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Additive neural network approximation of multidimensional response surfaces for synthesis of eddy-current probes

***Abstract**. A universal method for constructing multidimensional approximation models of surface eddy current probes with various structures of excitation systems is proposed. This method presupposes, firstly, the description of the eddy-current probe interaction with a testing object. Secondly, a computer design of the computational experiment based on quasi-random sequences with a minimum discrepancy is constructed. Thirdly, an approximation model is created using additive neural network regression and the assessment of the adequacy and information content of the obtained multivariate approximation model. The examples of approximation dependences of the eddy current density distribution are considered. Currents are generated by the uniform surface eddy current probes in the testing object. The results of reproduction of multidimensional response surfaces in the form of level lines are given. The lines were obtained on the basis of approximation models with an assessment of their quality using scatter diagrams. The value of the relative model error in the form of distribution histograms is presented.*

***Streszczenie.** Zaproponowano uniwersalną metodę konstruowania wielowymiarowych modeli aproksymacyjnych powierzchniowych sond wiroprądowych o różnych strukturach układów wzbudzających. Metoda ta zakłada, po pierwsze, opis interakcji sondy wiroprądowej z obiektem badanym. Po drugie, konstruuje się komputerowy projekt eksperymentu obliczeniowego oparty na sekwencjach quasi-losowych o minimalnej rozbieżności. Po trzecie, tworzony jest model aproksymacyjny z wykorzystaniem addytywnej regresji sieci neuronowych oraz ocena adekwatności i zawartości informacyjnej otrzymanego wielowymiarowego modelu aproksymacyjnego. Rozważane są przykładowe zależności aproksymacyjne rozkładu gęstości prądów wirowych. Prądy generowane są przez jednolite powierzchniowe sondy wiroprądowe w badanym obiekcie. Podano wyniki odwzorowania wielowymiarowych powierzchni odpowiedzi w postaci linii poziomicowych. Linie te otrzymano na podstawie modeli aproksymacyjnych z oceną ich jakości za pomocą wykresów rozrzutu. Przedstawiono wartość błędu względnego modelu w postaci histogramów rozkładu. (**Aproksymacja wielowymiarowych powierzchni odpowiedzi za pomocą addytywnych sieci neuronowych do syntezy sond wiroprądowych**).*

Keywords: uniform surface eddy current probe, eddy current density, uniform distribution, response hypersurface, multidimensional approximation models, computer design of experiment, additive neural network regression.
Słowa kluczowe: jednolita powierzchniowa sonda wiroprądowa, gęstość prądów wirowych, równomierny rozkład, hiperpowierzchnia odpowiedzi, wielowymiarowe modele aproksymacyjne, komputerowe projektowanie eksperymentu, addytywna regresja sieci neuronowych.

Introduction

The development of non-destructive eddy current testing means, dictated by the need to solve the defectometry problems, has led to a wide demand for uniform surface eddy current probes (USECP). The use of USECP, generating a uniform eddy current density distribution (ECD) in testing objects (TO), helps provide uniform sensitivity to continuity defects. Among the potential excitation system (ES) structures, homogeneous and heterogeneous structures of SECP excitation are distinguished. That is, there is a variety of options for ES structures, and intuitively it is impossible to give preference to any of them. Each variant of ES requires a careful study from the point of view of the possibility of providing a priori a given uniform distribution of ECD in the testing object area.

Literature review

The idea of the purposeful implementation of the probing properties of the electromagnetic field (EMF) is considered in works [1,2,3,4]. Its implementation provides a variety of design solutions for the ES with the improved ECP selectivity and sensitivity. Researchers have not previously considered the formulation of the problem of creating a predetermined ECD distribution taking into account the speed effect. The first attempts in this direction were made by the authors [5]. They proposed a method of surrogate nonlinear optimal metaheuristic synthesis of USECP. The use of surrogate optimization technology makes it possible to solve problems of optimal synthesis using ECP metamodels. This is due to the high computational performance of the metamodels. The creation of approximation models (metamodels) of SECP, which reproduce with the acceptable accuracy the multidimensional response surfaces in the general case, is an essential stage of the method. The method of metamodel constructing ultimately determines the success of the synthesis of the initially given uniform ECD distribution in the testing object area. The purpose of these researches is to create a universal method for approximating the response hypersurfaces of SECP with the sufficient accuracy. Its availability is the guaranty to the successful problem solutions of parametric surrogate probes synthesis with the uniform sensitivity in the testing zone [4,5].

