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Nonlinear surrogate synthesis of the surface circular eddy current probes

***Abstract**. The mathematical methods of non-linear surrogate parametric synthesis of surface circular non-axial eddy current probes are proposed. Examples of synthesis in the formulation of objective functions as a quadratic criterion are considered. The results of the obtained solution in the form of level lines of eddy currents density distribution and values of absolute synthesis error for different excitation structures are given. In the testing zone, the value of the reduced synthesis error is calculated.*

Streszczenie.** Zaproponowano matematyczne metody nieliniowej zastępczej parametrycznej syntezy kołowych powierzchniowych nieosiowych sond prądów wirowych. Rozważane są przykłady syntezy w formułowaniu funkcji celu jako kryterium kwadratowego. Podano wyniki otrzymanego rozwiązania w postaci linii poziomych rozkładu gęstości prądów wirowych i wartości bezwzględnego błędu syntezy dla różnych struktur wzbudzenia. W strefie testowej obliczana jest wartość zmniejszonego błędu syntezy.* ***Nieliniowa zastępcza synteza kołowej powierzchniowej sondy wiroprądowego

Keywords: surface eddy current probe, RBF-metamodel, non-linear surrogate synthesis, meta-heuristic hybrid algorithm for optimization, uniform sensitivity, eddy currents density.
Słowa kluczowe: sonda powierzchniowo prądów wirowych, metamodel RBF, nieliniowa synteza zastępcza, metaheurystyczny algorytm hybrydowy do optymalizacji, jednorodna czułość, gęstość prądów wirowych.

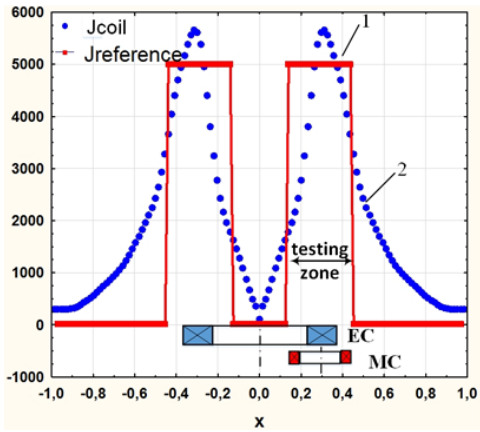
Introduction

The eddy current probes are widely used in non-destructive testing of materials and products. They are used to search for defects in continuity of conductive products, testing of electrical properties, geometrical dimensions, and the like. The surface eddy current probes (SECP), which are characterized by high sensitivity, are used in the testing of flat products, and in some cases in products with a curved surface. The uneven eddy current density distribution (ECD) J_{coil} in the volume of the testing object (TO), which depends on the geometric, electrophysical parameters and the relative position of its exciting coil concerning the testing surface, is inherent to classical surface eddy current probes (SECP). In SECP ECD is maximal in the surface layer of the conductive object and decreases when the excitations of the coil are removed from the coils along the surface (Fig. 1 a) and in deeper layers it decreases according to the exponential law. That is, in the case of such heterogeneous distribution ECD, the mutual arareament of SECP relative to the TO influences significantly on the method sensitivity. To ensure the defects detection and the determination of their geometric parameters by means of eddy current flaw detection, it is important to ensure a homogeneous ECD distribution in the testing zone (Fig. 1a). The problem of SECP creation with homogeneous sensitivity arises, and, consequently, a homogeneous distribution ECD $J_{reference}$ in the zone of the testing object. This problem can be solved within the framework of optimal parametric synthesis by definition of non-classical excitation system of SECP with corresponding parameters providing the necessary distribution of ECD for non-axial probe. Such excitation system is a set of consistently connected concentric circular sections in the form of coils of arbitrary radii located at the same height above the TO and switched on counter or consensually “across the field” (Fig. 1b).

