mm	1-4
Center distance between the pick-up and excitation coils c, mm	0-6
Excitation frequency f, kHz	0.5-5
Excitation current I, A	0.1-1
Magnetic permeability μ	1-3
Electrical conductivity σ, $\cdot 10^7$, S/m	0.1-0.14
Lift-off z_1, mm	0.5-3.0



a ***b***

Fig. 4

To create the design of experiment, we chose the orthogonal array $L_{27}(3^{13})$ for the controllable and $L_9(3^4)$ for the interfering parameters with three levels of gradation for both types [17, 18]. For this study, modified arrays were obtained from them for the required number of influencing factors, in particular, two redundant factors were removed from $L_{27}(3^{13})$, i.e., $L_{27}(3^{11})$ is obtained, and one redundant factor was removed from $L_9(3^4)$, that is, $L_9(3^3)$, which is allowed by the properties of orthogonal arrays.

**Taguchi`s quality loss function and SNR calculation.** The Taguchi`s robust design method involves the use of a certain quality loss function *Fitness*.

It represents the standard deviation of the studied quality characteristic, i.e. the output signal of the ECP, from its desired target value, which is calculated from the responses to the data set contained in the table of the design of experiment $Fitness = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{1}{E_i^{\,2}}$, where E_i is the output signal of the probe; n is the sample size.

Then, the signal-to-noise ratio, taking into account the "larger is better" property introduced by Taguchi, is calculated using a formula that mixes the average and variance together and assumes that the variance is proportional to the average $SNR = -10 \cdot \lg(Fitness)$. The larger the value of this indicator, the smaller the deviation of the ECP output signal from the target value.

Taguchi's design of experiment. The elements of the orthogonal arrays with three levels of gradation of factors, namely low, medium, and high, are recalculated into units of real physical quantities, i.e., a design of experiment for the interfering parameters (Table 2) and controllable parameters (Table 3) is obtained.

In the further course, according to the constructed plan, the next stage of research is carried out, namely, for each experiment with the specified design parameters (Table 3), the EMF of the probe E, ($\cdot 10^{-4}$ V) is determined at the specified settings for all noise factors (Table 2) and the SNR values are calculated, which are listed in Table 4.

Table 2

№	μ	$\sigma, \cdot 10^7$ S/m	z_1, m
1	1	0.1	0.0005
2	1	0.12	0.00175
3	1	0.14	0.003
4	2	0.1	0.00175
5	2	0.12	0.003
6	2	0.14	0.0005
7	3	0.1	0.003
8	3	0.12	0.0005
9	3	0.14	0.00175

Table 3

№	a_1, m	b_1, m	h_1, m	w_1, m	a_2, m	b_2, m	h_2, m	w_2, m	c, m	f, Hz	I, A
1	0.008	0.012	0.006	0.001	0.001	0.002	0.001	0.001	0	500	0.1
2	0.008	0.012	0.006	0.001	0.0035	0.005	0.0035	0.0025	0.003	2750	0.55
3	0.008	0.012	0.006	0.001	0.006	0.008	0.006	0.004	0.006	5000	1
4	0.008	0.014	0.008	0.003	0.001	0.002	0.001	0.0025	0.003	2750	1
5	0.008	0.014	0.008	0.003	0.0035	0.005	0.0035	0.004	0.006	5000	0.1
...	...	...	...	...	...	...	...	...	...	...	...
11	0.012	0.012	0.008	0.005	0.0035	0.008	0.001	0.0025	0.006	500	0.55
12	0.012	0.012	0.008	0.005	0.006	0.002	0.0035	0.004	0	2750	1
13	0.012	0.014	0.01	0.001	0.001	0.005	0.006	0.0025	0.006	500	1
14	0.012	0.014	0.01	0.001	0.0035	0.008	0.001	0.004	0	2750	0.1
15	0.012	0.014	0.01	0.001	0.006	0.002	0.0035	0.001	0.003	5000	0.55
...	...	...	...	...	...	...	...	...	...	...	...
23	0.016	0.014	0.006	0.005	0.0035	0.002	0.006	0.004	0.003	500	0.1
24	0.016	0.014	0.006	0.005	0.006	0.005	0.001	0.001	0.006	2750	0.55
25	0.016	0.016	0.008	0.001	0.001	0.008	0.0035	0.004	0.003	500	0.55
26	0.016	0.016	0.008	0.001	0.0035	0.002	0.006	0.001	0.006	2750	1
27	0.016	0.016	0.008	0.001	0.006	0.005	0.001	0.0025	0	5000	0.1

