Russian Journal of Nondestructive Testing, Vol. 41, No. 1, 2005, pp. 29–33. Translated from Defektoskopiya, Vol. 41, No. 1, 2005, pp. 40–46.

MAGNETIC, EDDY-CURRENT, AND ELECTRICAL METHODS

Structural Synthesis of Attachable Eddy-Current Probes with a Given Distribution of the Probing Field in the Test Zone

V. Ya. Gal'chenko and M. A. Vorob'ev
Lugansk Medical State University, Ukraine
Received April 9, 2004

Abstract—A method for designing attachable eddy-current probes with a given spatial distribution of the probing field is proposed. This method is based on a structural synthesis implemented using a genetic algorithm. An example of the numerical solution for the synthesis of a local cylindrical probe is given.

Certain requirements are set for the distribution of the probing electromagnetic field (EMF) in the inspection zone of an eddy-current probe (ECP). These requirements depend on the configuration of the conductive specimen and the testing procedure to be conducted. For example, in some cases, it is necessary to narrow the zone in which the ECP field interacts with the specimen and to limit the stray magnetic fields of the probe, thus improving its selectivity and protection against interference. These goals can be attained, among others, by using local ECPs. An EMF with a given topography and concentration in a given zone can be created in a local ECP using magnetic circuits, field concentrators made of nonferromagnetic conductive materials, specially shaped screens with or without "masks," and short-circuited turns. Such ECPs are particularly efficient for detecting flaws in objects that have a complex shape and limited dimensions; testing of these flaws is influenced by the effects of the object's boundaries on the ECP signals. At the same time, when screens are located at face ends of, e.g., a through probe, a negative effect is observed along with advantages. This negative effect is due to degradation of the field homogeneity in the testing zone. The use of "mask" ECPs yields improved locality and, at the same time, reduces the ECP sensitivity [1]. To our knowledge, a strictly substantiated technique for the calculation of local ECPs is unavailable. Developers select screen configurations based on their intuitive concepts and empiric regularities. This prevents creation of EMFs with given configurations in the testing zone.

Advantages of local ECPs may be retained in much simpler designs of ECPs that contain no concentrating and screening conducting elements. The predetermined properties of the probing EMF can be obtained by using either an ECP with a current density distributed nonuniformly in the generator coil [2–4] or an ECP with a nonstandard geometry of the exciting coil. The former type of ECPs can be designed using the approaches to the ECP synthesis described, for example, in [4–6]. The quoted papers consider the problem of the EMF synthesis in a linear approximation because the derived mathematical models are relatively simple owing to a linear dependence of the generated field on the current density. The problem of EMF synthesis reduces to solving a linear Fredholm integral equation of the first kind. A discrete analogue of this equation is an ill-conditioned set of linear algebraic equations.

The linear synthesis of the EMF features the following disadvantage: it yields actual values of the current density in the coil sections that can hardly be reproduced in a practical implementation of magnetic systems. It is also necessary to a priori specify the number of sections, the distances between them, and their geometrical dimensions. These disadvantages are partly eliminated in the approach from [7, 8]. In this approach the problem of the EMF synthesis is solved with respect to the coordinates and geometrical dimensions of sections, and the current density can only assume values of integers. This problem, which is described by the Uryson integral equation of the first kind, belongs to a class of linear ill-posed problems that can be solved using nonlinear optimization. Moreover, the functional being optimized has a multidimensional ravine surface thus requiring the development of special methods to search for an optimum solution in a multidimensional ravine situation.

It should be noted that the approaches described above belong to parametric-optimization problems, while the structure of the ECP being designed is selected by developers who base conclusions on their experience and intuition. If an ineffectual structure is selected, then any parametric-synthesis method will fail to attain the required results and the process of designing becomes iterative. Moreover, by use of these meth-

1061-8309/05/4101-0029 © 2005 MAIK "Nauka/Interperiodica"

ods, it is not possible to take into account various numerous requirements for the probe being designed, e.g., those regarding the technological complexity of the design and energy consumption. Therefore, designing ECPs with the use of the method for the structural analysis of magnetic-field sources proposed in [9, 10] seems a promising approach. The structural analysis of ECPs is intended for the implementation in the ECP design of new technological methods which improve their functional characteristics or for the reproduction of the already-obtained results, but with a significantly simplified design.

