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РАЗРАБОТКА КОНЦЕПЦИИ СИСТЕМЫ МОНИТОРИНГА МОЛНИЙ, КОТОРЫЕ ПОРАЖАЮТ СООРУЖЕНИЯ

Проведен анализ существующих систем мониторинга молний и предупреждения о грозовой активности. Разработана концепция системы мониторинга молний, которые поражают важные сооружения или ударяют вблизи них. В ней используют средства видеорегистрации, датчики (электрического и магнитного поля, светового и звукового сигналов) и компоненты для передачи, накопления и анализа информации по разрядам молний.

Ключевые слова: видеорегистрация молний, мониторинг молний, система мониторинга молний, система предупреждения о грозе.

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DEVELOPMENT OF A METHOD FOR MEASUREMENTS OF THE PARAMETERS OF THE EXTERNAL MAGNETIC FIELD OF TECHNICAL MEANS

На основі моделювання зовнішнього магнітного поля технічного засобу у вигляді сукупності просторових гармонік – мультиполів, розроблено магнітометричний метод вимірювання величин дипольних магнітних моментів. Метод базується на вимірюванні компонент напруженості магнітного поля за допомогою системи із восьми двокомпонентних індукційних давачів у восьми точках навколишнього простору. Оцінено методичну похибку, надано оцінку ефективності розробленого методу.

Ключові слова: напруженість магнітного поля, дипольний магнітний момент, методична похибка, індукційний датчик.

1. Introduction

At present, the sphere of application of magnetic measurements is constantly expanding. These measurements are in demand in many fields of science, engineering and industry, such as electric power engineering, design, development and operation of electrical machines and apparatus, space research, navigation, military science, electromagnetic

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compatibility, etc. The solution of a wide range of scientific and practical problems is directly related to the use of measured values of magnetic quantities such as magnetic field strength, magnetic flux and dipole magnetic moment. Measurements of these quantities are carried out using appropriate methods and means of measurement.

Technical facilities, which include electro-radio equipment, are considered as sources of external magnetic fields (EMF). Such technical objects form an electromagnetic state in the area of the surrounding space and have a negative impact on the functioning of other objects sensitive to the EMF impact. The EMF term denotes a magnetic field that arises in the region of the outer space relative to the surface of the technical means, which is the EMF source [1]. In connection with this, the task of measuring the EMF parameters, which is created by technical means, becomes topical. The resulting problems of electromagnetic compatibility, magnetic ecology, navigation and magnetic protection of equipment go beyond the capabilities of individual countries [2]. To solve these problems, the International Radiation Protection Association has developed recommendations for the application in European countries of the permissible and maximum permissible EMF levels in production and non-production conditions, on the basis of which national standards are developed.

One of the components of the solution of these problems is creation of effective methods and means for measuring the regulated magnetic parameters of the sources of magnetic fields. According to regulatory documents, such regulated parameters for sources of magnetic fields are their dipole magnetic moments, which, in contrast to the strength of the magnetic field, depend on the coordinates of the observation points. The dipole magnetic moment (M, $\text{A}\cdot\text{m}^2$) is the cumulative characteristic of the EMF of the technical object, through which it is possible to determine the field strength at any point in space, the structure and spatial configuration of the magnetic field of the technical field [3–6].

Therefore, there arises the need to solve interrelated problems of creating high-precision methods and systems for measuring dipole magnetic moments. This includes appropriate analytical EMF modeling, development of methods and means for its measurement, compensation of multipole interference and external electromagnetic interference [7, 8].

2. The object of research and its technological audit

The object of the research is methods and means of measuring the EMF parameters of technical objects. The main characteristic of the method and means of measurement is the measurement accuracy or the measurement error, inversely proportional to the accuracy.

The accuracy of measuring the EMF parameters of the object is determined by the nature of the field source, the choice of observation points, the degree of correspondence of the proposed mathematical model of the magnetic field of a real EMF. In addition, the task of monitoring the parameters of magnetic fields is complicated by the presence of non-stationary interference from external sources.

