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# DEVELOPMENT OF EXCITATION STRUCTURE RBF-METAMODELS OF MOVING CONCENTRIC EDDY CURRENT PROBE

***Introduction.** The work is devoted to metamodels creation of surface circular concentric eddy current probe. **Formulation of the problem.** In the problem of surface circular concentric eddy current probe synthesis in the general formulation, apriori given desired eddy currents density distribution in the control zone was used. The realization of the optimal synthesis problem involves a multiple solution to the analysis problem for each current structure of numerical calculations excitation, which are very costly in terms of computational and time costs, which makes it impossible to solve the synthesis problem in the classical formulation. By solving the critical resource intensiveness problem, there is the surrogate optimization technology using of that uses the surface circular concentric eddy current probe metamodel, which is much simpler in realization and is an approximation of the exact electrodynamic model. **Goal.** Creation of surface circular concentric eddy current probe RBF-metamodels, which can be used to calculate eddy currents density distribution in the control zone and suitable for use in optimal synthesis problems. **Method.** To develop an approximation model, a mathematical apparatus for artificial neural networks, namely, RBF–networks, has been used, whose accuracy has been increased with the help of the neural networks committee. Correction of errors in the committee was reduced by applying the bagging procedure. During the network training the regularization technique is used, which avoids re-learning the neural network. The computer experiment plan was performed using the Sobol LPτ–sequences. The obtained multivariable regression model quality evaluation was performed by checking the response surface reproducibility correctness in the entire region of variables variation. **Results.** The modelling of eddy currents density distribution calculations on exact electrodynamic mathematical models in the experimental plan points are carried out. For the immovable and moving surface circular concentric eddy current probe, RBF–metamodels were constructed with varying spatial coordinates and radius. **Scientific novelty.** Software was developed for eddy currents density distribution calculation in the surface circular concentric eddy current probe control zone taking into account the speed effect on exact electrodynamic mathematical models and for forming experiment plan points using the Sobol LPτ–sequences. The geometric surface circular concentric eddy current probe excitation structures models with homogeneous sensitivity for their optimal synthesis taking into account the speed effect are proposed. Improved computing technology for constructing metamodels. The RBF-metamodels of the surface circular concentric eddy current probe are built and based on the speed effect. **Practical significance.** The work results can be used in the surface circular concentric eddy current probe synthesis with an apriori given eddy currents density distribution in the control zone.* References 22, tables 6, figures 8.

*Key words*: **surface eddy current probe, eddy currents density distribution, excitation structure, mathematical model, optimal synthesis, computer experiment plan, LPτ–sequence, RBF–metamodel, neural networks committee**.

***Розроблено програмне забезпечення для розрахунку розподілу густини вихрових струмів в зоні контролю накладного вихрострумового перетворювача із врахуванням ефекту швидкості за «точними» електродинамічними математичними моделями. Розроблено програмне забезпечення для формування точок плану експерименту із використанням ЛП$_\tau$–послідовностей, що дозволило здійснювати відбір планів з рівномірним заповненням точками гіперпростору пошуку. Для нерухомого та рухомого накладних вихрострумових перетворювачів створено нейромережеві метамоделі на радіально-базисній функції Гауса. Оцінено адекватність та інформативність отриманих метамоделей накладних вихрострумових перетворювачів. Результати дослідження можуть бути використані при синтезі рухомих накладних вихрострумових перетворювачів із апріорі заданим розподілом густини вихрових струмів в зоні контролю.*** Бібл. 22, табл. 6, рис. 8.

*Ключові слова*: **накладний вихрострумовий перетворювач, розподіл густини вихрових струмів, структура збудження, математична модель, оптимальний синтез, комп'ютерний план експерименту, ЛП$_\tau$–послідовність, RBF–метамодель, комітет нейронних мереж.**

***Разработано программное обеспечение для расчета распределения плотности вихревых токов в зоне контроля накладного вихретокового преобразователя с учетом эффекта скорости по «точным» электродинамическим математическим моделям. Разработано программное обеспечение для формирования точек плана эксперимента с использованием ЛПτ-последовательностей, что позволило осуществлять отбор планов с равномерным заполнением точками гиперпространства поиска. Для неподвижного и движущегося накладных вихретоковых преобразователей созданы нейросетевые метамодели на радиально-базисной функции Гаусса. Оценены адекватность и информативность полученных метамоделей накладных вихретоковых преобразователей. Результаты исследования могут быть использованы при синтезе движущихся накладных вихретоковых преобразователей с априори заданным распределением плотности вихревых токов в зоне контроля.*** Библ. 22, табл. 6, рис. 8.

*Ключевые слова:* **накладной вихретоковый преобразователь, распределение плотности вихревых токов, структура возбуждения, математическая модель, оптимальный синтез, компьютерный план эксперимента, ЛПτ–последовательность, RBF–метамодель, комитет нейронных сетей**.

**Introduction.** The eddy current control method and the devices on its basis are widely used to determine the parameters of various objects of control (OC): imperfect material defects, control of the dimensions of the OC and vibration parameters, quality control of thermal and chemical-thermal processing of parts, the state of surface layers after machining, the presence of residual mechanical stresses, the reconstruction of the distribution of electrical conductivity and the magnetic permeability within the objects, and others.

Along with the significant advantages of the eddy current control method, there are some disadvantages, for example, the ability to control only the conductive objects, the relatively small depth of the eddy currents penetration, the heterogeneous sensitivity of the probes of classical design.

The typical surf ace eddy current probes (SECP) are characterized by a characteristic distribution of the eddy currents density (ECD) in the OC, which depends on the geometrical, electromagnetic parameters and the relative position of its exciting coil relative to the controlled surface. In SECP, the ECD is maximal in the surface layer of the conductive object and decreases at the removal from the excitation coil windings along the surface (Fig. 1,*a*) and in deeper layers according to the exponential law. That is, in such a heterogeneous distribution of the ECD (Fig. 1,*a*), the relative position of the SECP with respect to the OC significantly influences the sensitivity of the method. In the defectoscopy, for example, in the case where a surface fracture of a finite length is located under the geometric center of the excitation coil, the sensitivity will be close to zero (Fig. 1,*c*), the minimum sensitivity is observed for the case of the location of the surface crack in parallel to the vortex currents (Fig. 1,*d*) and the maximum one – if the crack is perpendicular to the direction of eddy currents (Fig. 1,*e*).

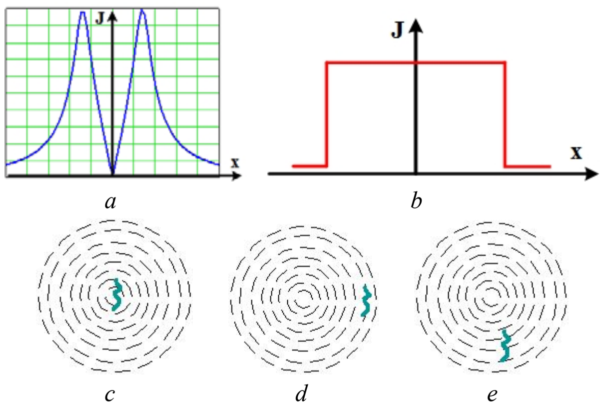



Fig. 1. Features of the SECP: distribution of ECD, inherent in classical designs of probes (*a*); uniform distribution of ECD (*b*); sensitivity close to zero (*c*); minimum sensitivity (*d*); maximum sensitivity (*e*)

In order to reduce the effect of the dependence of the sensitivity of the probes to the defect, regardless of its location in the control zone, it is desirable to have the distribution of the ECD in it homogeneous (Fig. 1,*b*). The problem arises of the creation of the SECP with homogeneous sensitivity, and, consequently, a homogeneous distribution of the ECD in the control zone of the object. This problem can be solved within the framework of optimal synthesis as a result of determining the rational structure of the excitation system of the SECP with the corresponding parameters that provide the necessary distribution of the ECD. It is also important to achieve homogeneous sensitivity of the SECP which are not only stationary relative to the OC or move at a low speed, when the effect of the transfer currents can be neglected, but also for mobile probes.