The problem of the structural synthesis of magnetic-field sources [9, 10], which includes, among others, the problem of the ECP synthesis, is formulated as a problem of the nonlinear optimization under many criteria with the variable dimension of the search space. The magnetic-field sources are considered as a set of sections of different shapes located and connected in a specific sequence. The number of the sections is also a desired parameter that makes the dimensionality of the search space variable. The number of sections in the source and the maximum relative deviation of the magnetic field generated by this source from a given field are the main and mandatory optimization criteria. Depending on the requirements set for the magnetic system being designed, the set of the optimization criteria may include other criteria such as the amperage in the sections, the average or total number of turns in the sections, the dimensions of the system, etc. The number of criteria mentioned above should be minimized according to the physical essence of the problem being solved. The approach to the structural analysis of magnetic-field sources proposed in [9, 10] is a version of stochastic optimization where the optimum solution is sought using a genetic algorithm [11].

In this paper we consider an application of the method described in [9, 10] for the synthesis of a cylindrical (according to classification from [4]) magnetic system of an ECP with a given distribution of the EMF in the plane parallel to the working front plane of the probe that determines the testing zone. The ECP magnetic system is composed of coaxial and sequentially connected circular sections, each of which is determined by its winding direction, number of turns, the z coordinate (z axis coincides with the system's axis), and the radius.

Thus, this paper considers the problem of the ECP probing-field synthesis in the formulation proposed in [4]; the only difference is that the number of sections, their radii, and their coordinates are also included in the set of the sought parameters. This means that, in contrast to [4], where a linear synthesis of the ECP magnetic field was performed with an a priori set number of sections, a higher-level optimization method is proposed here, namely, a structural synthesis. The aim of the structural synthesis as applied to the ECP magnetic field is to find an excitation system, which has the simplest design but nevertheless generates the given spatial distribution of the probing field. The simplicity of the magnetic system is determined by such parameters as the number of sections, number of turns, etc.

The ECP probing field is the primary field of the magnetic system neglecting the response of the object being tested [4]. The longitudinal component of the magnetic-field strength created by a circular section in the plane perpendicular to its axis is described by the expressions [12]

$$H_z(z, r) = \frac{Iw}{2\pi\sqrt{(R_K + r)^2 + (z - Z_K)^2}}\left[K(k) + E(k)\frac{R_K^2 - r^2 - (z - Z_K)^2}{(R_K - r)^2 + (z - Z_K)^2}\right],$$

$$k^2 = \frac{4R_K r}{(R_K + r)^2 + (z - Z_K)^2},$$

where Iw, R_K, and Z_K are the magnetomotive force (MMF), radius, and z coordinate of the section, respectively, and $K(k)$ and $E(k)$ are full elliptic integrals of the first and second kind, respectively. The resulting field of the system is calculated using the superposition principle.

The requirements for the system being designed set certain restrictions on the section parameters:

$$Iw_i < Iw_{\max};\; R_{\min} < R_i < R_{\max};\; Z_{\min} < Z_i < Z_{\max};\; i = \overline{1, N},$$

where Iw_i, R_i, and Z_i are the MMF, radius, and z coordinate of the ith section, respectively, and N is the number of sections in the ECP magnetic system.

The required distribution of the ECP magnetic field in the testing zone is set by an array of check points located in a plane perpendicular to the axis of the magnetic system. The values of the field strength at the checkpoints are set either in a tabular or analytical form.

The ECP magnetic system is set in the genetic algorithm as an array of chromosomes sequentially arranged by the number of sections $X = \overline{\underline{|\alpha_1|\alpha_2|\ldots|\alpha_N|}}$. Each chromosome contains the genes $\alpha_i =$

$\overline{|D_i|W_i|Z_i|R_i|}$ ($i = \overline{1, N}$) describing parameters of the corresponding section (winding direction, number of turns, coordinate, and radius). Real-valued parameters (coordinate and radius) are presented using a symbolic model that assumes splitting the range of possible values of a parameter into several equal parts. The gene determines to which part of the range the parameter value belongs. This value is calculated using a random distribution with equal probability within the specified section.