Table 4

№	Noise factors									SNR
	$\mu_1, \sigma_1, z_{1,1}$	$\mu_2, \sigma_2, z_{1,2}$	$\mu_3, \sigma_3, z_{1,3}$	$\mu_4, \sigma_4, z_{1,4}$	$\mu_5, \sigma_5, z_{1,5}$	$\mu_6, \sigma_6, z_{1,6}$	$\mu_7, \sigma_7, z_{1,7}$	$\mu_8, \sigma_8, z_{1,8}$	$\mu_9, \sigma_9, z_{1,9}$	
	1	2	3	4	5	6	7	8	9	
1	7.35	6.52	5.74	43.27	29.77	62.28	44.24	92.53	63.84	-59.218
2	5200	4510	3880	5340	3830	8440	4480	10400	6180	-5.959
3	39760	34250	29320	22610	20800	30380	16530	26650	19860	7.610
4	3610	3120	2680	3950	2750	6630	3220	8230	4660	-8.879
5	2810	2440	2100	1710	1540	2300	1240	1860	1510	-15.018
...	...	...	...	...	...	...	...	...	...	...
11	359.7	357.4	344.1	1159	1007	1269	1458	1778	1683	-24.850
12	10910	10170	9230	11010	9500	14510	9620	14600	11720	0.695
13	224	220.7	210.6	731.8	628.6	733.2	931.4	1064	1050	-29.040
14	1815	1640	1458	1853	1508	2532	1606	2900	2008	-14.909
15	8487	7322	6245	6581	5388	9406	4840	9070	6404	-3.601
...	...	...	...	...	...	...	...	...	...	...
23	42.77	43.62	42.82	121.2	11.4	131.9	159.7	171.8	178.74	-43.3
24	10760	10150	9294	12010	10400	15470	10640	15630	13206	1.158
25	308.8	310.1	301.3	948.1	845.5	1040	1205	1468	1381.52	-26.141
26	5547	5257	4820	5849	5137	7760	5148	7452	6353.21	-4.866
27	4789	4356	3849	4124	3539	5271	3157	4712	3919.82	-7.852

where we used the coding μ_i, σ_i, $z_{1,i}$, i = 1, ..., 9; j = 1, ..., 27 to set combinations of factors

Determination of optimal Taguchi`s parameters. The calculated values of signal-to-noise ratios for all experiments are used to further determine the optimal controllable parameters of the ECP, taking into account the "larger is better" property [9]. A number of statistical indicators for each controllable parameter at all levels of its gradation, namely, mean values $(\overline{SNR})^{cont}$; absolute error of the mean value $\Delta = (\overline{SNR}) - (\overline{SNR})^{cont}$, where $(\overline{SNR})$ is the mean value of the signal-to-noise ratio of all controllable parameters, which is - 14.671 dB; standard deviation St.Dev (Table 5), allows us to find the Taguchi`s parameters of the probe that provide the maximum SNR, i.e., their optimal values (Table 6).