**Literature review.** In [1], the problems of linear synthesis of a fixed SECP are considered, where the dependence of the output signal on the gap or the specific electrical conductivity of the investigated object is taken as the initial data. In order to solve an incorrect synthesis problem, the method of regularization is applied, i.e. certain restrictions were introduced on the desired functions. In [2] the questions of linear synthesis of a fixed SECP are considered. The plane of the control zone is parallel to the working face of the probe, where a given magnetic field structure was created. In [3] an algorithm for nonlinear synthesis of magnetic fields of excitation of a fixed SECP with a predefined configuration is presented. The solution of the problem is obtained by minimizing the average stepped approximation of the minimax functional, which provides the minimum deviation of the desired distribution of the electromagnetic field from the given one. In the paper [4] a structural-parametric synthesis of the excitation system of a fixed SECP is performed. The searched parameters are the number of sections, their radii and coordinates. The search for an optimal solution is performed using a genetic algorithm. The optimum values of the parameters of the coil sections, as well as the most constructively simple excitation system that provide the given distribution of the probe field in space, are obtained. Significant improvement of the quality of the generated field of the synthesized magnetic system, the essential simplification of the structure by the number of sections and the reduction of the length of the system, as well as reduced number of turns in sections at the same values of currents have been achieved. In [5] a methodology for optimizing the design of a coil of an eddy current probe (ECP) is proposed, which allows maximum approximation to the ideal excitation field in the multi-purpose statement of the problem. The research presents a method for optimizing the design of the excitation system to obtain a tangential and uniform distribution of multilinear eddy currents. In [6], a method for optimizing the parameters of an excitation coil was developed by solving a multi-parameter multi-purpose optimization problem. The imitation modeling of the behavior of an infinite coil with a tangential uniform field on the surface of the OC is carried out. As a result, a non-uniform multilayer design of the ECP coil has been obtained, which provides a uniform field of excitation. In [7], a genetic algorithm for solving the optimization problem of selecting the parameters of the ECP excitation field was used. For the excitation coil of the probe, the optimal values of frequency and size are obtained.

Thus, previously published studies devoted to the questions of synthesis of ECP [1-7] with a given configuration of the probe field in the control zone, considered the fixed OC and did not take into account the reaction of the conductive medium. It was enough to create a system of excitation of the SECP with a uniform distribution of the electromagnetic field, which was guaranteed to ensure a uniform distribution of the ECD in the OC. The account of the speed effect involves the synthesis of a homogeneous distribution of the ECD in the environment of the OC, which is a fundamental difference from the results of previous studies and can not be carried out by the means previously proposed.

**The goal and objectives of the study.** *The object of the study* is the processes of eddy current control of the quality of objects. *The subject of research* is a mobile circular SECP with a homogeneous distribution of the ECD in the control zone. *The goal of the work* is to create a RBF-metamodel for a mobile concentric circular SECP that can be used to calculate the distribution of the ECD in the control area and be suitable for use in optimal synthesis problems.

**Mathematical model of the mobile SECP.** As the initial input data for designing in the problem of synthesis of the SECP in the general formulation a priori given the desired distribution of the ECD $J_{reference}$ in the control zone is used. For the purpose of some simplification of the problem, we restrict ourselves first by obtaining this distribution of the ECD on the surface of the OC, specifying certain values of the ECD in the set of $N$ control points $Q$.

The structure of the excitation of the SECP consists of a system of $M$ coils of varying height of position $z_{0k}$, $k = 1\ldots M$ of the corresponding coil relative to the OC and radii $r_k$. The circuit of their connection is counter or coherent, and the supply current $I$ can be the same or different for each of the coils. As an option of the structure of excitation, Fig. 2,*a* shows a system of concentric coils with different radii which is located at the same height $z_0$ over OC. Fig. 2,*b* shows the excitation system of coils of different radii, which are located at the same height, with the centers of the coils shifted, that is, the coils are not concentric. Fig. 2,*c* shows a system of coils with different radii, which are located at different heights and with the displacement of the centers of one relative to the other.

In [8-13] a mathematical model of a single excitation coil of the SECP was developed, which allows to determine the distribution of the ECD in the OC, which we agree to call «accurate». For this, the following assumptions were made: the medium is linear, homogeneous, isotropic; the OC is mobile, conductive, of infinite width and length and has a finite thickness $d$; the coil is excited by alternating current $I$ of frequency $\omega$; the conductor of the coil is represented as infinitely thin; the electrical conductivity $\sigma$, the relative magnetic permeability $\mu_r$ and the speed of the probe $\vec{\upsilon} = (\upsilon_x, \upsilon_y, 0)$ are constant. In accordance with this mathematical model, three calculated areas are considered in which the complex values of magnetic flux density are determined:

- in the area $0 < z < z_0$

$$\vec{B}_1 = \vec{B}_i + \vec{B}_r,$$
$$\vec{B}_i = \mathrm{rot}\,\vec{A}_i, \quad \vec{A}_i = \frac{\mu_0}{4\pi}\int_l \frac{\vec{J}\,\mathrm{d}l}{R}, \qquad (1)$$
$$\Delta\vec{B}_r = 0, \quad \mathrm{rot}\,\vec{B}_r = 0,$$

where $\vec{B}_i$ describes the own magnetic field of a turn of length $l$ and current density $\vec{J}$, and $\vec{B}_r$ is the magnetic field of eddy currents induced in the medium of the OC;

- in the area $-d < z < 0$

$$\Delta\vec{B}_2 - \sigma\cdot\mu\cdot\mu_0\cdot\left(\upsilon_x\cdot\frac{\partial\vec{B}_2}{\partial x} + \upsilon_y\cdot\frac{\partial\vec{B}_2}{\partial y}\right) - j\cdot\omega\cdot\sigma\cdot\mu\cdot\mu_0\cdot\vec{B}_2 = 0, \qquad (2)$$
$$\mathrm{div}\,\vec{B}_2 = 0;$$

- in the area $z < -d$

$$\Delta\vec{B}_3 = 0, \ \mathrm{rot}\,\vec{B}_3 = 0. \qquad (3)$$

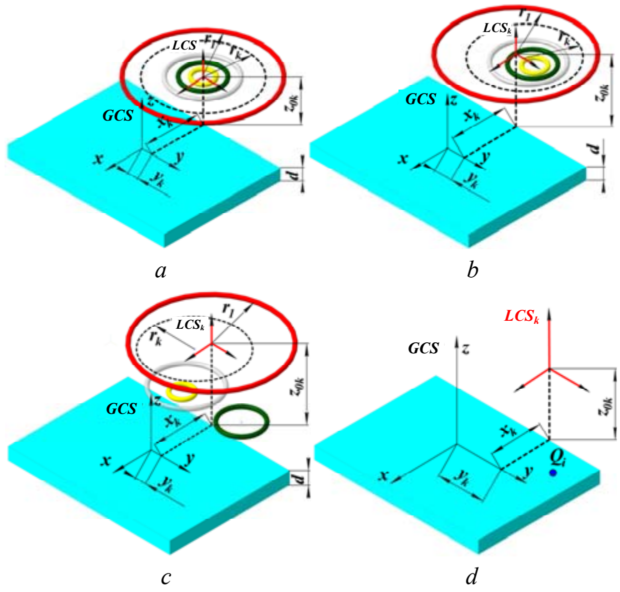



Fig. 2. Geometric models of SECP excitation structures: a system of concentric coils, where the coils are located at the same height $z_0$ (*a*); a system of coils where the coils are located at one height $z_0$, the centers of the coils shifted (*b*); a system of coils, where the coils are located at different heights, the centers of the coils shifted (*c*); general location of global and local coordinate systems of coils (*d*)