It was possible to find a wide range of known approaches to the construction of regression dependences from the available literary sources. Each of the approaches has both advantages and disadvantages that must be taken into account when applying them [6,7,8,9]. A detailed analysis of these methods is contained in a review article by the authors [10]. When creating metamodels for complex cases of response hypersurface topology, artificial neural networks are widely used due to their universal approximation properties. Let us formulate the problem of multidimensional approximation mathematically for a number of structures of ES SECP in the form of functional approximation dependences of the ECD distribution.

Planar (flat) circular ES structure is characterized by the presence of M coils with radii $r0_i$ (i = 1...M) with uniform Δr = const or uneven Δr = var of their location, placed at the same height z_0 above the TO. The planar frame ES structure is considered similar. In contrast to the planar ES structure, one more parameter is added for the volumetric ES characteristic, namely, the height of the coils location z_{0i} above the TO. The topology of the multidimensional ECD response surfaces is very complex and cannot be visualized. Therefore, the task of creating a method for approximating hypersurfaces ECD response with sufficient accuracy, that is, constructing metamodels for SECP, is relevant and deserves attention.

The task of creating approximations of the response hypersurfaces is performed in several stages. The first is the interaction characteristic of SECP with TO on the basis of an "exact" electrodynamic mathematical model. The second is the construction of a computer design for a computational experiment (DOE) [11,12]. The third is the creation of an approximation model. The final stage involves the establishment of the adequacy, information content and assessment of the accuracy of the obtained approximation model [13,14].

Governing equations

Analytical functional dependencies, that is, "exact" electrodynamic mathematical models describing the distributions of complex components of magnetic induction in an TO environment, were obtained by researchers in [15] by solving boundary-value problems in partial derivatives with the appropriate boundary conditions and assumptions. The medium was considered linear, homogeneous and isotropic. TO was regarded to be conductive, with the infinite width and length and finite thickness d. An infinitely ES thin loop moving at a speed υ relative to the TO is located at a height z_0 above the TO and is powered by an alternating current I with an angular frequency ω. The values of electrical conductivity σ, relative magnetic permeability μ_r of the TO material, as well as the speed of the probe $\vec{\upsilon} = \left(\upsilon_x, \upsilon_y, 0\right)$ are constant. Then the mathematical model of the ECD distribution in the TO is determined by means of the partial derivatives of the components of the magnetic induction B_x, B_y, B_z in spatial coordinates [15,5].

Principles and constructing metamodel

The metamodel construction using artificial neural networks (NN) provides for a training procedure on an array of data obtained by calculation for "exact" mathematical models. Therefore, it is quite logical to create an effective DOE, the choice of which significantly affects the accuracy of the approximation model. Since the topology of the ECD response hypersurface is complex, it is advisable to use non-classical methods of experiment planning, namely, computer methods for filling the multidimensional search space with reference points. Computer DOEs (CDOE) reproduce the global and local behavior of a multidimensional response surface better. It is necessary to fill the hyperparallelepiped search area with points uniformly, taking into account the initial uncertainty of the response surface topology. This increases the probability of their falling into the extrema region or curves of the response hypersurface [16,17].