Table 5

Factor	a_1			b_1			h_1		
Level	0.008	0.012	0.016	0.012	0.014	0.016	0.006	0.008	0.01
$(\overline{SNR})^{cont}$	-16.864	-14.322	-12.828	-16.231	-14.271	-13.512	-14.11	-14.631	-15.273
Δ	-2.193	0.349	1.844	-1.56	0.4	1.16	0.561	0.041	-0.602
St.Dev	18.712	17.399	16.415	19.862	16.278	16.364	27.246	9.846	9.573

Continuation of Table 5

Factor	w_1			a_2			b_2		
Level	0.001	0.003	0.005	0.001	0.0035	0.006	0.002	0.005	0.008
$(\overline{SNR})^{cont}$	-15.998	-14.382	-13.635	-18.6	-13.756	-11.659	-19.22	-13.856	-10.939
Δ	-1.326	0.29	1.036	-3.927	0.915	3.012	-4.549	0.816	3.733
St.Dev	19.825	16.211	16.510	19.634	15.97	16.205	23.016	10.282	16.0165

Continuation of Table 5

Factor	h_2			w_2			c		
Level	0.001	0.0035	0.006	0.001	0.0025	0.004	0	0.003	0.006
$(\overline{SNR})^{cont}$	-14.372	-14.731	-14.91	-16.335	-14.211	-13.468	-14.043	-14.456	-15.516
Δ	0.299	-0.06	-0.239	-1.664	0.461	1.203	0.628	0.216	-0.844
St.Dev	19.971	16.706	15.924	20.654	16.314	15.296	20.411	15.527	16.514

Continuation of Table 5

Factor	f			I		
Level	500	2750	5000	0.1	0.55	1
$(\overline{SNR})^{cont}$	-32.879	-8.158	-2.977	-26.928	-10.730	-6.356
Δ	-18.208	6.514	11.694	-12.257	3.941	8.316
St.Dev	13.184	7.875	11.015	17.7	11.078	15.211

Table 6

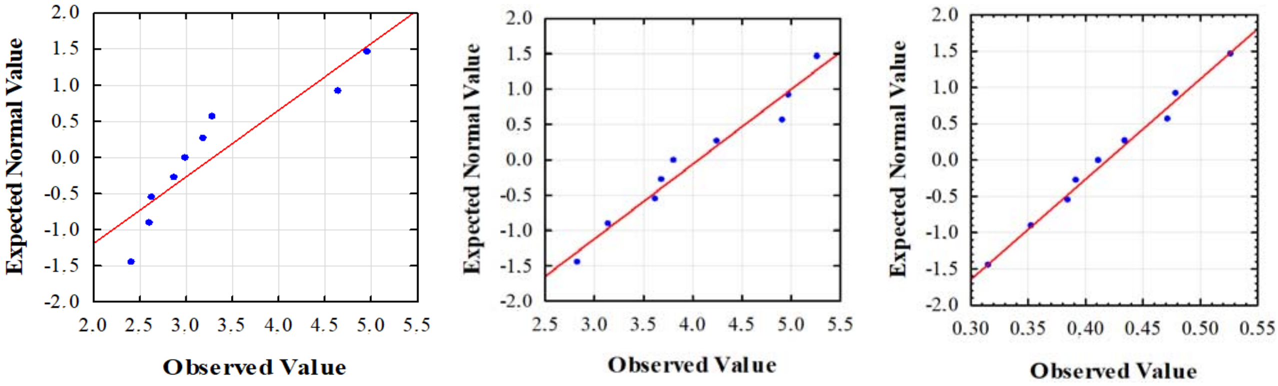
Taguchi-parameters	a_1=16 mm	b_1=16 mm	h_1=6 mm	w_1=5 mm	a_2=6 mm	b_2=8 mm	h_2=1 mm	w_2=4 mm	c=0 mm	f=5 kHz	I=1 A
$(\overline{SNR})^{cont}$,dB	1.843	1.159	0.561	1.036	3.012	3.732	0.299	1.203	0.628	11.69	8.315

