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MAGNETIC METHODS

Creating Uniform Magnetization in Short Cylindrical Ferromagnetic Samples

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Abstract—A method is proposed to achieve uniform magnetization in ferromagnetic samples based on the bionic parametric optimal synthesis of the magnetization source that provides the necessary magnetization distribution. Simulation results are reported that illustrate the efficiency of the method. Numerical examples show that the proposed method allows the achievement of more uniform magnetization in short samples by using a magnetization system with ferromagnetic elements.

Keywords: magnetic measurements, magnetic control, ferromagnetic sample, uniform magnetization, bionic synthesis

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INTRODUCTION

Uniform magnetization of a sample is an important technological operation in magnetic measurements. Inhomogeneity in the sample magnetization leads to accumulation of error in measurements of various magnetic properties. In magnetic-field testing, highly homogeneous magnetization of a ferromagnetic object favors defect detection and also produces a uniform magnetic field on the control zone, which does not hamper recording of the information magnetic field. It is known, however, that only ellipsoidal bodies can be uniformly magnetized in a uniform external field in an open magnetic circuit. The geometry and sizes of bodies that have any other shape have a prominent effect on the magnetization distribution and distort the uniform character of the external field. Nearly uniform magnetization is especially difficult to obtain in bodies of a small relative length. An instrumental approach to solving this problem is proposed in [1–3], which is based on compensation of surface currents and surface charges by introducing additional field sources into the measuring circuit and subsequent measuring its intensity near the sample for fixing the compensation moment. This approach is a laborious one, since it requires conducting additional measurements. Furthermore, it is rather of a theoretical interest as it has not been proven experimentally. Another approach based on synthesis of a magnetic field that would provide the uniform magnetization of samples is more promising.

The goal of this work is the development of a method that would provide at least more uniform magnetization of examined short cylindrical samples in order to improve metrological characteristics of magnetic measurement and control methods.

FORMULATION OF THE PROBLEM

Let the examined object be a cylindrical sample of a limited length L and a diameter $D = 20$ mm, made from a ferromagnetic material with a nonlinear, in a general case, magnetic characteristic $\mathbf{M} = \chi(H) \cdot \mathbf{H}$. The geometrical model of the sample placed in the magnetization system is plotted in Fig. 1.

Both the magnetization system and the sample are axially symmetric. The magnetization system consists of a magnetic circuit with two pole tips and two coils in accordant connection and the current density of $j = 2$ A/mm^2. For the sake of simplicity, the materials of the magnetic circuit, pole tips, and the sample are considered to be the same, although this is not a necessary condition for the applied mathematical model. The pole tips are composed of several cylindrical pole tips, the number of which is specified a priori. Four types of the magnetization procedure of a ferromagnetic sample were simulated: (I) the sample in an ideally uniform external field of intensity $H_0 = 3$ kA/m; (II) the sample in the field generated by a pair of coils; (III) the sample in the field of the magnetization system shown in Fig. 1 with $h_1 = L/2$; and

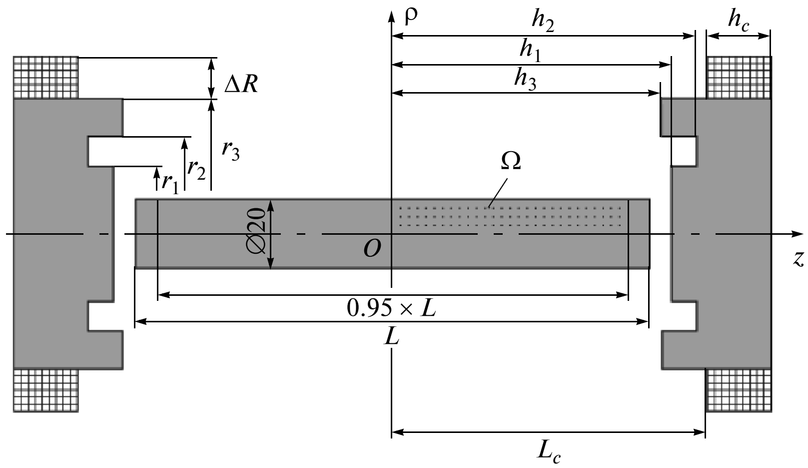

Fig. 1. The geometric model of the magnetization system with a sample.