The solution of the system of equations (1)-(3) in conjunction with the conditions of continuity of the tangential component of the magnetic field strength and the normal component of magnetic flux density on the boundaries of the media interfaces $z = 0$ and $z = -d$, allows to obtain the distribution of components of the magnetic flux density in the medium of the OC:

$$B_{2x} = \frac{\mu_0\cdot\mu_r\cdot I}{8\cdot\pi^2}\cdot\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\xi}{\eta\cdot\left(1-e^{2\cdot\gamma\cdot d}\right)}\times$$
$$\times\left[\left\{-(1+\lambda_0)\cdot e^{2\cdot\gamma\cdot d}+\nu_0\cdot e^{\left(\gamma-\sqrt{\xi^2+\eta^2}\right)\cdot d}\right\}\cdot e^{\gamma\cdot z}+\right.$$
$$\left.+\left\{1+\lambda_0-\nu_0\cdot e^{\left(\gamma-\sqrt{\xi^2+\eta^2}\right)\cdot d}\right\}\cdot e^{-\gamma\cdot z}\right]\times \qquad (4)$$
$$\times e^{-z_0\cdot\sqrt{\xi^2+\eta^2}}\cdot S(\xi,\eta)\cdot e^{-j(x\cdot\xi+y\cdot\eta)}d\xi d\eta;$$

$$B_{2y} = \frac{\mu_0\cdot\mu_r\cdot I}{8\cdot\pi^2}\cdot\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{\left(1-e^{2\cdot\gamma\cdot d}\right)}\times$$
$$\times\left[\left\{-(1+\lambda_0)\cdot e^{2\cdot\gamma\cdot d}+\nu_0\cdot e^{\left(\gamma-\sqrt{\xi^2+\eta^2}\right)\cdot d}\right\}\cdot e^{\gamma\cdot z}+\right.$$
$$\left.+\left\{1+\lambda_0-\nu_0\cdot e^{\left(\gamma-\sqrt{\xi^2+\eta^2}\right)\cdot d}\right\}\cdot e^{-\gamma\cdot z}\right]\times \qquad (5)$$
$$\times e^{-z_0\cdot\sqrt{\xi^2+\eta^2}}\cdot S(\xi,\eta)\cdot e^{-j(x\cdot\xi+y\cdot\eta)}d\xi d\eta;$$

$$B_{2z} = j \cdot \frac{\mu_0 \cdot \mu_r \cdot I}{8 \cdot \pi^2} \cdot \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\xi^2 + \eta^2}{\eta \cdot \gamma \cdot \left(1 - e^{2 \cdot \gamma \cdot d}\right)} \times$$

$$\times \left[ \left\{ -\left(1 + \lambda_0\right) \cdot e^{2 \cdot \gamma \cdot d} + \nu_0 \cdot e^{\left(\gamma - \sqrt{\xi^2 + \eta^2}\right) \cdot d} \right\} \cdot e^{\gamma \cdot z} - \right.$$

$$\left. - \left\{ 1 + \lambda_0 - \nu_0 \cdot e^{\left(\gamma - \sqrt{\xi^2 + \eta^2}\right) \cdot d} \right\} \cdot e^{-\gamma \cdot z} \right] \times \qquad (6)$$

$$\times e^{-z_0 \cdot \sqrt{\xi^2 + \eta^2}} \cdot S(\xi, \eta) \cdot e^{-j(x \cdot \xi + y \cdot \eta)} d\xi d\eta,$$

where $B_{2x}$, $B_{2y}$, $B_{2z}$ are the components of the magnetic flux density by spatial coordinates; $S(\xi, \eta)$ is the function of the shape of the coil,

$$S(\xi, \eta) = -j \cdot \frac{2 \cdot \pi \cdot r \cdot \eta}{\sqrt{\xi^2 + \eta^2}} \cdot J_1\left(r \cdot \sqrt{\xi^2 + \eta^2}\right);$$

$$\gamma = \sqrt{\begin{matrix} \xi^2 + \eta^2 - j \cdot \sigma \cdot \mu_0 \cdot \mu_r \cdot \left(\upsilon_x \cdot \xi + \upsilon_y \cdot \eta\right) + \\ + j \cdot \omega \cdot \sigma \cdot \mu_0 \cdot \mu_r \end{matrix}};$$

$$\lambda_0 = \frac{\left\{\gamma^2 - \mu_r^2 \cdot \left(\xi^2 + \eta^2\right)\right\} \cdot \left(1 - e^{-2 \cdot \gamma \cdot d}\right)}{\left(\gamma + \mu_r \cdot \sqrt{\xi^2 + \eta^2}\right)^2 - \left(\gamma - \mu_r \cdot \sqrt{\xi^2 + \eta^2}\right)^2 \cdot e^{-2 \cdot \gamma \cdot d}};$$

$$\nu_0 = \frac{4 \cdot \mu_r \cdot \gamma \cdot \sqrt{\xi^2 + \eta^2} \cdot e^{\left(\sqrt{\xi^2 + \eta^2} - \gamma\right) \cdot d}}{\left(\gamma + \mu_r \cdot \sqrt{\xi^2 + \eta^2}\right)^2 - \left(\gamma - \mu_r \cdot \sqrt{\xi^2 + \eta^2}\right)^2 \cdot e^{-2 \cdot \gamma \cdot d}},$$

where $\upsilon_x$, $\upsilon_y$ are the components of the velocity of the circular SECP relative to the OC; $d$ is the OC thickness; $\xi$, $\eta$ are the variables of integration.

These expressions are adequate in the local coordinate system (LCS), where the origin of the coordinates coincides with the center of the turn. Multiple non-proper integrals of the first kind, which they contain, are calculated numerically by the truncation method.

Expressions (4) – (6) allow to obtain an «exact» mathematical model of the distribution of the ECD in the OC for the circular SECP. The components of the ECD by spatial coordinates $x$, $y$, $z$ are respectively determined by the formulas:

$$J_x = \frac{1}{\mu_0 \cdot \mu_r} \cdot \left[ \frac{\partial B_{2z}}{\partial y} - \frac{\partial B_{2y}}{\partial z} \right];$$

$$J_y = \frac{1}{\mu_0 \cdot \mu_r} \cdot \left[ \frac{\partial B_{2x}}{\partial z} - \frac{\partial B_{2z}}{\partial x} \right]; \qquad (7)$$

$$J_z = \frac{1}{\mu_0 \cdot \mu_r} \cdot \left[ \frac{\partial B_{2y}}{\partial x} - \frac{\partial B_{2x}}{\partial y} \right].$$

The coordinates of the control points $Q_i$, $i = 1 \ldots N$ are specified in the global coordinate system (GCS), then they are recalculated to the $k$-th LCS. In the LCS, the ECD calculation is performed at each control point, and then the resulting values are obtained as a superposition at each point $i = 1 \ldots N$ from all $M$ coils (Fig. 2,*d*).

In the general case, the objective function for the problem of optimal synthesis in the classical formulation has the form:

$$F_{target} = \sum_{i=1}^{N} \left( \sum_{k=1}^{M} J_{ik} - J_{reference} \right)^2 \to \min, \qquad (8)$$

where $J_{reference}$ is the desired value of the eddy current currents at the control point; $J_{ik}$ is the density of the eddy current in the control point of the OC with the number $i$, created by the $k$-th coil of the excitation system of the SECP; $N$ is the number of control points in the area; $M$ is the number of coils in the system of excitation of the circular SECP. As a result of the synthesis, the spatial configuration and geometric parameters of the structure of excitation of the SECP are obtained, which collectively provide the implementation of the required characteristics. The realization of the problem of optimal synthesis involves a multiple solution to the problem of analysis for each current structure of excitation by numerical calculations. In [14, 15] it is established that calculations on these expressions are very costly in terms of computational and time costs, which makes it impossible to solve the problem of synthesis.

One of the solutions of the problem of critical resource intensity is the use of surrogate optimization technologies [16, 17] and stochastic meta-heuristic optimization [18, 19]. That is, for the purpose of formulating the goal function within the framework of the optimal synthesis problem, a SECP metamodel can be used, which is much simpler in implementation and less resource-intensive [14, 15] and is an approximation of the «exact» electrodynamic model.

To achieve this goal, the following tasks were solved: creation of software for calculating the distribution of the ECD in the control zone of the SECP taking into account the effect of speed by «exact» electrodynamic mathematical models; creation of software for forming points of an experiment plan using the Sobol LPτ–sequences to select the most perfect experimental plans individually for the approximated surfaces of the response; to create geometrical models of excitation structures of circular SECPs with homogeneous sensitivity for their optimal synthesis taking into account the effect of speed; to improve the computational method of constructing metamodels of objects that are characterized by considerable computational resource intensities in the simulation of physical processes; to create RBF-metamodels of the concentric circular SECP (fixed one and taking into account the effect of speed).