The statistical significance of the influence of design parameters, i.e. factors, on the performance sign in the form of the ECP signal was assessed by multifactorial analysis of variance ANOVA [19, 20]. The method is based on the division of the total variance of the studied factor into separate parts, each of which characterizes the influence of a particular parameter on the performance sign. A precondition for the use of ANOVA is the fulfillment of a number of conditions: the observations are independent of each other; have a normal distribution and homogeneous variance. Therefore, the initial data for each of the 27 experiments, i.e., the values of the output signal, were subjected to the procedure of checking their compliance with the normal distribution law. In this study, each experiment has a sample of 9 elements. For this purpose, we used the Shapiro-Wilk criterion, which is the most effective method for solving this problem for small samples, and the d'Agostino-Pearson test, which is an integration of tests for analyzing skewness and kurtosis.

Table 7 shows the results of checking the initial data for their compliance with the normal distribution law according to these two criterions. Also, for some experiments, in particular, № 22, 17, 27, normal probability plots are shown in Fig. 5 a, b, c, respectively, which provide an additional opportunity to visually verify the assumptions about the normality of the data distribution.

Table 7

№	Shapiro-Wilk Test				d'Agostino-Pearson Test			
	W-stat	p-value	alpha	normal	DA-stat	p-value	alpha	normal
1	0.917	0.373	0.05	yes	0.467	0.791	0.05	yes
2	0.833	0.0493	0.05	no	4.556	0.103	0.05	yes
3	0.969	0.887	0.05	yes	0.446	0.799	0.05	yes
4	0.823	0.037	0.05	no	4.549	0.102	0.05	yes
5	0.972	0.911	0.05	yes	0.465	0.792	0.05	yes
6	0.915	0.352	0.05	yes	0.508	0.775	0.05	yes
7	0.954	0.742	0.05	yes	0.672	0.714	0.05	yes
8	0.914	0.351	0.05	yes	0.647	0.723	0.05	yes
9	0.837	0.054	0.05	yes	3.315	0.19	0.05	yes
10	0.959	0.794	0.05	yes	0.357	0.836	0.05	yes
11	0.88	0.157	0.05	yes	2.137	0.343	0.05	yes
12	0.84	0.057	0.05	yes	2.0	0.366	0.05	yes
13	0.863	0.104	0.05	yes	2.304	0.315	0.05	yes
14	0.855	0.085	0.05	yes	3.566	0.168	0.05	yes
15	0.941	0.596	0.05	yes	1.04	0.594	0.05	yes
16	0.85	0.075	0.05	yes	3.881	0.143	0.05	yes
17	0.94	0.591	0.05	yes	1.079	0.582	0.05	yes
18	0.86	0.0977	0.05	yes	2.383	0.303	0.05	yes
19	0.885	0.181	0.05	yes	1.415	0.492	0.05	yes
20	0.986	0.99	0.05	yes	0.187	0.91	0.05	yes
21	0.882	0.165	0.05	yes	2.08	0.353	0.05	yes
22	0.82	0.034	0.05	no	3.221	0.199	0.05	yes
23	0.857	0.09	0.05	yes	2.47	0.29	0.05	yes
24	0.87	0.123	0.05	yes	1.568	0.456	0.05	yes
24	0.88	0.16	0.05	yes	2.059	0.357	0.05	yes
26	0.863	0.105	0.05	yes	1.918	0.383	0.05	yes
27	0.987	0.991	0.05	yes	0.0807	0.96	0.05	yes