Literature review

The linear problem of the synthesis of the eddy current probe (ECP) with the given structure of the excitatory field in the testing zone is solved in [1]. However, the practical implementation of such probes is complicated, since in the linear synthesis, actual values of current density in the sections of the coil are obtained. The variant of the immovable probe is considered. The case when obtaining a given structure of the field is achieved by parameters of the probe, which are non-linear included in the calculation formula of the exciting field, is not considered in the work.

a)



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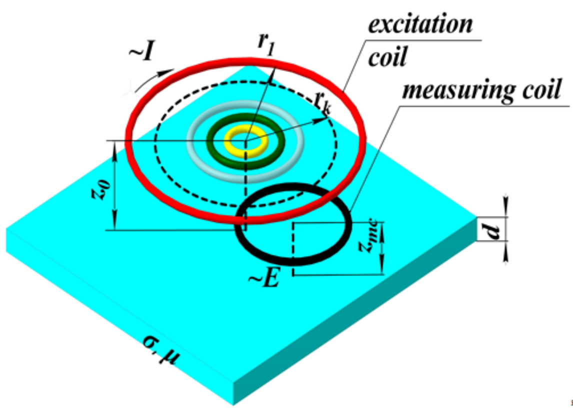

Fig. 1. Non-axial SECP: a) ECD distribution; b) geometric SECP model with partitioned excitation coil; 1 – ECD distribution, inherent in classical structures; 2 - desired uniform ECD distribution, EC - excitation coil; MC - measuring coil

In [2] the problem of non-linear optimal synthesis was realized. Under the condition of fixed excitation current density the solution to the problem of the location of windings of sections of excitation coils in space with the definition of their geometric sizes is made.

Approaches considered in [1, 2] are parametric optimization methods, while the problem of choosing the structure of the ECP excitation system is still unsolved. The method of structural-parametric synthesis of the source of the electromagnetic field of excitation, proposed in [3], allows us to solve these problems.

In [4] a methodology for optimization of the design of the excitation system of SECP is proposed. By using a multipurpose genetic algorithm for optimization a tangential and even distribution of eddy currents using a planar coil of linear eddy currents was obtained. In this case it is possible to take into account the numerous requirements for the projected probe.

Synthesis by the finite element method in conjunction with the Monte Carlo optimization methods and the genetic algorithm was demonstrated in [5, 6]. The use of such numerical methods for analyzing the exciting field improves the accuracy of the calculation, but the time of simulation is significantly increased. In the study the authors confined themselves to considering coils of circular shape and planar coils of linear eddy currents. At the same time, the contribution of the transfer currents to the formation of the excitatory field was not taken into account, that is, the variant of the immovable probe was considered.

The idea of suppressing eddy currents on the surface of the TO, which provides a deeper penetration of eddy currents into the thickness of the material, is proposed in [7]. This is realized with a combination of several coils. The excitation currents of these coils have different amplitudes and phases, which gives the possibility of emulation of the desired effect. The definition of the structure of the excitation system and the effect of the transfer currents in the TO for movable ECP remain unresolved issues in this paper. The perspectives of the research proposed in this article are to create excitation systems of movable circular SECP, which provide a uniform distribution of ECD on the surface of the TO.

The **purpose** of this work is the non-linear parametric synthesis of eddy current probes with uniform sensitivity in the testing zone, which is provided by using conventional surrogate optimization using a stochastic metaheuristic method of search for the solution of an extreme problem.

Governing equations

In order to solve such a problem in the general case, it is necessary to have a functional dependence for the calculation of the ECD from the electrophysical parameters of the object, the frequency of the excitation current, the geometry of the TO and probe. Then the synthesis problem can be reduced to optimization, the solution of which are the parameters of the excitation system of the probe, providing apriori present ECD distribution in the testing zone In [8-11] the researchers analytically obtained a functional dependence by solving a boundary value problem in partial derivatives with corresponding boundary conditions and assumptions. We consider that the medium is linear, homogeneous, isotropic; TO is movable, conductive of infinite width and length and finite thickness *d*; the coil is placed at an altitude z_0 above the TO and is excited by an alternating current *I* and a circular frequency ω; the conductor of the coil seems to be infinitely thin; the electrical conductivity σ, the relative magnetic permeability μ_r and the speed of the probe $\vec{\upsilon} = \left(\upsilon_x, \upsilon_y, 0\right)$ are constant. In accordance with this mathematical model, we considered three calculated areas in which the complex values of magnetic induction were determined:

• in the area 0 <z <z0

$$\begin{aligned} &\vec{B}_1 = \vec{B}_i + \vec{B}_r, \\ &\vec{B}_i = \operatorname{rot}\vec{A}_i, \vec{A}_i = \frac{\mu_0}{4\pi}\int_l \frac{\vec{J}\,\mathrm{d}l}{R}, \\ &\Delta\vec{B}_r = 0, \operatorname{rot}\vec{B}_r = 0, \end{aligned} \tag{1}$$

where: $\vec{B}_i$ - the actual magnetic field of the coil of length *l* and current density $\vec{J}$, $\vec{B}_r$ - the magnetic field of eddy currents given in the environment of the OK;

• in the area -d <z <0

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

• in the area z <-d

$$\Delta\vec{B}_3 = 0, \ \operatorname{rot}\vec{B}_3 = 0. \tag{3}$$

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 induction on the boundaries of the medium section z = 0 and z = -d allowed the authors [8-11] to obtain the distribution of the components of the magnetic Induction in the medium of TO:

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

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

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

(6)
$$\times \left[\left\{ -\left(1 + \lambda_0\right) \cdot e^{2 \cdot \gamma \cdot d} + \nu_0 \cdot e^{\left(\gamma - \sqrt{\xi^2 + \eta^2}\right) \cdot d} \right\} \cdot e^{\gamma \cdot z} - \right.$$
$$\left. - \left\{ 1 + \lambda_0 - \nu_0 \cdot e^{\left(\gamma - \sqrt{\xi^2 + \eta^2}\right) \cdot d} \right\} \cdot e^{-\gamma \cdot z} \right] \times$$
$$\times e^{-z_0 \cdot \sqrt{\xi^2 + \eta^2}} \cdot S(\xi, \eta) \cdot e^{-j(x \cdot \xi + y \cdot \eta)} d\xi d\eta$$

where: B_{2x}, B_{2y}, B_{2z} - the components of magnetic induction by spatial coordinates; $S(\xi,\eta)$ – the function of the coil shape,

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

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

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

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

where: υ_x, υ_y – the components of the velocity of circular SECP relative to the TO; d – the thickness of TO; ξ, η - the variables of integration.

A homogeneous distribution of ECP in the testing zone may be provided by a certain system of excitation coils. For a system of excitation coils, the target function for the optimal synthesis problem in the classical formulation is the form of a quadratic functional:

(7)
$$F_{target} = \sum_{i=1}^{N} \left(\sum_{k=1}^{M} J_{ik} - J_{reference} \right)^2 \to \min,$$

where: $J_{reference}$ - the desired value of module ECD at the i-th testing point; J_{ik} - the module ECD at the testing point TO with number i, created by k-th coil of the excitation system of SECP; N - a number of testing points in the zone; M - a number of coils in the excitation system of circular SECP.

Principles and constructing metamodel

The optimal synthesis involves a multiple solution to the problem of analysis, that is, a direct problem, for each current excitation structure by computer numerical calculations. However, an obstacle of the realization of the synthesis problem is sufficiently costly numerical calculations within the framework of the direct problem of "exact" mathematical models [12]. One of the ways to solve the problem of critical resource intensity is to use surrogate optimization technologies [13-15] and stochastic meta-heuristic optimization [16-20]. That is, for the formulation of the target function in the optimal synthesis problem the SECP metamodel can be used, which is much simpler in numerical implementation and less resource-intensive and represents a neural network approximation of the "exact" electrodynamic model [21-23]. In a number of papers, the authors proposed computing technology for constructing RBF- and MLP-metamodels for approximating the J_{ik} component of the target function in problems of optimal design of eddy current probes [24]. In this study, an artificial RBF-neural network is used as an approximator of the multidimensional response surface.

Improved accuracy of metamodels is achieved using multiple neural networks, in particular their committees and composites. The construction of a composite neural network is that the first received neural network is used in the training of the next one, where the absolute error of approximation, which is the result of the construction of the first neural network, is used at the learning stage. This procedure is repeated by adding the required number of neural networks until a satisfactory value of the mean absolute percentage error (MAPE) is obtained. With such a construction of the neural network composite, the error of approximation decreases gradually from the network to the network. The general response of the surface J_Σ is obtained by adding responses from each neural network's output $J_1, J_2, ..., J_n$ (Fig. 2).

The construction of the neural network committee assumes their training on bootstrap-samples, which is a dataset with duplicates from their previous training set. The committee makes the final decision using separate solutions of several neural networks, that is, using the bagging methodology.