To calculate the «exact» electrodynamic mathematical models (4) – (7), software was developed in the MathCAD 15 package.

The calculation of the distribution of the ECD for the turn of the excitation coil of the circular shape in order to visualize it was performed for the case of variation of the two parameters $J = f(x, y)$ (Fig. 2,*a*) and the other fixed ones by the formulas (4) – (7) of the «exact» mathematical models with the following input data: for the case of a fixed SECP $–x = 0…30$ mm, $y = 0…30$ mm, $r = 5$ mm; for the case of a moving SECP – $\upsilon = (40; 0; 0)$ m/s; $x = –30…30$ mm, $y = 0…30$ mm, $r = 5$, 10, 15 mm; thickness of the conductive material $d = 10$ mm; height of the placement turn of the coil over OC $z_0 = 3$ mm; frequency $f = 100$ Hz; electrophysical parameters of the material $\sigma = 3.745 \cdot 10^7$ S/m, $\mu_r = 1$, current $I = 1$ A.

Fig. 3,*a*-*h* show the 3D distribution of the ECD and the level lines for some excitation coil turns radiuses. For example, Fig. 3,*a*,*b* show the simulation results for a fixed SECP, and Fig. 3,*c*-*h* present the results of calculating the distribution of the ECD taking into account the effect of speed.

The computational complexity of a one-time calculation of the ECD distribution by an «exact» mathematical model with variations of only two spatial coordinates $J = f(x, y)$ at $r = \text{const}$ is sufficiently large and ranges from 5 to 8 hours.

**Main points and development of metamodels.** In [14, 17], the authors proposed a general computational method for constructing metamodels using modern achievements in the field of artificial intelligence and the theory of experiment planning. A number of examples have proved the effectiveness of its use. Neural networks have been used to construct a substitute model, which provide the ability to quickly and easily calculate the output of the network, even with a sufficiently large number of neurons in hidden layers. In [15, 16] some features of the application of this technology in relation to the problems of the synthesis of the SECP are considered. Below, attention is focused on the details of the construction of metamodels of the circular SECP with certain structures of the excitation system, namely, the variant illustrated in Fig. 2,*a*, that is, approximation $\hat{J} = f(x, y, r)$.

In contrast to the previous studies of authors, increasing the accuracy of the neural network solution of approximation problems was achieved with the help of the neural networks committee [20]. The committee makes the final decision using separate solutions of several neural networks, that is, the method of bagging. Thus, the bagging committee is used to reduce the correlation of neural network errors. This methodology involves training neural networks on bootstrap-samples, which represent a set of elements with repetitions from a previous training set of data. Bagging provides the most effectiveness in the case of a fairly large number of input training data. Thus, for the construction of an approximation model, the mathematical apparatus of artificial neural networks was used namely the bagging committee of RBF-networks with the Gaussian activation core function.

The creation of a metamodel involves the construction of a computer experiment plan, at which points the distribution of the ECD is calculated by the «exact» mathematical model, the construction of an approximation model and validation of the model.

The experiment plan is implemented with the help of uniform computer filling by the points of the 3D search space, namely, using the Sobol LPτ–sequences [21]. The points of the experiment plan are generated using LPτ–sequences ($\zeta_1$, $\zeta_2$, $\zeta_4$) and their total number is: for the case of a fixed SECP – $N = 2048$ and $N = 3315$ – for a moving SECP. For each section of the surface by the radius there is approximately $N_{cut} = 146$ and $N_{cut} = 255$ points, respectively.

The obtained ECD values at the points of the plan are used as the initial data for the implementation of the next stage – construction of the metamodel. The number of points of calculation essentially depends on the symmetry of the distribution of the ECD relative to the coordinate axes (Fig. 3), so for the fixed SECP the points of the plan are given in the I quadrant, and for the moving one – in the I and II quadrants.

Fig. 4 is presented in order to provide a visual representation of the experiment plan. Fig. 4,*a* shows the location of the points of LPτ–sequences for their small number $N = 250$ in the 3D space $k = 3$, and Fig. 4,*b* shows the location of the indicated points in subspaces of smaller dimension $k = 2$ for the combined factors ($\xi_1$, $\xi_2$, $\xi_4$). Fig. 4,*c*-*f* present a 3D distribution of points for fixed radii 1, 5, 10 and 15 mm when generating them according to this plan.

For realization of the second stage the heuristic method of constructing metamodels with the help of neural networks is used. The construction of the RBF-metamodels is accomplished with the help of an automatic strategy and multiple sub-samples.

In the automatic mode, the samples are formed by random division in the ratio: 70 % – training, 15 % – control, 15 % – test, where the test population was used for cross-checking.

In the second series of constructing metamodels, using the method of multiple sub-samples, a bagging algorithm was used in which 20 repetitive samples were generated based on the training set and training was performed based on these bootstrap-samples of the 20 neural networks. Elements not included in the next sample are used as a test set for the corresponding neural network. For neural networks, the problem of «retraining» is inherent, which is associated with the number of neurons in the hidden layer. During the training of the network the technique of regularization is used, which avoids retraining the neural network. Unsuccessful versions of networks with productivity less than 90 % were filtered off. All other networks were evaluated by subjective analysis of histograms of residues, scattering diagrams and numerical values of indicators: determination coefficient $R^2$ (performance), the ratio of standard deviations of forecast error and training data *S.D.ratio*, the average relative value of the model error *MAPE*, the residual median square $MS_R$.