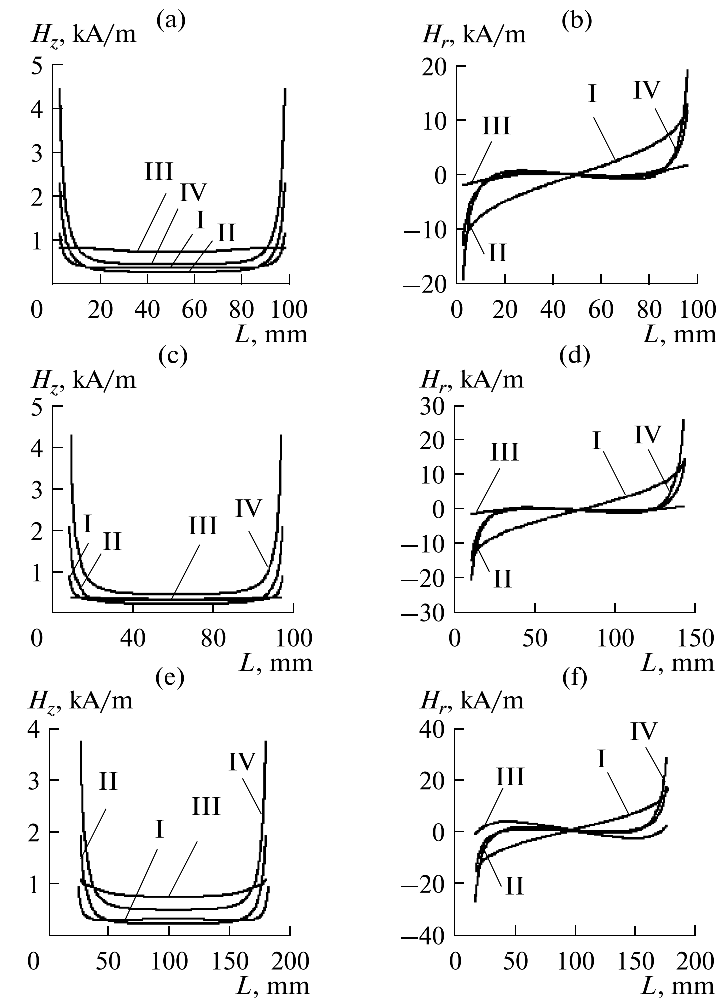

Fig. 2. Distribution of the axial and radial components of the magnetic-field intensity along the sample at a distance of 0.5 mm above its surface for the studied magnetization types and the following values of L: (a, b) 100; (c, d) 140; (e, f) 168 mm.

(IV) a case that is similar to (III) but with a technological gap between the sample and the pole tips, in which measuring sensors should be placed near the faces of the sample.

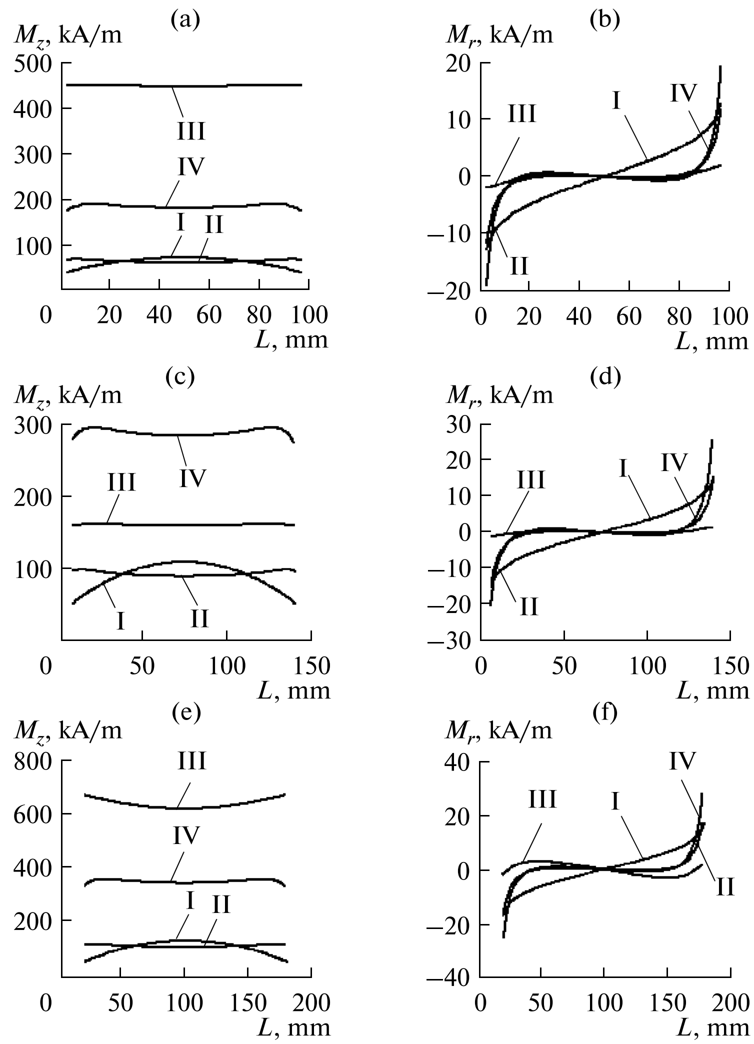

Fig. 3. Distribution of the axial and radial components of the sample magnetization along its length at the distance of 0.5 mm below its surface for the studied magnetization types and the following values of L: (a, b) 100; (c, d) 140; (e, f) 168 mm.