The proposed version of the genetic algorithm involves the following operators: a selection operator based on the displacement technique and Pareto's domination principle for handling the vector of criteria, panmixia and genotypic inbreeding and outbreeding for the selection of parent couples, and one- and two-point crossover and mutations involving chromosome arrays of a variable length.

```
BEGIN /*genetic algorithm*/
    randomly generate an initial set of magnetic systems
    P^0 = (a_1^0, ..., a_N^0)
    t = 0 /*iteration counter*/
    UNTIL the break condition is satisfied REPEAT
    BEGIN
        R^t = P^t /*reproduction array*/
        FOR p = 1 to p = N_p REPEAT
        BEGIN
            select a mating pair a_i^t, a_j^t from P^t:
            a_i^t, a_j^t = B(P^t)
            apply the breeding operator:
            a_{2p-1}^{t+1/2}, a_{2p}^{t+1/2} = C(a_i^t, a_j^t)
            place new systems into the reproduction array:
            R^t = R^t ∪ { a_{2p-1}^{t+1/2}, a_{2p}^{t+1/2} }
        END
        FOR each system from P^t with probability P_m (k = 1, 2, ...)
        REPEAT
        BEGIN
            apply the mutation operator:
            a_{2N_p+k}^{t+1/2} = M(a_m^t), a_m^t from P^t
            place new systems into the reproduction array:
            R^t = R^t ∪ { a_{2N_p+k}^{t+1/2} }
        END
        selection operator S: R^t ⟶ P^{t+1}
        t = t + 1
    END
END
BEGIN /*selection operator*/
    FOR each system from R^t REPEAT
    BEGIN
    select the rank equal to the number of systems dominating this system using Pareto's principle
    END
    sort the systems according to their fitness (rank): if the ranks of two systems are equal, the system
    with a lower value of the generalized criterion is fitter
    UNTIL there are systems with the same genotypes AND the dimension R^t > N
    REPEAT
```

Table 1. Section parameters of the ECP magnetic system

Section No.	Winding direction	Number of turns	Z coordinate	Radius
1	Clockwise	54	0.0098	0.0097
2		54	0.0020	0.0051

Table 2. Section parameters in the example from [4]

Section No.	1	2	3	4	5	6	7	8
Number of turns	–35.5	–619.4	5867.6	–8114	–4185	1460.2	4752.7	6148.4

BEGIN

find, beginning with the worst, two systems with the same genotypes and remove the least fit

END

IF the dimension $R^t > N$

THEN leave N fittest systems

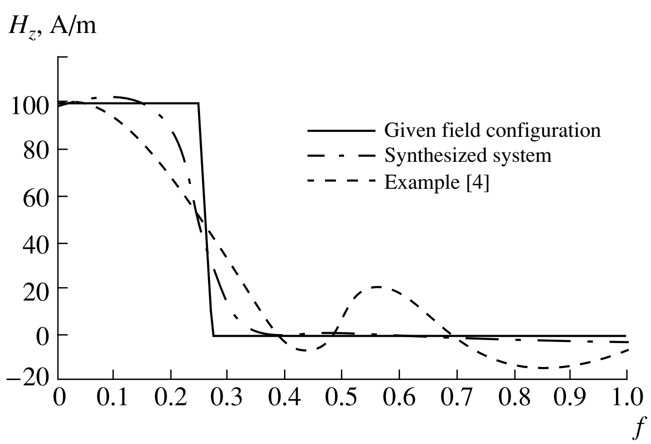
END

The genetic algorithm is described in more detail in [9, 10]. The application of the considered method is illustrated below through the example of the synthesis of an ECP magnetic system with a U-shaped probing field. The required distribution of the magnetic-field strength is set in the plane $Z_0 = 0$. The radii and coordinates of sections may vary in the following ranges: $(0.003 \le R_i \le 0.01)$m and $(0.002 \le Z_i \le 0.01)$m. To enable comparison of the example from [4] with the parameters calculated for the section radius $R = 0.01$ m, we have used the field-distribution function that is the same as in [4]:

$$H_Z(r) = \begin{cases} 100 \text{ A/m}, & (0 \le r \le 0.005) \text{ m} \\ 0, & (0.005 < r \le 0.02) \text{ m}. \end{cases}$$

The number of checkpoints is 39. The checkpoints are located at a distance of 5×10^{-4} m from one another within a segment [0; 0.02] m.

The considered field-distribution function has a point of discontinuity. This significantly complicates its implementation and does not allow the maximum relative deviation of the magnetic-field strength in the checkpoints to be used as an adequate optimization criterion. This situation differs from that described in [9, 10]. In the described example, we have replaced the maximum relative deviation of the magnetic-field strength with the average relative deviation. The number of sections and the total number of turns in all sections were also used as optimization criteria.



Distribution of probing EMFs generated by the compared ECPs in the probed zone.

Table 1 contains parameters of the sections of the synthesized magnetic system. The amperage in the sections, as yielded by the synthesis procedure, is 18.6 mA.

To assess the results, let us compare the obtained magnetic system to the cylindrical system quoted in [4] as an example of the ECP synthesis. The latter system, consisting of sections with equal radii, is described by the following parameters: the number of sections $N = 8$, the section radius $R = 0.01$ m, and the Z coordinate of the first section $Z_1 = 0.002$ m; the distance between adjacent sections is 0.0047 m. The number of turns in the sections for amperage $I = 18.6$ mA is given in Table 2 (the sign determines the coil-winding direction). The figure shows the magnetic-field distributions for the considered systems. The coordinates of the checkpoints are displayed in the graph in dimensionless relative units calculated as the ratio of the coordinate of a point to the length of the segment on which it is located. The average relative deviations of the magnetic-field strength for the synthesized system and the example quoted in [4] are 3.977 and 13.461%, respectively.