If using the proposed methods of constructing metamodels can not achieve the required accuracy due to significant non-linearity and irregular behavior of the response surface, then a hybrid approach is used, which is to simultaneously apply the decomposition of the search area and technologies of multiple artificial neural networks.

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In this study, all three approaches were used to create a metamodel: at the first stage a decomposition of the search space was made, in each area of which approximation dependences were obtained using the neural networks composite, and at the final stage of compositing construction a bagging-committee was used for neural networks with productivity greater than 0,9.

Since the topology of the hypersurface of the response is complex, therefore, the experimental plan for creation the substitution function is implemented by means of uniform computer filling with the points of the multidimensional search space, that is, using the set of Sobol's LPτ-sequences $\xi_1, \xi_2, ..., \xi_{52}$ [25].

Results of the computational experiment

For definiteness let consider a model example, in which, in the testing points with the obtained coordinates the values of the resource-intensive "exact" model were calculated at the following output data: d = 10 mm; z_0 = 3 mm; frequency f = 1 kHz; electrophysical parameters of the material σ = 3,745·10^7 Sm/m, μ_r = 1.

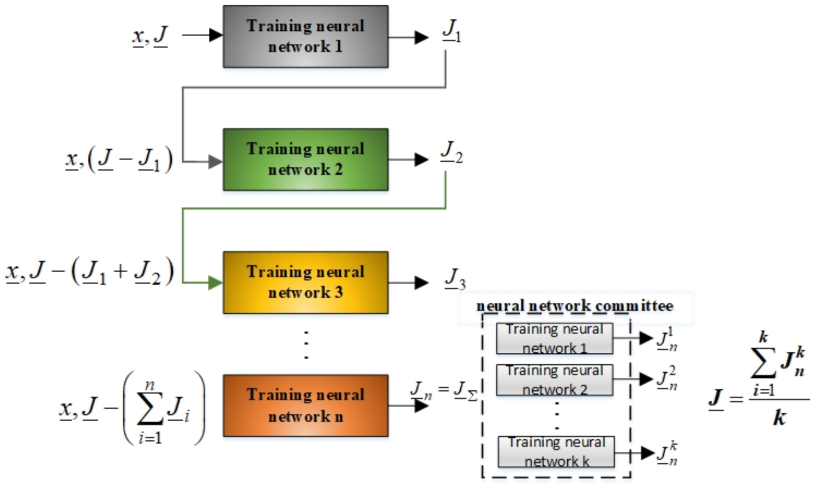

Fig.2. Hybrid construction of neural network metamodel

Table 1. Information on the developing of the SECP metamodel

Decomposition sub-areas	$N_{training}/N_{reconstitution}$	Composite neuron networks	Metamodels constituting the composite	Committee networks
2≤r≤6 mm	1036/2060	*J1*	RBF-3-299-1 (1)	-
		J2	RBF-3-302-1 (5)	-
		J3	RBF-3-300-1 (30)	-
		J4	RBF-3-305-1 (46)	-
		$J5 = J_\Sigma$	RBF-3-297-1 (4)	№4, №9, №12, №48
			RBF-3-298-1 (9)	
			RBF-3-299-1 (12)	
			RBF-3-306-1 (48)	
6<r≤11 mm	1299/2575	*J1*	RBF-3-329-1 (8)	-
		J2	RBF-3-332-1 (1)	-
		J3	RBF-3-328-1 (8)	-
		$J4 = J_\Sigma$	RBF-3-326-1 (3)	№3, №20, №42, №80
			RBF-3-329-1 (20)	
			RBF-3-326-1 (42)	
			RBF-3-332-1 (80)	
11<r≤15 mm	1040/2060	*J1*	RBF-3-297-1 (2)	-
		J2	RBF-3-300-1 (11)	-
		J3	RBF-3-300-1 (13)	-
		J4	RBF-3-306-1 (77)	-
		$J5 = J_\Sigma$	RBF-3-297-1 (1)	№1, №22, №63
			RBF-3-301-1 (22)	
			RBF-3-309-1 (63)	

For simplification the construction of the metamodel was made with the variation of three parameters within the area of x = 0...30 mm; y = 0...30 mm; r = 2...15 mm, $\vec{\upsilon}=(0,0,0)$ that is, it was considered that the SECP is immovable. In the search area a decomposition was made on three sub-areas: 2 ≤ r ≤ 6 mm, 6 < r ≤ 11 mm, 11 < r ≤ 15 mm. For each of the sub-areas, groups of RBF-neuron networks were created for the experiment plan with the number of $N_{training} \in N_{reconstitution}$ points, from which the best (Table 1) were selected due to the parameters of the coefficient determination R^2, the standard deviations ratio *S.D.ratio*; mean absolute percentage error (or average error of approximation) *MAPE,%* [25].