At this time the theory of generation of one-dimensional quasi-random expandable sequences with low divergence rates has been well developed [12,16]. As shown in [18], the construction of the CDOE becomes much more complicated if the dimension of the space becomes more than three. That is, the additional research on the optimized choice of the so-called basic sequence parameters is needed. In [18], such studies were carried out in relation to Sobol's LP_τ-sequences. As a result of the research, a number of combinations of LP_τ-sequences for three-, four- and five-dimensional designs were obtained, which are characterized by the best indicators of homogeneity. Also, when DOE constructing for multidimensional factor spaces, it is advisable to use sets of nonparametric additive recursive one-dimensional R-sequences [17]. Multivariate DOEs based on these sequences have acceptable, although not the best, characteristics of homogeneity compared to DOEs based on LP_τ-sequences. However, they do not require additional research to assess their quality. Therefore, when creating multidimensional approximation models for various variants of the ES SECP, the authors use multidimensional CDOEs based on quasi-random non-parametric additive Kronecker R-sequences and combinations of Sobol's LP_τ-sequences with the best indicators of centred and wrap-around discrepancies. The Kronecker sequence is generated using irrational numbers, which in turn, are derived from the generalized Fibonacci sequence [19,20,21]. Let us consider in detail via examples the features of using NN technologies to create multiparameter approximating models of hypersurfaces of SECP with the acceptable accuracy indicators. It should be noted that the quality of all created multidimensional approximating models is obligatory assessed by a set of statistical indicators. These include: coefficient of determination R^2; ratio of standard deviations *S.D.ratio*; the average relative value of the model error *MAPE,%*; the sum of squares of residuals SS_R; mean square of residues MS_R [13,14]. Besides, for visual analysis of the results and their better perception, a graphical representation is used in the form of histograms of relative errors and scatter diagrams.

The work [22] considered the simplest case of constructing an approximation model for a circular SECP with a planar ES structure with three varying parameters $\hat{J} = f\left(x, y, r_0\right)$. The results obtained show the impossibility of achieving the required accuracy of the approximation model using the global single RBF-ANN network. And only the application of the NN committees with the decision making by averaging over the ensemble with the boosting procedure made it possible to obtain a satisfactory accuracy of the approximation.

The accuracy of this approximation model was significantly improved by using a hybrid approach. The approach simultaneously employs technologies of decomposition of the search area and NN, built on the techniques of associative machines with different methods of solution obtaining. Thus, in [5], it was proposed to use the additive NN-regression [10] with the decomposition of the search space and averaging over the ansemble. It was sufficient to divide the space into three subregions along the ES loop radius to obtain an acceptable *MAPE,%* at the level of 4.78 % - 6.76 %. The additive NN-regression with ansemble averaging at the last approximation level and the boosting procedure was applied for each of the found subregions. The boosting procedure was carried out by forming subsamples by means of the bagging procedure. Slices of the hypersurface were used to visualize the obtained results of approximation of the multidimensional response surface. Figure 1a shows the result of the ECD distribution reconstruction in the form of level lines for a slice of the response hypersurface (r_0 = 13.5 mm), obtained with the help of an approximation model using additive NN-regression.

In what follows, we will dwell on a more complicated example of an approximation problem for a circular movable SECP $\hat{J} = f\left(x, y, r_0, z_0\right)$, which is characteristic of the volumetric ES structure. Due to the irregular behavior of the ECD response hypersurface, in this case, the search area is decomposed both in terms of the height of the ES probe and along the radius of its components. In each area of decomposition the number of CDOE points is set individually. As a result, it is possible to achieve a certain compromise between the accuracy of constructing of the approximation model and the minimum number of points of $N_{training}$ for CDOE. It turned out to be insufficient to implement the above approach for this case in order to ensure the required accuracy.