From visual inspection of the graph and the values of the average relative deviations, it is evident that the quality of the field generated by the synthesized magnetic system is significantly better than that in the example from [4]. At the same time, the structure is significantly simplified: the number of sections decreased from 8 to 2, the length of the system is reduced from 0.033 to 0.008 m, and the number of turns in sections is reduced for the same amperage values by 2 orders of magnitude.

The advantages of the U-shaped distribution of the ECP probing field for the quoted example are discussed in [4], where the significant improvement of the characteristics of the synthesized ECPs is shown experimentally. It is important that these advantages are only due to the probing-field structure and do not depend on the design of the specific exciting system or on the method of EMF synthesis. Hence, one can conclude that the ECP characteristics of the magnetic system synthesized in this work have been significantly improved as compared to the example quoted in [4], since both the accuracy with which the given field distribution is reproduced and the specifications of the system design have been significantly improved. Using the technique proposed in [13], the spatial structure of the exciting field can also be determined using the given ECP characteristics. The spatial structure can be further implemented by using the proposed method regardless of the specific structure.

The method considered in this paper can be used for synthesizing ECPs of other types, e.g., frame ECPs or ECPs containing sections of different shapes, and also for synthesizing through ECPs with a uniform field generated in a given volume.

REFERENCES

1. *Pribory dlya nerazrushayushchego kontrolya materialov i izdelii* (Instruments for Nondestructive Testing of Materials and Products), Klyuev, V.V., Ed., Moscow: Mashinostroenie, 1986, vol. 2.
2. Fedosenko, Yu. K., The Theory of Eddy-Current Testing by Transducers with Nonuniform Winding Density, *Defektoskopiya*, 1980, no. 3, pp. 82–92.
3. Sandovskii, V.A., The Formation of an Electromagnetic Field in a Specimen under Testing, *Defektoskopiya*, 1984, no. 2, pp. 46–49.
4. Steblev, Yu. I., The Synthesis of Eddy-Current Transducers with a Given Structure of Exciting Field in the Testing Zone, *Defektoskopiya*, 1986, no. 4, pp. 58–64.
5. Yakovenko, V.V., Gal'chenko, V.Ya. and Donskaya, L.V., Synthesis of a Coil in the Magnetic System of a Linear Displacement Sensor, *Izv. Vyssh. Ucheb. Zaved., Ser.: Elektromekhanika*, 1990, no. 6, pp. 75–78.
6. Yakovenko, V.V., Gal'chenko, V.Ya., and Bondarenko, V.E., The Synthesis of Magnetic Systems with Discrete Field Sources, *Izv. Vyssh. Ucheb. Zaved., Ser.: Elektromekhanika*, 1991, no. 8, p. 16.
7. Pavlov, A.K. and Gal'chenko, V.Ya., Information Models for Designing Sources of Magnetic Fields, *Inform. Tekhnol.*, 2002, no. 7, pp. 47–53.
8. Gal'chenko, V.Ya. and Pavlov, A.K., Parametric Nonlinear Synthesis of Round and Rectangular Multiloop Systems of Magnetic Field Sources, *Ukr. Metrolog. Zh.*, 2002, no. 1, pp. 25–30.
9. Gal'chenko, V.Ya. and Vorob'ev, M.A., The Use of Genetic Algorithms in the Structural Synthesis of Sources of Magnetic Fields with Predicted Properties, *Inform. Tekhnol.*, 2003, no. 7, pp. 7–12.
10. Vorob'ev, M.A., Intelligence system of Computer Designing of Solenoidal Multisectional Sources of Magnetic Fields with Predicted Spatial Field Distribution, *Iskusstv. Intellekt*, 2004, no. 1, pp. 144–152.
11. Skurikhin, A.N., Genetic Algorithms, *Novosti Iskusstv. Intellekt.*, 1995, no. 4, pp. 6–46.
12. Alievskii, B.L. and Orlov, V.L., *Raschet parametrov magnitnykh polei osesimmetrichnykh katushek* (Calculation of Parameters of Magnetic Fields of Axisymmetric Coils), Moscow: Energoatomizdat, 1983.
13. Steblev, Yu. I., Synthesis of Exciting Fields of Eddy-Current Transducers for Testing Locally Inhomogeneous Products and Media, *Defektoskopiya*, 1988, no. 5, pp. 47–56.