One of the most important stages of the measurement procedure is the stage of constructing or selecting the model of the measurement object. This stage is the most important in the planning of measurements, since errors made at this stage can not be corrected in the future. In the course of measurements, the object model can only be clarified. The discrepancy of the chosen model with the real object is the source of the error, by classification refers to the methodological component of the overall measurement error. This error is always present, because it is impossible to build or choose a model that is completely adequate to the object of measurement. The more accurately the model reflects the object, the less the methodical component of the error. Therefore, the problem of choosing the EMF source model requires more detailed consideration.

One of the most problematic areas of existing methods for measuring the magnetic moments of sources of magnetic fields is the presence of a significant methodological error. For magnetometric methods, its value is 10 %, for integral 20–30 % [8, 9]. This is due to the imperfection of the theoretical foundations of the method.

3. The aim and objectives of research

The aim of research is development and improvement of the metrological support of magnetic measurements by creating effective methods and means of measuring the parameters of electromagnetic objects of technical objects that ensure an increase in the measurement accuracy.

To achieve this aim, the following tasks must be solved:

1. To propose a mathematical model describing EMF created by a technical object.
2. To develop a method for measuring the magnetic moments of magnetic fields of technical objects.
3. To evaluate the effectiveness of the developed method.

4. Research of existing solutions of the problem

The existing methods for measuring the dipole magnetic moment can be divided into:

– magnetometric – the so-called point, magnetic-field-based values of the magnetic field strength at one or more points in space;
– integral, based on the measurement of the magnitude of the magnetic flux [9–12].

The shortcomings of the integral method are given in [8, 9]. This is the complexity of the design and large dimensions of the primary measuring transducer when measuring the magnetic moment of large objects, as well as significant measurement errors (up to 20–30 %). Point methods of measurement are considered in [13, 14]. They are distinguished by the simplicity and low cost of the primary measuring transducers. However, such methods also have low accuracy (for example, the methodological error of the standardized chitritic method is 10 %) due to the insufficient selectivity of the dipole magnetic moment by the sensor system from the full field spectrum. This is due to the imperfection of the theoretical foundations of the method.

The use of point methods that use inductive sensors as primary measuring transducers greatly simplifies the implementation of measurement systems that implement point methods. This gives them the property of mobility, which makes it possible to use point-based magnetometric devices for their small working volume to control EMF sources in industrial conditions and on stationary magnetometric test benches [10].

In [5, 6], the character of the distribution of the magnetic field is investigated. The need to improve the metrological characteristics, the used measuring instruments is established. In work [7] it is shown that in the development of systems for measuring magnetic parameters, it is important to increase the accuracy of measurement and to compensate for interference from external sources. In [15], the importance of choosing an adequate mathematical model for the theoretical justification of methods for measuring the parameters of a magnetic field is shown. In [11, 12] alternative methods for measuring the magnetic moment are proposed, but certain limitations of the application of these methods to magnetic field sources of various sizes are shown.

Thus, the need to increase the accuracy of measuring dipole magnetic moments requires:

- development of effective point-based magnetometric methods and new more noise-proof measuring devices;
- methods to assess the methodological error and the degree of interference immunity of measuring devices from the magnetic field of external sources.

5. Methods of research

To achieve the aim set in the study, methods of EMF analytical representation and its simulation, magnetometric methods for measuring the magnetic field strength, and methods for processing the measurement results are used. Theoretical studies related to the application of mathematical models are based on the use of the method of multipole analysis of EMF, the classical method of EMF representation, methods for solving systems of algebraic equations and methods of matrix algebra.