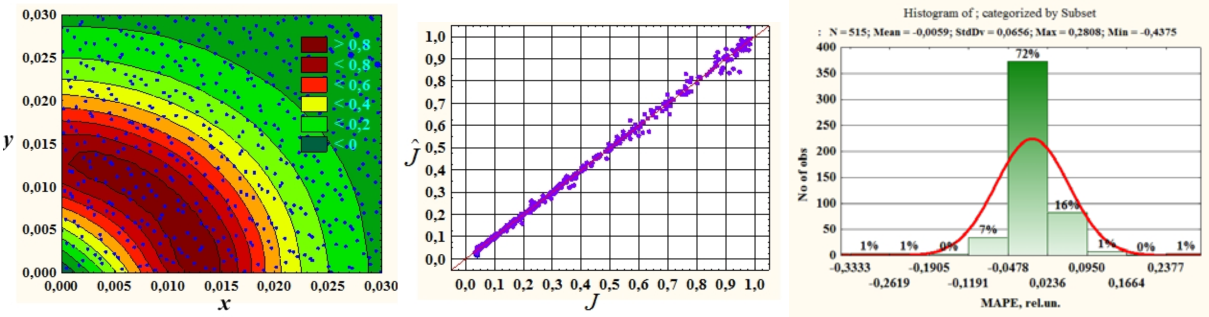


Fig.1 Reconstruction of the response surface by means of an approximation model based on the additive NN-regression for a stationary SECP with a planar ES structure: a) level lines for a slice of the surface; b) scatter diagram; c) histogram of the distribution of the relative model error

Therefore, the additive NN-regression is complicated, namely, at its intermediate levels, NN committees from those networks whose productivity was at least 95 % were applied. The employed method provides an acceptable MAPE error, which varies at the stage of training of the NN from 4.35 % to 14.87 % and from 5.41 % to 24.76 % at the stage of reproducing the response hypersurface.

The response hypersurface is reproduced in all decomposition regions to check the quality of the obtained multivariate approximation model. Also, its adequacy and information content is assessed by a set of statistical indicators. Figure 2 shows the results of reconstructing the response surface for an SECP with a volumetric ES structure. The results were obtained using the created multivariate approximation model in the entire range of variation of the variables at a much larger number of points than was used at the training stage ($N_{reconstitution} > N_{training}$). The numerical values of MAPE obtained at the stage of reconstitution the response hypersurface for two cases of slices ($4 \le r \le 5$ mm, $11 \le r \le 12$ mm) located at heights of $3 \le z_0 \le 4$ mm are 9.95 % and 14.3 %.

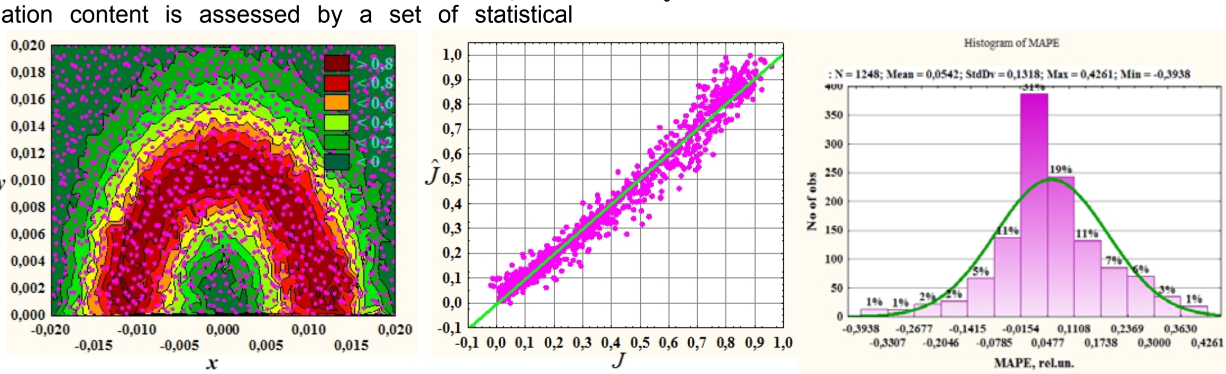


Fig. 2. Reconstruction of the response surface ($11 \le r \le 12$ mm) using an approximation model for a circular movable SECP with a volumetric ES structure: a) level lines for the surface slice; b) scatter diagram; c) histogram of the distribution of the relative model error

A similar approach is used to construct a metamodel of a movable frame SECP with a planar ES structure (square shape of the loop). In this case, the search area along the linear dimension of the loop a was divided into six subregions. We used averaging over the NN ensemble at each level of additive NN-regression for all six decomposition subregions to obtain an acceptable *MAPE,%* result of the approximation model in the range from 7.97 % to 14.91 % (Table) and (Fig. 3).