a *b* *c*

Fig. 5

Thus, according to the Shapiro-Wilk criterion, only three experiments fail to confirm the hypothesis that the experimental data are distributed according to the normal law, while the d'Agostino-Pearson criterion confirms it in all cases. Nevertheless, even in cases where the data does not follow the normal distribution law, there are minor deviations from it. However, it should be noted that Fisher's criterion, used in analysis of variance to determine the significance of factors, is characterized by resistance to deviations from normality and homogeneity of variances [21], so there is every reason to use it. The statistical significance of the influence of each factor on the signal-to-noise ratio of ECP is assessed by this criterion by comparing the corresponding sample variance *MS* and the variance of reproducibility $MS_{residual}$, which, in turn, is due to random factors. If $(MS/MS_{residual}) > F_{\alpha,m_1,m_2}$, where α is the accepted level of significance equal to 0.05, m_1 is the number of degrees of freedom of the relevant factor, m_2 is the number of degrees of freedom of all random factors, then the influence of the evaluated factor on the performance sign is insignificant. In the case $(MS/MS_{residual}) > F_{\alpha,m_1,m_2}$, the difference between the variances of *MS* and $MS_{residual}$ is significant and, accordingly, a significant influence of the evaluated factor is observed. Also, the conclusion about the significance of the factors can be made by comparing the accepted significance level α with the indicator p obtained for each factor, where *p* is the probability that the influence of the factor on the resultant sign is random. If $p < 0.05$, then the hypothesis of no influence of the factor is rejected and a conclusion is made about its statistical significance. The critical value of Fisher's criterion for this research is $F_{0.05,2,4}$=6.94. Further, comparing the actually obtained values of the variance ratios for each factor, the insignificance of the parameters h_1 and h_2 was revealed (Table 8). Table 8 uses the following notation: SS is the sum of squares of the variance component, F is the variance ratio at the degree of freedom $m_1 = 2$, Q is the percentage contribution of each factor.

Table 8

Parameters	SS	MS	F	p	Q, %
a_1	74.964	37.482	51.664	0.001389	1
b_1	35.448	17.724	24.430	0.005726	0.47
h_1	6.109	3.055	4.210	0.103712	0.08
w_1	26.254	13.127	18.093	0.009907	0.35
a_2	228.014	114.007	157.141	0.000158	3.06
b_2	317.624	158.812	218.898	0.000082	4.26
h_2	1.353	0.676	0.932	0.465233	0.018
w_2	39.850	19.925	27.463	0.004608	0.53
c	10.388	5.194	7.159	0.047678	0.14
f	4596.362	2298.181	3167.694	0.000001	61.63
I	2114.187	1057.094	1457.043	0.000002	28.36
residual	2.902	0.726			

A visual assessment of the best settings for each controllable parameter based on the average SNR values with an indication of the twofold limits of the standard error St.error around its mean is shown in Fig. 6. The ratio $(\overline{SNR})^{cont}$ by levels of the controllable parameters for the excitation coil is shown in Fig. 6, *a*; for the pick-up coil – in Fig. 6, *b*; for the axial relative position of the coils relative to each other – in Fig. 6, *c*; for the operating parameters – in Fig. 6, *d*.