The task was to estimate the degree of homogeneity of the sample magnetization in all four magnetization types. To achieve this, K test points were chosen inside the sample with a 1 mm spacing along its length and radius; 95% of the total sample length was covered with the test points. For the cases (II)–(IV), the magnetization was controlled after the parametric synthesis of the magnetization system with the sample in it had been performed. The optimal, with regard to the homogeneity, magnetization regime was achieved by searching for the sizes of the pole tips and parameters of the magnetizing coils. The optimal synthesis problem was solved with the following restraints on the varied parameters: $10 \le r_1 \le r_2 \le r_3 \le 45$ and $L/2 \le h_1, h_2, h_3 \le L/2 + 35$ for the radii and horns of the pole tips; $5 \le \Delta R \le 50 - r_3$, $L/2 \le L_c \le L/2 + 35$, and $5 \le h_c \le L/2 + 40 - L_c$ for the sizes and positions of the coils. The discretization grid that was necessary to solve the problem was generated with a spacing of 1 mm.

The direct and inverse problems were solved according to the algorithm that was described in [4]; the only difference was that some changes were introduced in the mathematical model and algorithmic part that significantly accelerate the calculation process, as described in [5]. The improved mathematical model was tested on the case of a long ferromagnetic cylinder placed in an ideal uniform external field with an intensity of $H_0 = 1$ kA/m. For this case Rosenblatt obtained a semiempirical analytical expression for determination of the permeability of a cylindrical sample, which is applicable at $\mu \to \infty$. Using this expression, he derived the magnetization distribution along the magnetized sample (see [5]). For a sample with