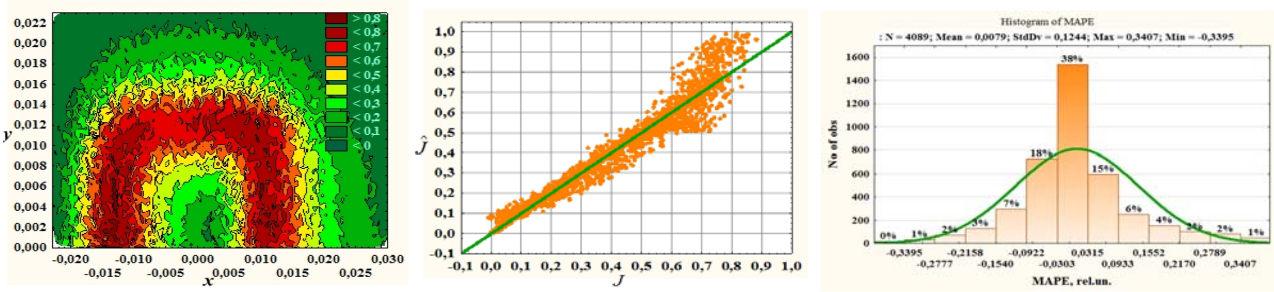
Table. Selected indicators for assessing the adequacy of the approximation model at the stages of training (TS) and reconstitution (RS) for a frame SECP with a planar ES structure.

decomposition subregions [mm]	$N_{training}$ / $N_{reconstitution}$	*MAPE,%*		SS_R		MS_R	
		TS	RS	TS	RS	TS	RS
3≤a<5	2070/4090	7,78	8,07	2,195	4,84	0,00106	0,00118
5≤a<7	2082/4090	7,55	8,22	3,316	6,287	0,00159	0,00153
7≤a<9	2076/4090	7,38	7,97	3,607	7,91	0,00173	0,00193
9≤a<11	2075/4090	8,13	8,69	3,932	8,705	0,00189	0,00213
11≤a<13	2081/4090	8,85	9,43	4,733	9,909	0,00227	0,00242
13≤a≤15	2143/4162	14,91	14,24	5,495	12,872	0,00256	0,00309

The approximation models created in this way in the procedure of surrogate optimal parametric synthesis, which is implemented on the basis of the PSO method [23] are applied. They make it possible to efficiently construct SECP with ES of any complexity with the minimal time investment. They can also be used for a preliminary assessment of the quality of the obtained solution in order to select the best one for further reproduction of the response surface using an "exact" mathematical model.

Conclusions

Thus, the paper proposes and demonstrates by examples a universal method for constructing multidimensional approximation models of SECP with different ES structures. It consists in the step-by-step execution of a number of specific interrelated tasks. It is proposed to implement CDOEs for a multidimensional factor space on the basis of a set of nonparametric additive recursive one-dimensional R-sequences and combinations of Sobol's LP_τ-sequences with the best divergence indicators.



a b c

Fig. 3. Reconstruction of the response surface (11 ≤ a ≤ 13 mm) using an approximation model for a frame movable SECP with a planar ES structure: a) level lines for a slice of the surface; b) scatter diagram; c) histogram of the distribution of the relative model error

Their use is the best way to reproduce the global and local behavior of the multidimensional response surface. A hybrid approach to construct multidimensional approximation models due to significant nonlinearity and irregular behavior of the response hypersurface is used. It provides for the simultaneous application of technologies for decomposition of the search area and NN, constructed on the techniques of associative machines, as well as additive NN-regression. To improve the accuracy of the additive NN-regression, several methods are employed, namely, averaging over the NN ansemble and boosting using bagging. As a result of such actions, as well as due to the complication of the structural features of additive NN-regression by using NN committees at the last or any intermediate level of approximation, it is possible to achieve an acceptable MAPE error of the multidimensional SECP metamodel.

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