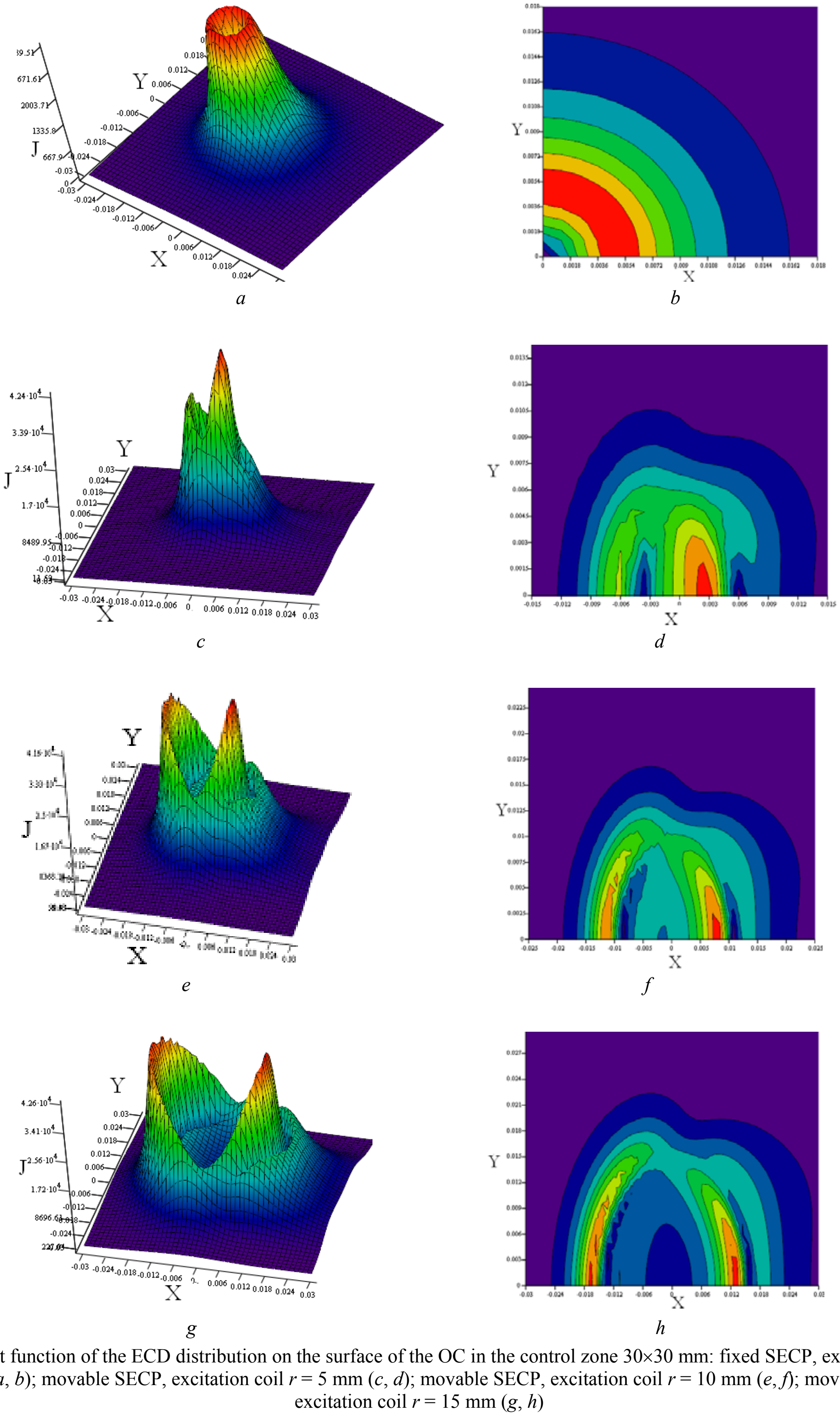
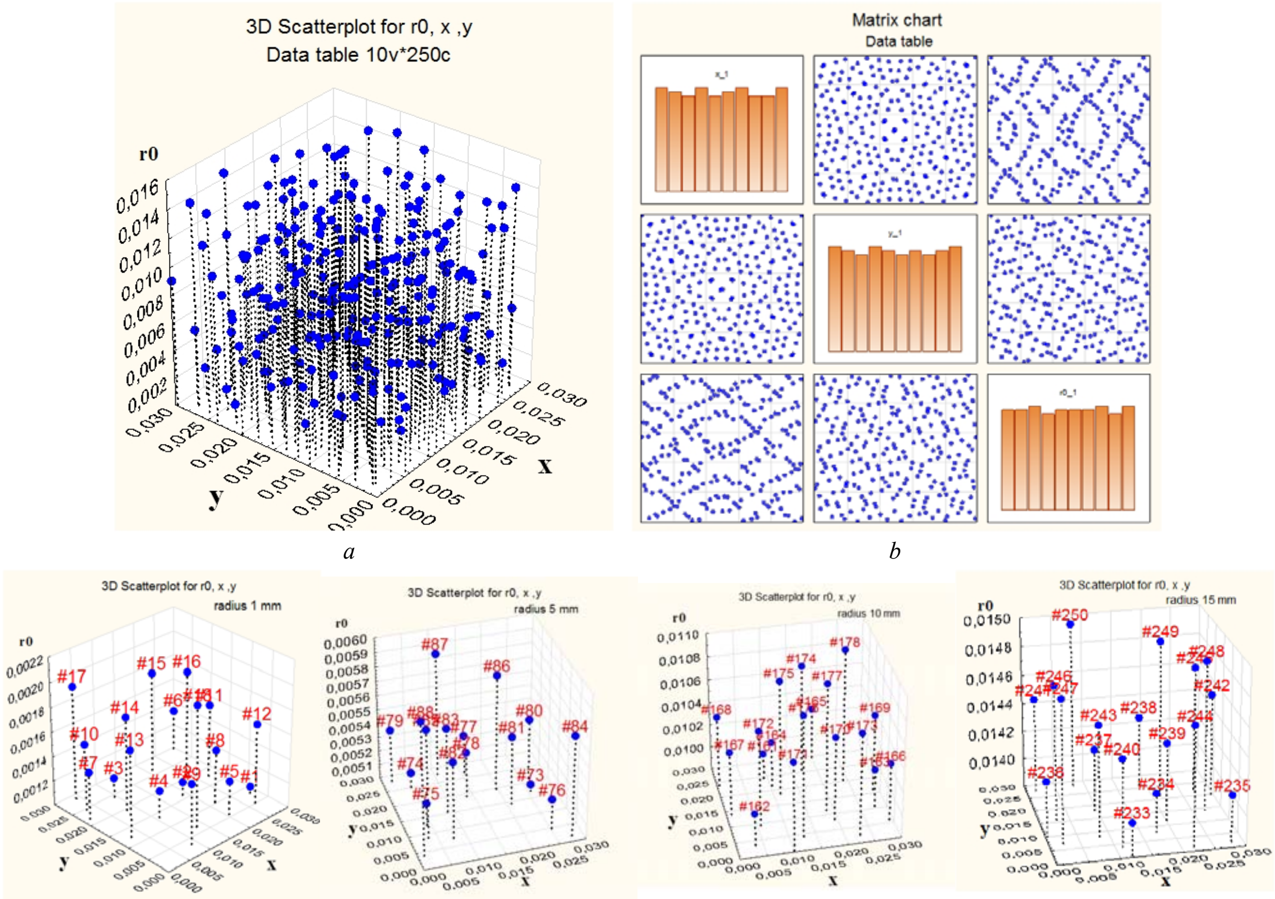


Fig. 3. Exact function of the ECD distribution on the surface of the OC in the control zone 30×30 mm: fixed SECP, excitation coil $r$ = 5 mm (*a*, *b*); movable SECP, excitation coil $r$ = 5 mm (*c*, *d*); movable SECP, excitation coil $r$ = 10 mm (*e*, *f*); movable SECP, excitation coil $r$ = 15 mm (*g*, *h*)




*a* *b*

*c* *d* *e* *f*

Fig. 4. Locations of the points of LPτ-sequences ($\xi_1$, $\xi_2$, $\xi_4$) in the 3D factor space: for $r$ = 1 ... 15 mm, number of points $N$ = 250 (*a*); matrix representation of sequences ($\xi_1$, $\xi_2$, $\xi_4$) in 2D projections (*b*); for a radius of an excitation coil of 1 mm (*c*); for a radius of 5 mm (*d*); for a radius of 10 mm (*e*); for a radius of 15 mm (*f*)

To construct a metamodel of a fixed SECP with variation of three parameters within $x$ = 0 ... 30 mm; $y$ = 0 ... 30 mm; $r$ = 1 ... 15 mm almost 320 RBF-neuron networks are created for the plan $N$ = 2048 with the number of hidden neurons from 280 to 350, of which the best (Table 1) are selected for the indicated indicators. Networks with a productivity of more than 0.9 were used together, organizing a networks committee.

To improve accuracy, as a rule to make a decision the average value of the networks included in the committee is used. For the neural networks committee, in Fig. 5,*b*,*d*,*f* lines of the level of the surface of the response are presented in the previously determined ranges of variations of variables reproduced at 2048 points of the training sample. Each section of the surface in the radius accounts for about 145 points. Table 2 shows the results of the approximation of the ECD distribution by the created committee for radii 5, 10, 15 mm.

To construct the metamodel of the SECP taking into account of the effect of speed $\upsilon$ = (40; 0; 0) m/s and variation of three parameters within $x$ = –30…30 mm; $y$ = 0…24 mm; $r$ = 2…15 mm, almost 95 RBF-neuron networks were created for the plan $N$ = 3315 with the number of hidden neurons from 200 to 700, of which the best (Table 3, 4) were selected for the indicated indicators.

For the neural networks committee, Fig. 6,*b*,*d*,*f* show lines of the level of the surface of the response, reproduced at 3315 points of the training sample. In each section of the surface in a radius in this plan is 255 points.