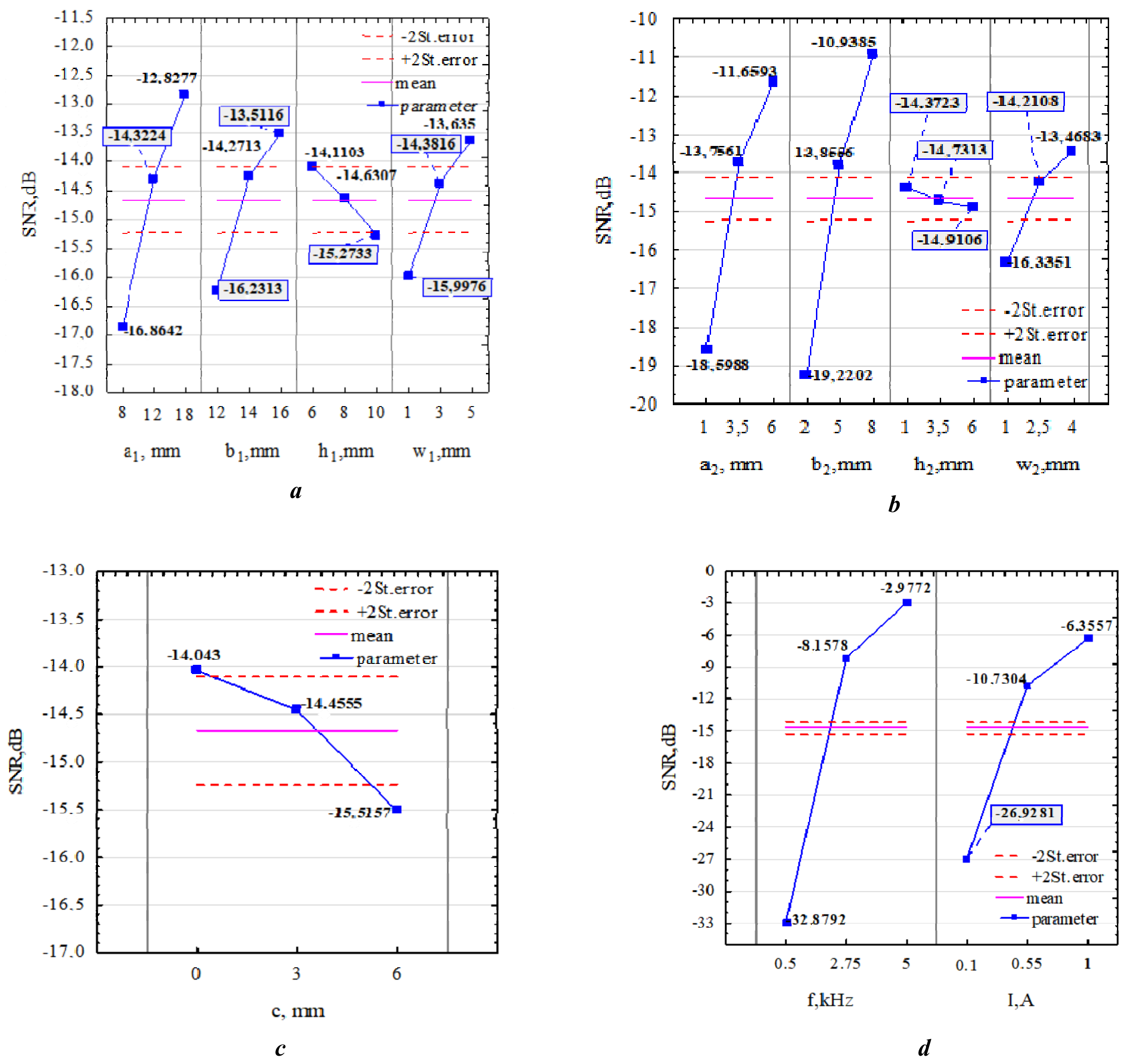


Fig. 6

Confirmation of the reliability of the optimal configuration of the ECP design. The reliability of the found optimal configuration of the ECP design was proved by confirmatory calculations. Thus, with the determined optimal parameters of the ECP (Table 6), we have the best value SNR = 18.815 dB, which is greater than any value obtained in Table 4 of the design of experiments. At the same time, the deviation of the ECP output signal from the target value is minimal and does not exceed 0.107. Thus, the correctness of the found controllable parameters of the designed ECP is confirmed**.**

Table 9

Parameters	z_1, m					
	0.0005	0.001	0.0015	0.002	0.0025	0.003
E_{calc}, V	10.346	9.514	8.791	8.147	7.563	7.027
$\overline{E}_{meas}$, V	10.412	9.461	8.75	8.214	7.532	6.981
Relative error, %	0.63	0.557	0.466	0.822	0.41	0.655