The verification of the metamodel as a whole was performed by checking the correctness of the reproducibility of the response surface in all three sub-areas. The results of the recovery of the response surface for a real SECP are shown in Fig. 3. They were obtained using the hybrid composite - the committee of the neural network, executed in the entire area of variation of variables on a greater number of points $N_{reconstitution} > N_{training}$. In this case, about 511 points can be received the cut-offs of the surface on the radii, which is quite informative.

At the stage of reproduction of the response surface the adequacy of the received metamodel was evaluated according to the indicators: the sum of the squares corresponding to the regression, the remnants, the total one; average squares of the same indicators; dispersion of reproducibility, adequacy, total one; standard error of reproducibility estimation, estimation of adequacy, total estimation; coefficient determination; *S.D.ratio*; *MAPE* [25]. Some of these indicators for each of the sub-areas received on the last cascade of the composite are given in Table 2.

Further, using the obtained metamodel the problem of optimal synthesis was realized.

We distinguish the linear and non-linear surrogate synthesis of eddy current probes. In the framework of linear synthesis, apriori given uniform distribution of ECD (Fig. 1) is obtained by determining the magnetomotive force (MMF) of each coil in the excitation system of SECP under the condition of their given number and location coordinates in space. In this paper we consider non-linear synthesis, namely, the variant of mixed synthesis, when simultaneously all variables that are included in the calculation formula are linearly and non-linearly determined at the same time.

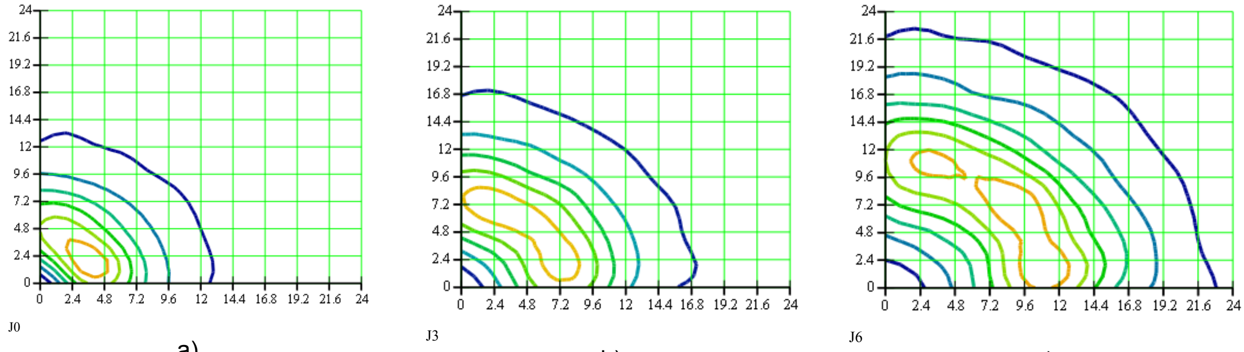

Fig.3. Recovery of the surface of the response using a metamodel based on the hybrid composite committee of the neural network for a immobile SECP: a) line level for a radius of 4.5 mm; b) 9.75 mm; c) 14.5 mm respectively

Table 2. Selective indicators for assessing the adequacy of the metamodel of immovable CECP

Decomposition subregions	Metamodels, which are a composite hybrid of the neural networks "composite-committee" J_{Σ}	$N_{training}$ / $N_{reconstitution}$	*MAPE,%*		MS_R		SS_R	
			TS	*RS*	*TS*	*RS*	*TS*	*RS*
$2 \le r < 6$ mm	RBF-3-297-1(4); RBF-3-298-1(9); RBF-3-299-1(12); RBF-3-306-1(48)	1036/2060	5,38	6,76	0,000038	0,00029	0,0394	0,597
$6 \le r < 11$ mm	RBF-3-326-1(3); RBF-3-329-1(20); RBF-3-326-1(42); RBF-3-332-1(80)	1299/2575	4,48	4,8	0,0000894	0,000146	0,116	0,378
$11 \le r \le 15$ mm	RBF-3-297-1(1);RBF-3-301-1(22); RBF-3-309-1(63)	1040/2061	3,56	4,78	0,000136	0,000379	0,142	0,782