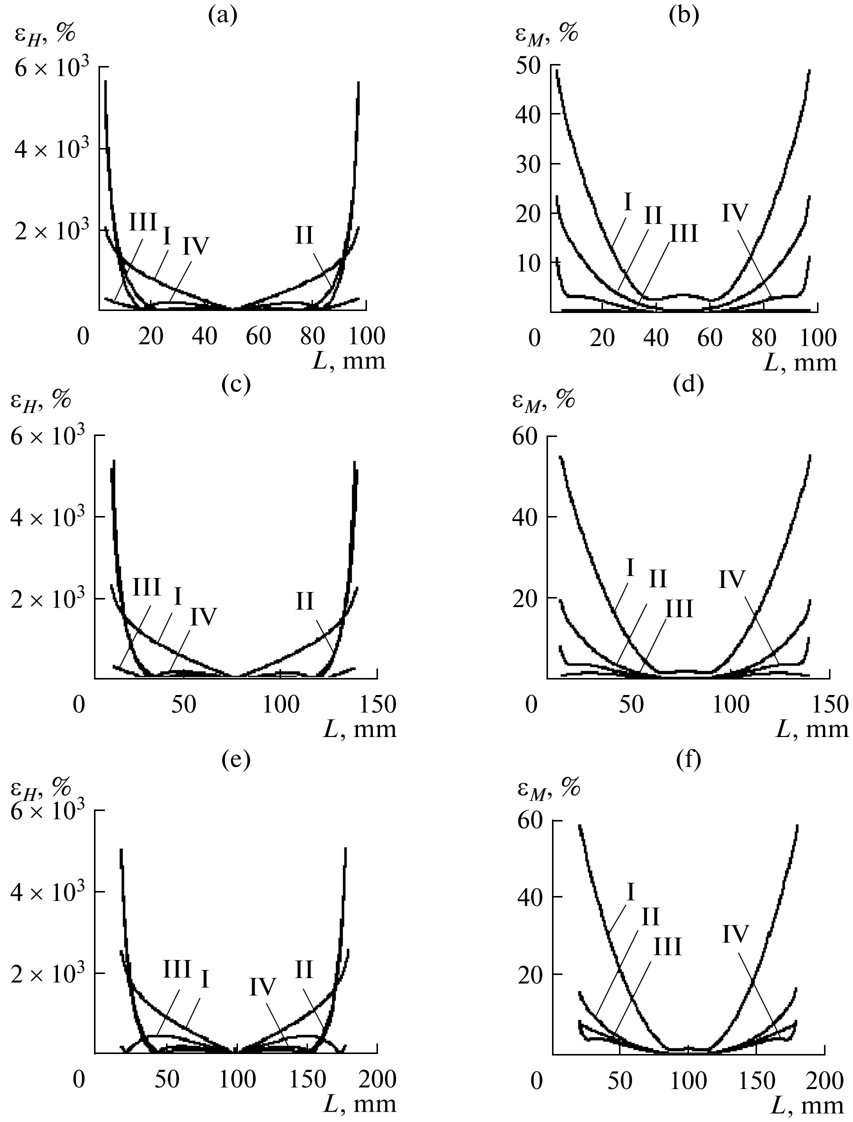

Fig. 4. The distributions of the errors in the homogeneity of the magnetic field intensity and magnetization vectors along the sample with respect to the centered value of $H_c(M_c)$ and measured at a distance of 0.5 mm above and below its surface, respectively, for the L values of (a, b) 100, (c, d) 140, and (e, f) 168 mm.

$L/D = 20$ approximated by ring-shaped elements with a 1 mm periodicity and a linear magnetic characteristic, the maximum error in calculating the intensity of the magnetic field along the sample length with $\mu = 1000$ and 10000 did not exceed 2.8 and 0.9%, respectively. The synthesis method was verified on a shape synthesis of a uniformly magnetized ferromagnetic body made of a set of thin coaxial hollow cylinders and placed in a uniform magnetic field. It was shown in [6] that calculating the lengths of the coaxial cylinders yielded an ellipsoid of rotation, which proved that the developed software was working correctly. In the bionic parametric optimal synthesis method, which is capable of finding a global extremum, the following expression was used as an objective function:

$$f(\mathbf{X}) = \sum_{i=1}^{K} \frac{[(M_{ri})^2 + (M_{zi} - M_c)^2]V_i}{M_c V}, \tag{1}$$

where M_{ri} and M_{zi} are the radial and axial components of the magnetization in the ith point of the control zone, respectively; M_c is the magnetization in the sample's center; V_i is the volume of the ith ring-shaped discretization element; V is the volume of the 95% control zone of the sample.