In addition, the results of theoretical studies were experimentally verified on a prototype. For the experiment, we used a TO making of 12X18H10T material with a diameter of D = 105 mm and a thickness that is twice the depth of penetration of the electromagnetic field, such as h = 10 mm. The excitation of the tested ECP, which has geometric dimensions (Table 6), was carried out by an OWON XDG3082 arbitrary waveform generator. It provides the generation of sinusoidal signals in the frequency range of 1 μHz – 80 MHz with an accuracy of ± 1 ppm and an amplitude of 1 mV – 5 V with an accuracy of ± 1 % with an amplified signal output of up to 2 A. The output signal of the pick-up coil was recorded by an ANENG AN888S PRO voltmeter with an accuracy of ± 0.3 %. In this experiment, of the three noise factors, only the change in the lift-off z_1 can be performed with a certain step, and the variation of the electrophysical characteristics of the TO cannot be ensured. Therefore, the TO is characterized by constant electrophysical properties $\mu = 1.5$, $\sigma = 0.135 \cdot 10^7$ S/m, and the lift-off between the TO and the eddy current probe was set in the range of 0.5 – 3 mm with a step of 0.5 mm and measured with a digital micrometer MCD – 50 - 0.001 with an error of ± 0.002 mm. The average EMF value based on the results of three measurements under the specified experimental conditions is shown in Table 9. In addition, the EMF values obtained by calculations using the mathematical model (1) and the corresponding relative measurement errors are also given there for comparison.

Thus, the maximum signal measurement error does not exceed 1 %.

Conclusions. Thus, in the study, on the example of an eddy current geometric anomaly measurement, we carried out its computer robust design using a comprehensive integrated approach combining numerical modeling and the Taguchi`s method. The physical process of measurement is analyzed and, as a result, influential controllable and uncontrollable factors are identified.

Software for the implementation of robust design of an eddy current measurement was created. Based on test calculations using the finite element method, the software was verified by comparing the results of calculating the x-component of magnetic induction. Graphs of the change in the magnetic induction modulus of the secondary electromagnetic field depending on uncontrolled parameters of the TO, in particular, magnetic permeability and electrical conductivity, at different excitation frequencies were obtained and the lower and upper limits of the change in all influencing factors were determined for further research. Taking into account the number of factors, two types of orthogonal arrays, namely $L_{27}(3^{13})$ and $L_9(3^4)$ with three levels of their gradation, were chosen to build a design of experiments. As a result of the numerical experiments, the design and operating optimal parameters of the eddy current measurement were determined, which ensure signal immunity to interference with SNR = 18.815 dB. The reliability of the found optimal configuration of the ECP design was proved by confirmatory calculations. In addition, the experimental verification of the research results was carried out on the prototype, which showed the reliability of measurements by the designed ECP with a maximum relative error of no more than 1 %.

The scientific novelty of the research is the creation of a method of computer robust parameter design of frame ECPs for measuring geometric anomalies of static planar objects using an integrated approach combining numerical modeling and the Taguchi`s method, which ensures signal stability to changes in air lift-off and variations in TO parameters.

Within the framework of the proposed design method and using the universal magnetodynamic model of the ECP, similar studies are promising for the measurement testing of planar moving electrically conductive products of considerable thickness; planar static and moving two-layer electrically conductive products; dielectric and electrically conductive coatings on a static conductive basis.

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РОБАСТНЕ ПАРАМЕТРИЧНЕ ПРОЄКТУВАННЯ НАКЛАДНИХ ВИХРОСТРУМОВИХ ПЕРЕТВОРЮВАЧІВ. ВИПАДОК ВИМІРЮВАННЯ ГЕОМЕТРИЧНИХ АНОМАЛІЙ У НЕРУХОМОМУ ОБ'ЄКТІ КОНТРОЛЮ