Table 1

The best RBF-metamodels for a fixed SECP

| No. | Neural network | $R^2$ for training, control and test samples | S.D.ratio | MAPE, % | $MS_R$ |
|---|---|---|---|---|---|
| 1 | RBF-3-282-1(156) | 0.9949; 0.9946; 0.993 | 0.086 | 22.6 | 0.00057 |
| 2 | RBF-3-293-1(218) | 0.993; 0.994; 0.994 | 0.0904 | 27.9 | 0.000614 |
| 3 | RBF-3-293-1(219) | 0.994; 0.992; 0.989 | 0.0939 | 28.6 | 0.000674 |
| 4 | RBF-3-300-1(254) | 0.9949; 0.993; 0.989 | 0.0891 | 26.8 | 0.000631 |
| 5 | RBF-3-322-1(284) | 0.995; 0.992; 0.988 | 0.09 | 22.9 | 0.000613 |
| 6 | RBF-3-343-1(307) | 0.996; 0.993; 0.996 | 0.0739 | 22.1 | 0.000424 |

Table 2

Results of approximation of the ECD distribution by the networks committee for a fixed SECP

| Radius, mm | S.D.ratio | MAPE, % | $MS_R$ |
|---|---|---|---|
| 5 | 0.164 | 13.08 | 0.000506 |
| 10 | 0.061 | 5.89 | 0.000316 |
| 15 | 0.083 | 6.43 | 0.000947 |

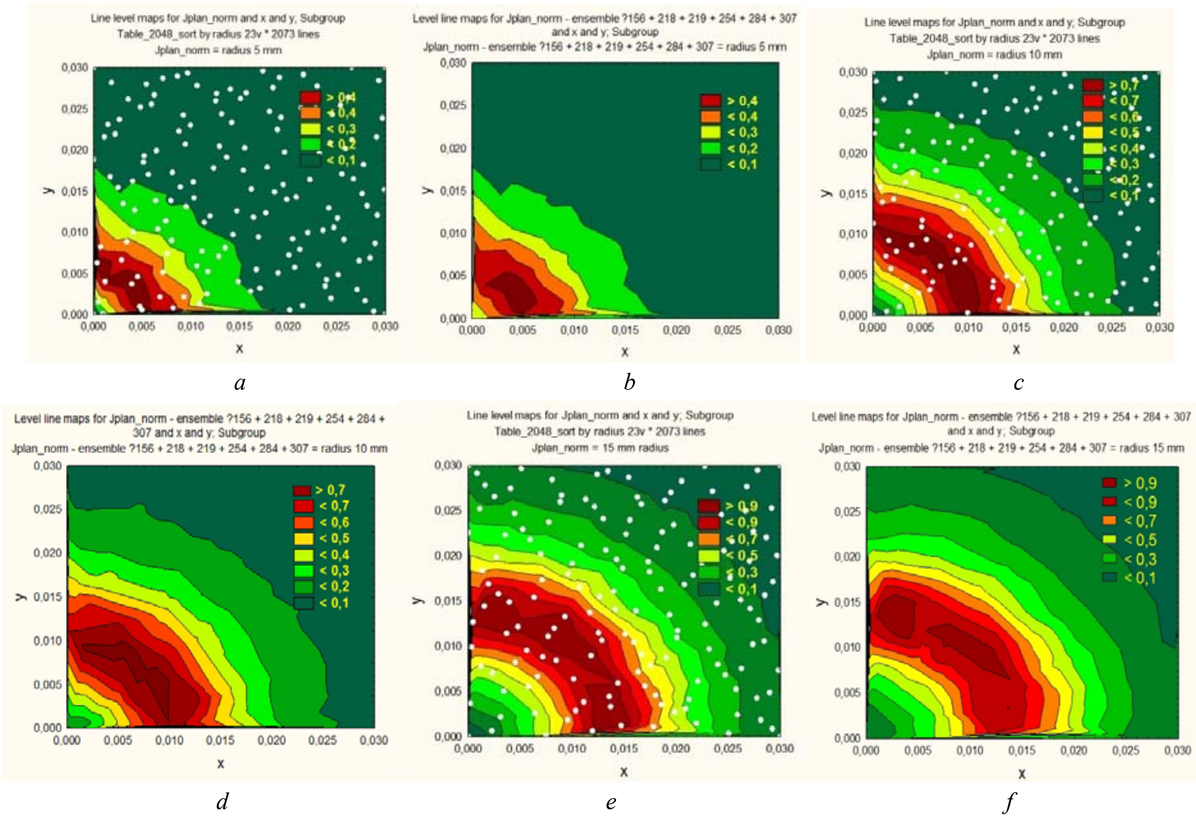


Fig. 5. Lines of the level of the surface of the response of a fixed SECP: the plan of experiment $N$ = 145, applied on the lines of the level of the «exact» model, for the sections of the surface of radii $r$ = 5, 10, 15 mm respectively (*a*, *c*, *e*); the surface of the response, reproduced at the points of the training sample using the networks committee (*b*, *d*, *f*)

Table 3

The best RBF-metamodels for a movable SECP

| No. | Neural network | $R^2$ for training, control and test samples | S.D.ratio | MAPE, % | $MS_R$ |
|---|---|---|---|---|---|
| 1 | RBF-3-610-1(2) | 0.944; 0.933; 0.926 | 0.278 | 46 | 0.00458 |
| 2 | RBF-3-620-1(8) | 0.958; 0.942; 0.935 | 0.263 | 41.2 | 0.00355 |
| 3 | RBF-3-627-1(15) | 0.96; 0.941; 0.918 | 0.272 | 44.1 | 0.00367 |
| 4 | RBF-3-635-1(28) | 0.96; 0.947; 0.933 | 0.265 | 37.74 | 0.00345 |
| 5 | RBF-3-635-1(29) | 0.96; 0.949; 0.924 | 0.261 | 38.3 | 0.00349 |
| 6 | RBF-3-665-1(31) | 0.958 0.95; 0.938 | 0.261 | 39.2 | 0.00347 |
| 7 | RBF-3-665-1(34) | 0.96; 0.948; 0.937 | 0.262 | 32.9 | 0.00341 |

Table 4

Results of approximation of the ECD distribution by the networks committee for a movable SECP

| Radius, mm | S.D.ratio | MAPE, % | $MS_R$ |
|---|---|---|---|
| 5 | 0.242 | 31 | 0.001151 |
| 10 | 0.293 | 23 | 0.002382 |
| 15 | 0.381 | 21.7 | 0.008434 |