Table 3. The calculation results of parameters of excitation system coils of the SECP

	k	1	2	3	4	5	6	7
M=4	$\frac{Iw_k}{r_k \cdot 10^{-3}}, \frac{\mathrm{A\times turn}}{\mathrm{m}}$	$\frac{0,8633}{11,6231}$	$\frac{3,737}{2,817}$	$\frac{1,816}{3,09}$	$\frac{6,117}{2,492}$	-	-	-
M=5		$\frac{0,7}{12.672}$	$\frac{2,375}{7,032}$	$\frac{-0,891}{8,591}$	$\frac{-1,342}{4,443}$	$\frac{1,603}{2}$	-	-
M=6		$\frac{-0.471}{3.466}$	$\frac{0,384}{1,047}$	$\frac{0,728}{12,612}$	$\frac{0,352}{5,321}$	$\frac{0,304}{5,365}$	$\frac{0,544}{2}$	-
M=7		$\frac{0,383}{6}$	$\frac{-0,325}{3,471}$	$\frac{-1,729}{5,937}$	$\frac{0,692}{12,648}$	$\frac{0,610}{6,957}$	$\frac{1,465}{5,623}$	$\frac{-0,140}{4,286}$

The sign "-" means the counter coil connection.

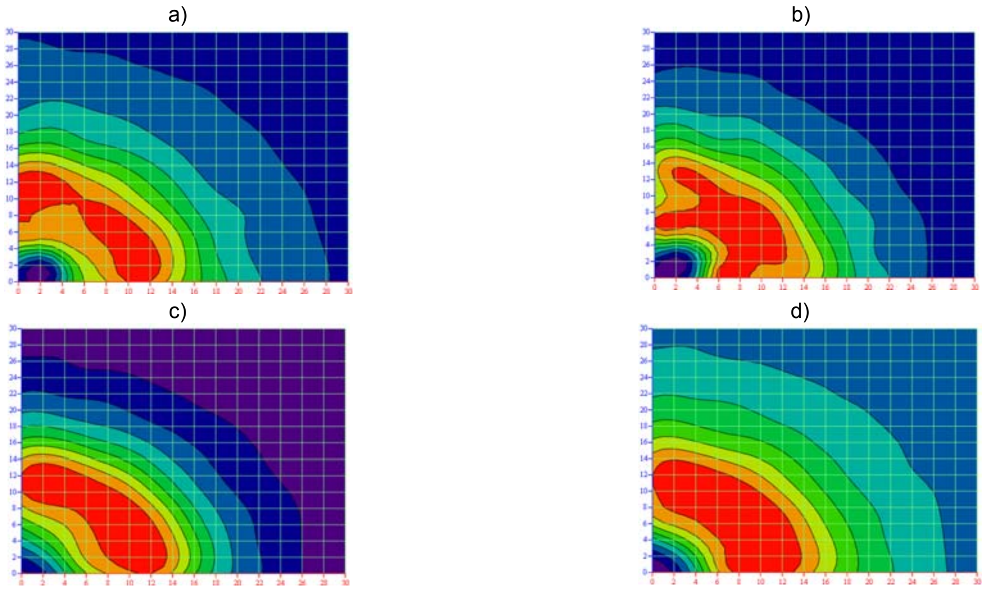

Fig.4. Solution of the distribution of ECD SECP for various excitation structures in the form of line levels: a) *M* = 4; b) *M* = 5; c) *M* = 6; d) *M* = 7