6. Research results

6.1. Results of the development of a method for measuring the parameters of the external magnetic field of technical means. Any EMF source at each instant of time can be represented as a set of a finite number of elementary magnetic dipoles, each of which is located in the center of a small volume element. According to the principle of superposition, the sum of the elements of elementary dipoles is equal to the equivalent dipole moment, which is shifted relative to the origin of the adopted coordinate system, which is related to the EMF source [1, 3].

To represent the mathematical model of the external magnetic field of a source in order to estimate the level of its magnetic field strength, it is sufficient to clarify the nature of the function. This function describes the distribution of the components of the field strength of an equivalent displaced then arbitrarily oriented in space magnetic dipole. The magnetic field of the source in the surrounding space outside the conductors with current, that is, in the region of space where the current density is zero and $rot\,\bar{H}=0$ can be characterized with the help of a scalar magnetic potential U. In this case, the vector of magnetic field strength $\bar{H}$ is defined as a vector equal in magnitude and directed opposite to the potential $\bar{H}=-grad\,U$. The magnetic potential U is a solution of the Laplace equation $\nabla^2 U=0$ with the corresponding boundary conditions, which are plotted on a closed outer surface surrounding the source of the external magnetic field [15]. The components of the magnetic field strength are determined by differentiating the magnetic potential U with the current coordinates x, y, z. The classical method describes the intensity of the magnetic field of a source through the parameters of its eccentric equivalent magnetic dipole, the components of the resulting dipole magnetic moment of the source of the field, and the coordinates of the eccentricity of the magnetic dipole. For a magnetic field source of the «black box» type, these parameters are unknown quantities and for this reason to determine by the classical method the total value of the magnetic field strength of such source at given points of the external space is very problematic. In this case, EMF describe with sufficient accuracy the dipole model through the magnetic parameters of the components of the equivalent dipole magnetic moment of the field source, determined experimentally for the black box source. Thus, the magnetic field of the source of the magnetic dipole, displaced and arbitrarily oriented in space, found by the classical method, can be described with a given accuracy by the dipole model. In this case, it is necessary to determine experimentally the components of the dipole moment M_x, M_y, M_z of the EMF source of the «black box» type. Then calculate the values of the magnetic field strength of this source in given zones of external space.

The multipole model of the EMF representation [15, 16] can be obtained by expanding the magnetic potential in a stepwise series with respect to the radius of the observation point. The magnetic potential of the EMF source is described by the spherical harmonic Gaussian series (1) as a sum of multipoles of spatial harmonics of the dipole, quadrupole, octupole, and so on. The components are:

$$U=\frac{1}{4\pi}\sum_{n=1}^{\infty}\frac{1}{R^{n+1}}\sum_{m=0}^{n}\left(g_{nm}\cos m\varphi+h_{nm}\sin m\varphi\right)P_n^m(\cos\theta), \quad (1)$$

where R,φ,θ – the spherical coordinates of the observation point; g_{nm}, h_{nm} – constant coefficients of the series that determine the values of the zonal, theserial and sectorial harmonics of the multipole magnetic moments of the EMF source [$A\cdot m^{n+1}$]; n – the ordinal number of the spatial harmonic of the EMF of the Gaussian series; m – the ordinal number of the elementary multipole of the n-th harmonic; $P_n^m(\cos\theta)$ – the adjoint Legendre functions.

The components of the magnetic field strength of the harmonic Gaussian series in a spherical coordinate system are found by differentiating the potential of expression (1) in the coordinates R,φ,θ:

$$H_R=-\frac{\partial U}{\partial R}=$$
$$=\frac{1}{4\pi}\sum_{n=1}^{\infty}\frac{n+1}{R^{n+2}}\sum_{m=0}^{n}\left(g_{nm}\cos m\varphi+h_{nm}\sin m\varphi\right)\cdot P_n^m(\cos\theta); \quad (2)$$