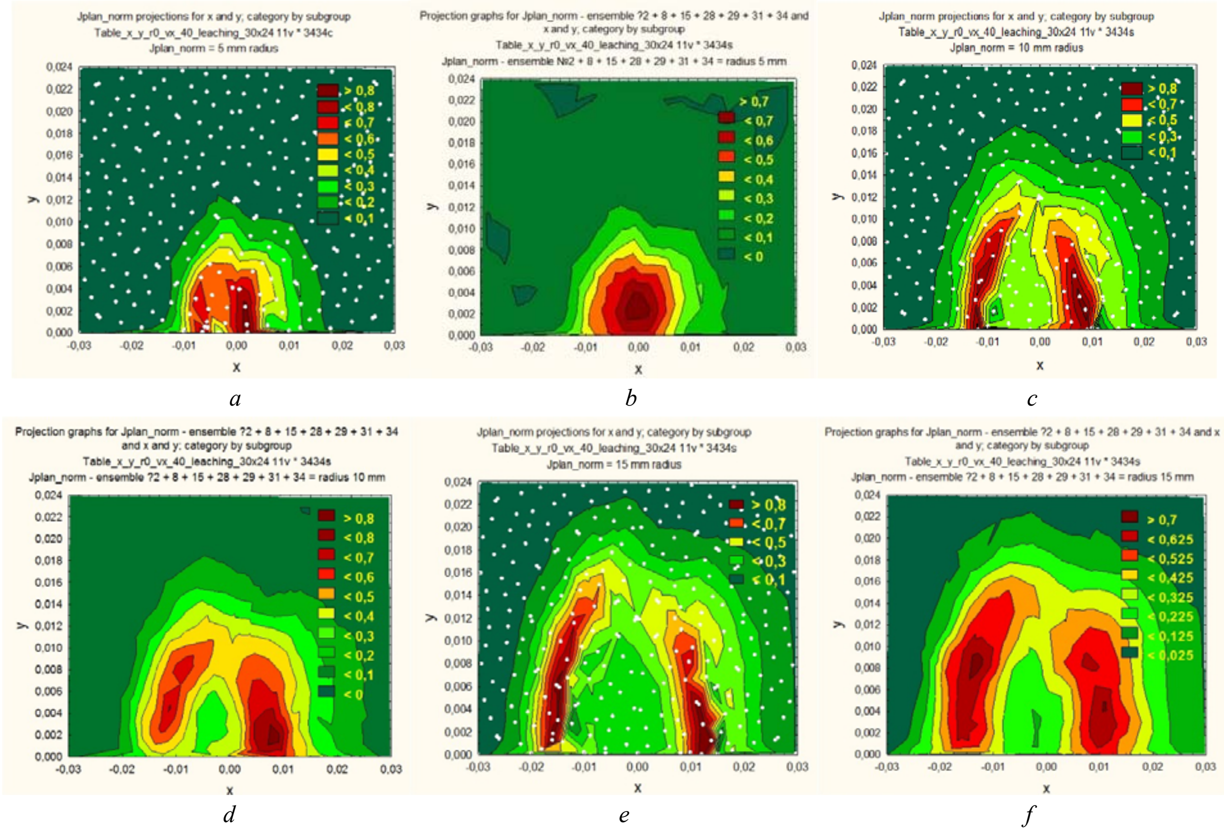



Fig. 6. Lines of the level of the surface of the response of a movable SECP: the plan of experiment $N = 255$, applied on the lines of the level of the «exact» model, for the sections of the surface of radii $r = 5$, 10, 15 mm respectively (*a*, *c*, *e*); the surface of the response, reproduced at the points of the training sample by the networks committee (*b*, *d*, *f*)

**Validation and verification of SECP metamodels.** One of the criteria for the quality of a multivariate regression model is to verify the correctness of the reproducibility of the response surface using the resulting mathematical model throughout the modeling area. Fig. 7 shows the results of the reproduction of the response surface for a fixed SECP obtained with the help of the neural networks committee, executed in the entire range of variation of variables at a considerably increased number of points 7154. In this case, the sections of the surface with radii 5, 10, 15 mm accounted for 511 points.

At the stage of reproduction of the response surface, the adequacy of the obtained metamodel is evaluated according to the indicators: the sum of the squares corresponding to the regression, the remnants, the total; middle squares; dispersion of reproducibility, adequacy, general; standard error of reproducibility estimation, estimation of adequacy, overall; determination factor; ratio of standard deviations; average relative value of model error (or average error of approximation) [22]. The estimation of these indicators is summarized in Table 5.

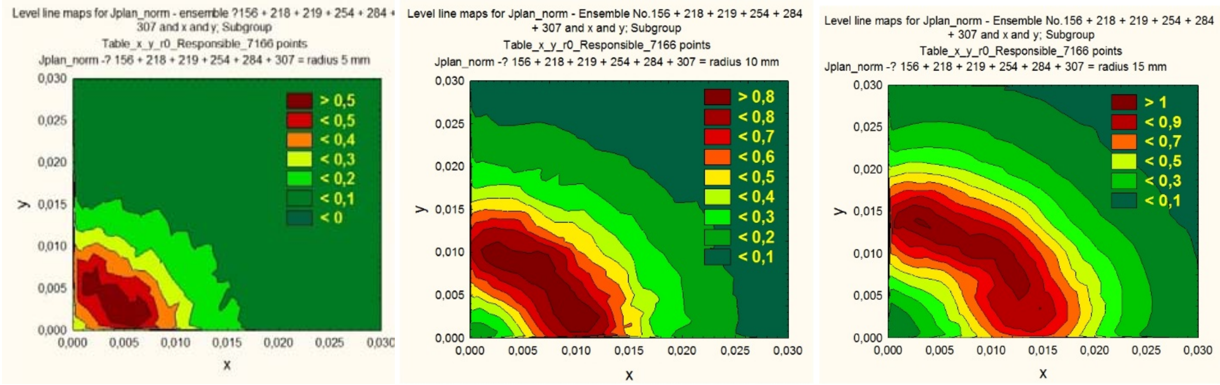
Fig. 8 shows the result of the reproduction of the response surface received by the neural networks committee for a moving SECP, executed throughout the range of variation of variables at 6643 points. On the sections of the surface of radii 5, 10, 15 mm in this example there are 511 points.

For the created neural networks committee, the indicators characterizing the adequacy and informativeness of the metamodel are estimated, the results of which are summarized in Table 6.

Table 5

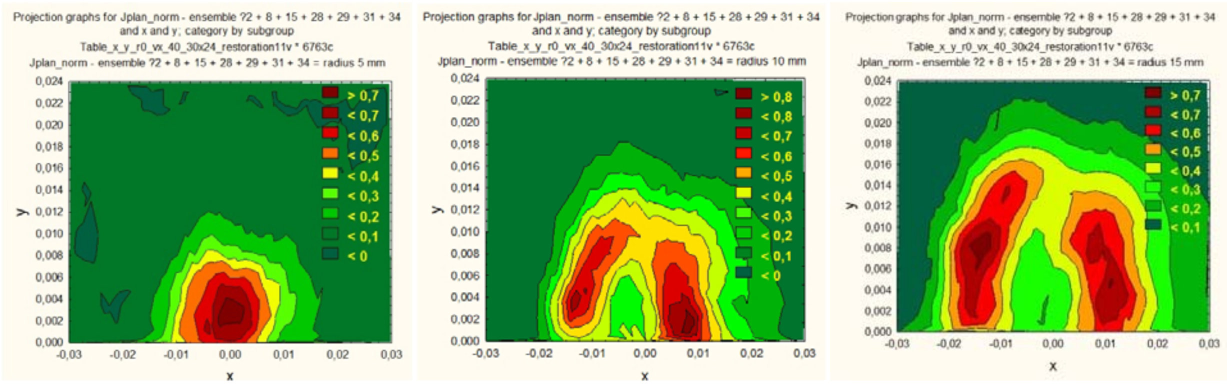
Verification of the adequacy and informativeness of the metamodel of a fixed SECP

| Dispersion components ($N = 7154$): | | Sum of squares | Middle square | Dispersion | Standard estimation error |
|---|---|---|---|---|---|
| regression | | $SS_D = 369.265$ | $MS_D = 123.088$ | $\sigma^2_D = 0.051537$ | $S_D = 0.227018$ |
| remnants | | $SS_R = 1.91$ | $MS_R = 0.000266$ | $\sigma^2_R = 0.000266$ | $S_R = 0.016325$ |
| general | | $SS_T = 374.088$ | $MS_T = 0.052221$ | $\sigma^2_T = 0.052210$ | $S_T = 0.228496$ |
| Fisher criterion $F^{experimental}_{\nu_D;\nu_R} > F^{table\ value}_{\alpha;\nu_D;\nu_R}$ | | $F^{experimental}_{3;7150} = 193.74$; $F^{table\ value}_{0,05;3;7150} = 2.6079$ | | | |
| determination factor $R^2$ | | 0.9945 | | | |
| average error of approximation, MAPE, % | $r = 5$ mm | 16.56 % | | | |
| | $r = 10$ mm | 5.92 % | | | |
| | $r = 15$ mm | 5.41 % | | | |
| ratio of standard deviations S.D.ratio | | 0.071445 | | | |




*a* *b* *c*

Fig. 7. Reproduction of the response surface with the help of the neural networks committee for a fixed SECP. Level lines reproduced at $N = 511$ points for sections of the surface with radii 5, 10, 15 mm respectively (*a*, *b*, *c*)




*a* *b* *c*

Fig. 8. Reproduction of the response surface with the help of the neural networks committee for a movable SECP. Level lines reproduced at $N = 511$ points for sections of the surface with radii 5, 10, 15 mm respectively (*a*, *b*, *c*)

Table 6

Verification of the adequacy and informativeness of the metamodel of a movable SECP

| Dispersion components ($N = 6643$) | | Sum of squares | Middle square | Dispersion | Standard estimation error |
|---|---|---|---|---|---|
| regression | | $SS_D = 244.1923$ | $MS_D = 81.397$ | $\sigma^2_D = 0.036111$ | $S_D = 0.190030$ |
| remnants | | $SS_R = 27.5733$ | $MS_R = 0.004077$ | $\sigma^2_R = 0.004077$ | $S_R = 0.06385$ |
| general | | $SS_T = 278.9221$ | $MS_T = 0.041248$ | $\sigma^2_T = 0.041248$ | $S_T = 0.203097$ |
| Fisher criterion $F^{\text{experimental}}_{\nu_D;\nu_R} > F^{\text{table value}}_{\alpha;\nu_D;\nu_R}$ | | $F^{\text{experimental}}_{3;6639} = 8.857$; $F^{\text{table value}}_{0,05;3;6639} = 2.6079$ | | | |
| determination factor $R^2$ | | 0.901353 | | | |
| average error of approximation, MAPE, % | $r = 5$ mm | 40.38 % | | | |
| | $r = 10$ mm | 23.54 % | | | |
| | $r = 15$ mm | 24.79 % | | | |
| ratio of standard deviations S.D.ratio | | 0.314381 | | | |

The results of the study can be used in the synthesis of mobile SECP with a priori set ECD distribution in the control zone.