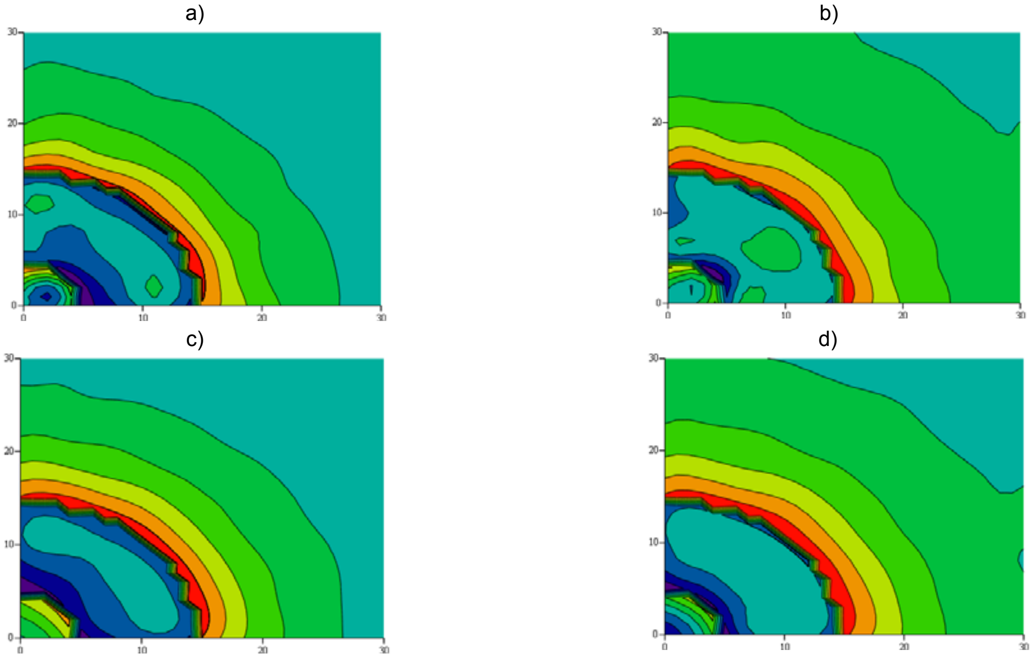

Fig.5. Lines of the level distribution of the absolute value of the error of various excitation structures synthesis: a) M = 4; b) M = 5; c) M = 6; d) M = 7

The excitation structure consists of M coils coaxially with arbitrary radii r_k (k = 1...M) located at the same distance z_0 over TO. All coils are connected in series-counter or in series-agreed, and have different MMFs of the Iw_k. The problem of parametric synthesis is to simultaneously determine the values of MMFs of the Iw_k in each of the coils and, accordingly, their radii, which will ensure the approximation of the created ECD distribution to the given. Fig. 4 illustrates the result of the synthesis of a non-axial SECP, which has a given P-shaped distribution of ECD:

(8) $$J_{reference}=\begin{cases}0 \ \text{at} \ 0\le r\le 4{,}5\cdot10^{-3}\,\text{m; and } r>14{,}55\cdot10^{-3}\,\text{m}\\ 5000\,\dfrac{\text{A}}{\text{m}^2} \ \text{at} \ 4{,}5\cdot10^{-3}<r\le 14{,}55\cdot10^{-3}\,\text{m}\end{cases}.$$

The testing points in the area of the adequacy of the metamodel ($x \times y$) = (30 × 30) mm were evenly distributed and their number was large enough and was 210. For the solution of inverse non-linear problems, it is advisable to use optimization algorithms that do not use derivatives and are well proven when looking for a global extremum of multidimensional "ravine" target functions [26, 27]. The authors used a population meta-heuristic algorithm for optimizing the swarming of particles with evolutionary formation of the swarm, which is a low-level hybridization of the genetic algorithm and the PSO algorithm and has high convergence [16]. The results of numerical experiments of non-linear synthesis of SECP are presented by lines of the level of distribution of ECD in Fig. 4, and the parameters of the MMFs coils are shown in Table 3.

Also, lines of level in Fig. 5 show the absolute value of the error of the solution obtained. The value of the reduced synthesis error in the area 4.5 mm ≤ r ≤ 14.55 mm for various structures of the excitation systems at M = 4, 5, 6, 7 is 9.12 %; 8.07 %; 8.59 %; 8.68 % respectively.

Conclusion

In this work, numerical experiments illustrate the efficiency of the solution of problems of non-linear surrogate synthesis of SECP with evenly sensitivity.

The proposed methods and algorithms of surrogate optimal parametric synthesis allow us to obtain an acceptable precision of synthesis in the testing zone of SECP.

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