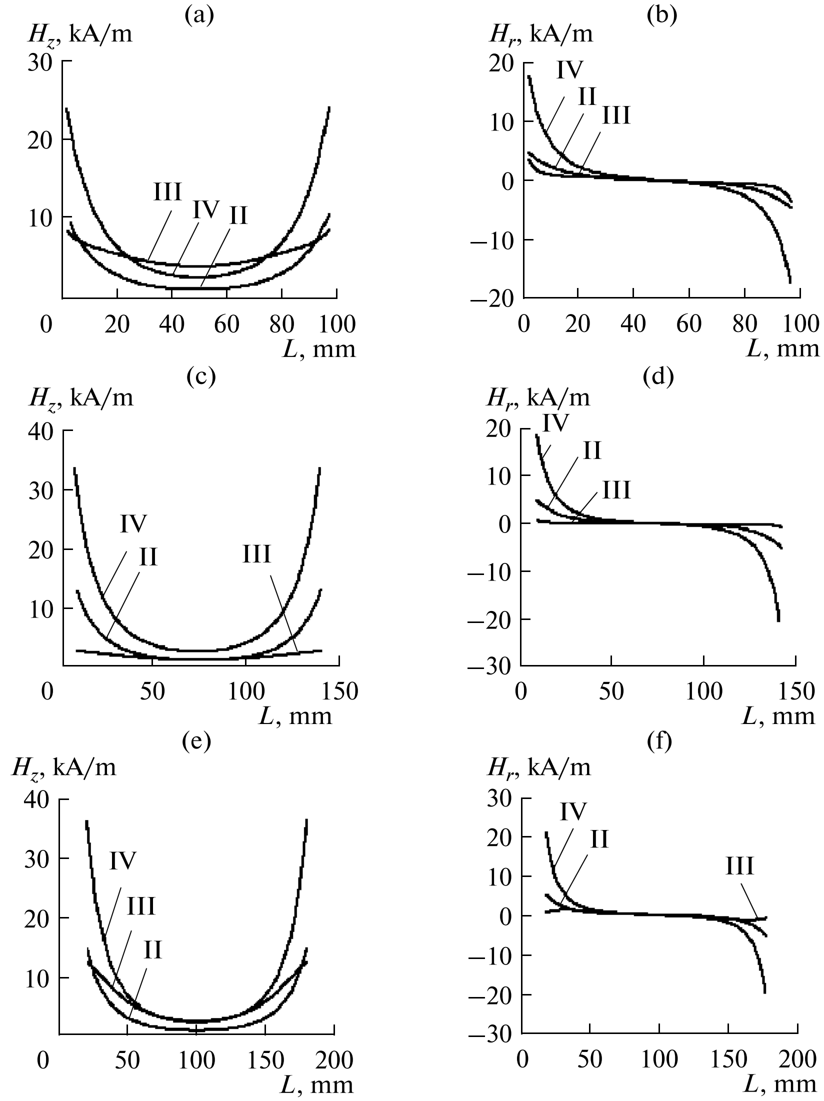

Fig. 5. The distribution of the axial and radial components of the magnetic field intensity of the synthesized source (magnetization types (II)–(IV)) in the control zone along the length of the imaginary sample at the distance of 0.5 mm above its surface and the L values of (a, b) 100, (c, d) 140, and (e, f) 168 mm.

Minimization of this functional allows us to provide the minimal volume-averaged centered error of the magnetization homogeneity $\bar{\varepsilon}_M$ in the control zone with the largest magnetization value M_c in the sample's center. A series of examples with different sample lengths were studied: $L = 100$, 140, and 168 mm. The experiments were thus performed with short samples having L/D ratios of 5, 7, and 8.4, respectively. The results are shown in Figs. 2–4. The distributions of the components of the magnetic field intensity of the synthesized sources without the magnetized samples in their work zone are also of interest (Fig. 5).

In Table 1 (where $\Delta R = R_2 - R_1$) the optimal parameters of the components of the magnetic system that were found are given, which provide the most uniform magnetization of the sample. Note that three pole tips degenerate into two or one tip in the synthesis of the magnetization type (IV).

Some quantitative parameters that describe each of the investigated cases are listed in Table 2.

Here $\varepsilon_{H,\max}$ is the maximum error in the homogeneity of the magnetic field in the control zone above the sample surface, given with respect to the central value of H_c; $\varepsilon_{M,\max}$ is the maximum error over the volume in the homogeneity of the sample magnetization in its 95% control zone (with respect to the central

Table 1. The geometric parameters of the synthesized magnetization sources

Magnetization type	Sample length	L_c	h_c	R_1	R_2	ΔR	r_1	r_2	r_3	h_1	h_2	h_3
II	100	50	36	10	29	19	–	–	–	–	–	–
	140	70	39	10	34	24	–	–	–	–	–	–
	168	84	40	10	38	28	–	–	–	–	–	–
III	100	50	37	39	50	11	10	31	39	50	84	50
	140	72	36	44	50	6	10	28	44	70	104	70
	168	84	39	34	50	16	17	21	34	84	118	84
IV	100	51	30	8	32	24	8	–	–	53	–	–
	140	71	38	8	40	32	8	–	–	73	–	–
	168	85	38	9	46	37	8	9	–	87	97	–

Table 2. Simulation results

L/D	5				7				8.4			
magnetization type	I	II	III	IV	I	II	III	IV	I	II	III	IV
H_c, A/m	628	237	670	354	641	288	389	501	660	327	734	533
M_c, kA/m	67	58	443	174	104	86	157	300	133	111	623	347
$\varepsilon_{H,\max}$, %	2052	5068	290	5362	2311	5194	315	5666	2373	5058	444	5086
$\varepsilon_{M,\max}$, %	70	30	1.3	18	73	31	1.4	18	73	30	7.8	16
$\bar{\varepsilon}_H$, %	616	484	72	480	707	424	74	446	756	443	251	439
$\bar{\varepsilon}_M$, %	19	4.3	0.3	1.6	20	3.3	0.6	1.5	21	3.2	2.3	1.6

value of H_c); $\bar{\varepsilon}_M$ is the volume-averaged error over the control zone in the intensity of the magnetic field (with respect to the central value of H_c; $D/2 \le r_c \le D/2 + 3$ is the radius variation range of the control zone).

These results alter the traditional ideas about magnetization systems with ferromagnetic elements and without a technological gap that are adduced in the literature and recommend using samples with a large L/D ratio in order to improve the magnetization homogeneity.

CONCLUSIONS

1. A method is proposed for uniform magnetizing of ferromagnetic samples, based on the bionic parametric optimal synthesis of the magnetization source that provides the given magnetization distribution over the sample volume.

2. Simulation results are presented that show the efficiency and possibilities of the method.

3. Application of the method for short samples and magnetization systems with ferromagnetic elements was shown to provide smaller errors in the magnetization homogeneity as compared with other magnetization methods.

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