**Conclusions.**

1. For the first time, RBF-metamodels of a concentric circular SECP (both fixed one and taking into account the speed effect) are created.
2. Based on modern computer methods of planning the experiment, artificial intelligence and data analysis, the computational technique of constructing metamodels characterized by a lower computational resource intensity during simulation is improved.
3. For the first time, geometric models of excitation structures of circular SECPs with uniformity of sensitivity for their optimal synthesis taking into account the effect of speed are proposed.
4. The task of creating software for calculating the ECD distribution in the control zone of the SECP taking into account the effect of speed by «exact» electrodynamic mathematical models is solved. The task of creating software for forming points of an experiment plan using the Sobol LPτ–sequences is solved, which made it possible to select the most perfect experiment plans individually for the approximated surfaces of the response.

REFERENCES

*1.* Stelblev Yu.I. Synthesis of the given characteristics of eddy current converters. *Defectoscopy*, 1984, no.11, pp. 12-20. (Rus).

*2.* Stelblev Yu.I. Synthesis of eddy current transformers with a given structure of the excitatory field in the control zone. *Defectoscopy*, 1986, no.4, pp. 58-64. (Rus).

*3.* Halchenko V.Ya., Pavlov O.K., Vorobyov M.O. Nonlinear synthesis of magnetic fields of excitation of eddy-current converters of flaw detectors. *Methods and instruments of quality control*, 2002, no.8, pp. 3-5. (Ukr).

*4.* Gal'chenko V.Ya., Vorob'ev M.A. Structural Synthesis of Attachable Eddy-Current Probes with a Given Distribution of the Probing Field in the Test Zone. *Russian Journal of Nondestructive Testing*, 2005, vol.41, no.1, pp. 29-33. **doi: 10.1007/s11181-005-0124-7.**

*5.* Su Z., Ye C., Tamburrino A., Udpa L., Udpa S. Optimization of coil design for eddy current testing of multi-layer structures. *International Journal of Applied Electromagnetics and Mechanics*, 2016, vol.52, no.1-2, pp. 315-322. **doi: 10.3233/JAE-162030.**

*6.* Su Z., Efremov A., Safdarnejad M., Tamburrino A., Udpa L., Udpa S.S. Optimization of coil design for near uniform interrogating field generation. *AIP Conference Proceedings*, 2015, vol.1650, no.1, pp. 405-413. **doi: 10.1063/1.4914636.**

*7.* Stawicki K., Gratkowski S. Optimization of Exciter Coils in Eddy Current Transducer for Testing Thick Conducting Plates. *International Symposium on Electromagnetic Fields in Electrical Engineering; Electromagnetic fields in mechatronics, electrical and electronic engineering: ISEF'05*; 2005; Baiona, Spain in studies in applied electromagnetics and mechanics; 27; Oxford, Amsterdam, IOS Press, 2006. pp. 497-502.

*8.* Itaya T., Ishida K., Kubota Y., Tanaka A., Takehira N. Visualization of eddy current distributions for arbitrarily shaped coils parallel to a moving conductor slab. *Progress In Electromagnetics Research M*, 2016, vol.47, pp. 1-12. **doi: 10.2528/PIERM16011204.**

*9.* Itaya T., Miki T., Takehira N., Tanaka A., Ishida K. Eddy current distribution for a rectangular coil arranged parallel to a moving conductor slab. *IET Science, Measurement & Technology*, 2012, vol.6, no.2, pp. 43-51. **doi: 10.1049/iet-smt.2011.0015.**

*10.* Ishida K., Itaya T., Tanaka A., Takehira N. Magnetic Field Analysis of an Arbitrary Shaped Coil Using Shape Functions. *IEEE Transactions on Magnetics*, 2009, vol.45, no.1, pp. 104-112. **doi: 10.1109/TMAG.2008.2005119**.

*11.* Panas S., Kriezis E.E. Eddy current distribution due to a rectangular current frame moving above a conducting slab. *Archiv für Elektrotechnik*, 1986, vol.69, no.3, pp. 185-191. **doi: 10.1007/BF01574623**.

*12.* Thollon F., Lebrun B., Burais N., Jayet Y. Numerical and experimental study of eddy current probes in NDT of structures with deep flaws. *NDT & E International*, 1995, vol.28, no.2, pp. 97-102. **doi: 10.1016/0963-8695(94)00010-h.**

*13.* Theodoulidis T., Bowler J.R. Interaction of an Eddy-Current Coil With a Right-Angled Conductive Wedge. *IEEE Transactions on Magnetics*, 2010, vol.46, no.4, pp. 1034-1042. **doi: 10.1109/TMAG.2009.2036724.**

*14.* Trembovetska R.V., Halchenko V.Ya., Tychkov V.V. The MLP-Metamodels Application In The Surrogate Optimization Tasks. *Young Scientist*, 2018, vol.6, no.2, pp. 32-39. (Ukr).

*15.* Halchenko V.Ya., Trembovetska R.V., Tychkov V.V. Neural network metamodel of a cylindrical overhead eddy current converter as a component of surrogate optimal synthesis. *Bulletin of Kherson National Technical University*, 2018, no.3(66), vol.1, pp. 32-38. (Ukr).

*16.* Galchenko V.Ya., Trembovetska R.V., Tychkov V.V. Application of metamodels for solving problems of synthesis of eddy current converters with a homogeneous distribution of current density in the control zone. *Zbirnik tez dopovidej XVII Mizhnarodnoï naukovo-tehnichnoï konferencіï «Priladobuduvannja: stan i perspektivi»* [Materials of the XVII Int. Sci.-Pract. Conf. «Instrumentation: state and prospects»]. Kyiv, NTUU «KPI», 15-16 May, 2018, pp. 146-147. (Ukr).

*17.* Halchenko V.Y., Trembovetska R.V., Tychkov V.V. The neurocomputing using of the development metamodels stage in the optimal surrogate antennas synthesis process. *Visnyk NTUU KPI Seriia – Radiotekhnika Radioaparatobuduvannia*, 2018, no.74, pp. 60-72. **doi: 10.20535/radap.2018.74.60-72.**

*18.* Kuznetsov B.I., Nikitina T.B., Tatarchenko M.O., Khomenko V.V. Multicriterion anisotropic regulators synthesis by multimass electromechanical systems. *Tekhnichna Elektrodynamika*, 2014, no.4, pp. 105-107. (Rus).

*19.* Kuznetsov B.I., Nikitina T.B., Voloshko A.V., Bovdyj I.V., Vinichenko E.V., Kobilyanskiy B.B. Single-circuit active screening of magnetic field generated by several overhead transmission lines in residential area. *Electrical engineering & electromechanics*, 2018, no.1, pp. 41-45. **doi: 10.20998/2074-272X.2018.1.06**.

*20.* Haykin Simon. *Neironnye seti: polnyi kurs* [Neural Networks: A Complete Course]. Moscow, Williams Publ. House, 2006. 1104 p. (Rus).

*21.* Sobol I.M., Statnikov R.B. *Vybor optimal'nyh parametrov v zadachah so mnogimi kriterijami* [Choosing Optimal Parameters in Problems with Many Criteria]. Moscow, Drofa Publ., 2006. 175 p. (Rus).

*22.* Radchenko S.G. *Metodologija regressionnogo analiza: monografija* [Methodology of regression analysis: monograph]. Kyiv, Korniychuk Publ., 2011. 376 p. (Rus).

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