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Вступ. *Зменшення впливу перешкоджаючих факторів на формування сигналу вихрострумового перетворювача ще на етапі проєктування є важливою задачею під час конструювання вимірювачів геометричних аномалій. Реалізація цього можлива низкою методів, серед яких виділяється доволі проста техніка робастного параметричного проєктування на основі методу Тагучі у процесі пошуку оптимальної конфігурації конструкції перетворювачів.* ***Метою*** *роботи є розробка методу підвищення відношення сигнал/шум вихрострумових вимірювачів геометричних аномалій у статичних пласких об'єктах без фактичного усунення притаманних їм впливів шумових факторів, які в більшій мірі властиві об'єктам контролю.* ***Методологія*** *досліджень передбачає наступні основні етапи, які необхідні задля виконання проєктування вихрострумових перетворювачів за методом Тагучі:*

– виокремлення вимірюваної перетворювачем характеристики об'єкту контролю, яка фіксується його вихідним сигналом;
–ідентифікація контрольованих параметрів вихрострумових перетворювачів та можливих рівнів їх градації у разі варіюваняі;
– визначення шумових факторів та їх рівнів градації;
– призначення інтервалів змін контрольованих та шумових факторів;
– обрання ортогональних масивів;
– створення плану експериментів та проведення їх за універсальною магнітодинамічною моделлю задля обчислення вихідного сигналу вихрострумових перетворювачів із використанням комп'ютерного моделювання;
– на основі ANOVA-аналізу впливу факторів на індуковану електрорушійну силу перетворювача та розрахованих для кожного іспиту значень відношення сигнал/шум на базі функції втрати якості Тагучі виконання обрання оптимального варіанту конфігурації конструкції вихрострумових перетворювачів за відповідною комбінацією рівнів градації контрольованих факторів, що максимізує показник SNR;
– проведення підтверджуючих чисельних експериментів щодо перевірки знайдених оптимальних параметрів конфігурації конструкції перетворювачів.

Оригінальність *проведених досліджень полягає у використанні методу Тагучі з поєднанням чисельного моделювання задля розробки методу комп'ютерного робастного параметричного проєктування рамкових вихрострумових перетворювачів для вимірювання геометричних аномалій статичних пласких об'єктів, котрий забезпечує під час вимірювань стійкість сигналу до змін повітряного зазору та варіації шумових параметрів об'єктів контролю, тобто підвищення значень відношення сигнал/шум.* ***Результати.*** *На прикладі знайдена робастна конфігурація конструкції вихрострумового перетворювача, тобто такий її технічний варіант, який забезпечує зменшення дисперсії вихідного сигналу навколо його середнього значення, тобто стійкість до шумових збурень, завдячуючи тільки відповідному визначенню значень контрольованих конструктивних та режимних параметрів перетворювачів без усунення неконтрольованих завад, притаманних об'єктам контролю. Задля робастного проєктування низки вихрострумових вимірювачів різного функціоналу запропонована універсальна магнітодинамічна модель накладного рамкового перетворювача, яка разом із використанням ортогональних масивів дає змогу розробити та реалізувати плани експериментів Тагучі. Програмне забезпечення, що реалізує цю модель, пройшло верифікацію, в тому числі співставленням із результатами розрахунків на тестових прикладах, виконаних методом скінченних елементів. Досягнута при цьому точність дає можливість стверджувати про адекватність створеної комп'ютерної програми. Отримані в рамках виконання плану Тагучі дані використано для оцінки варіантів конструкцій за допомогою функції втрат якості типу «larger is better» та обчислених на її основі значень відношень сигнал/шум, що дало змогу обрати оптимальну комбінацію конструктивних та режимних параметрів вихрострумового перетворювача. Достовірність відшуканої оптимальної конфігурації конструкції вихрострумового перетворювача доведена підтверджуючими розрахунками. Також на дослідному зразку проведена експериментальна перевірка результатів досліджень.* Бібл. 21, рис. 6, табл. 9.

Ключові слова: робастне параметричне проєктування, вимірювання геометричних аномалій, прямокутний накладний вихрострумовий перетворювач, подавлення шумів, універсальна магнітодинамічна модель перетворювача, план експериментів Тагучі, функція втрат якості, відношення сигнал/шум.

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