$$H_\varphi=-\frac{1}{R\sin\theta}\frac{\partial U}{\partial\varphi}=$$
$$=\frac{1}{4\pi}\sum_{n=1}^{\infty}\frac{1}{R^{n+2}}\sum_{m=0}^{n}m\left(g_{nm}\sin m\varphi-h_{nm}\cos m\varphi\right)\frac{P_n^m(\cos\theta)}{\sin\theta}; \quad (3)$$

$$H_\theta=-\frac{1}{R}\frac{\partial U}{\partial\theta}=$$
$$=-\frac{1}{4\pi}\sum_{n=1}^{\infty}\frac{1}{R^{n+2}}\sum_{m=0}^{n}\left(g_{nm}\cos m\varphi+h_{nm}\sin m\varphi\right)\frac{\partial P_n^m(\cos\theta)}{\partial\theta}. \quad (4)$$

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The constant coefficients g_{nm} and h_{nm} in expressions (2)–(4) have a certain physical meaning, since they are equal to the magnetic moments of elementary multipoles of the *m*-th order of the spatial n-th harmonic. The coefficients g_{10}, g_{11}, h_{11} are equal to the components of the dipole magnetic moment of the zonal $(n=1, m=0)$ and sectorial $(n=1, m=1)$ harmonics of the dipole field, $h_{11}=M_y$, $g_{10}=M_z$.

EMF multipole model is the basis for creating methods and measuring systems with the so-called point location of primary measuring transducers. These methods are intended for the indirect measurement of the magnitudes of the components of the dipole magnetic moments M_x, M_y, M_z.

The development of the method and the measuring system that realizes it is based on the implementation of a point magnetometric method for measuring the dipole magnetic moments of EMF sources along three orthogonal directions near their surface. The essence of the proposed method is as follows: a system of eight two-component induction sensors is proposed, divided into two groups of four sensors in each group. The sensors are located around exploring EMF source in the equatorial plane *XYZ* $(\theta=90°)$ on the circles of given radii R_1 and R_2 at points with the value of the angular coordinates $\varphi_i=(2i-1)45°$, $\varphi_k=(2k-9)45°$, where $i=1...4$, $k=5...8$ – the sensor numbers of the first and second group of sensors of the measuring system. The layout of the two-component sensors 1–8 of the measuring system around the EMF source, which parameters are measured, is shown in Fig. 1.

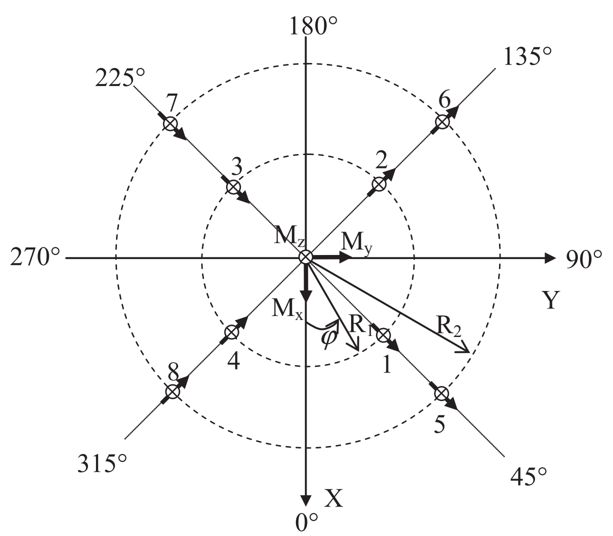

Fig. 1. Arrangement of the sensors of the measuring system around the source of the external magnetic field

Fig. 1 shows:

M_x, M_y, M_z – the measured dipole magnetic moment of the magnetic field source along the three orthogonal directions *X*, *Y*, *Z*, respectively;

1...8 – two-component sensors which longitudinal magnetic coil axes are indicated by arrows, the beginning and the end of these arrows is determined by the rule of the right screw connected with the direction of winding turns of the sensor coils;

R_1, R_2 – the radii of the circles on which the sensors 1–4 and 5–8 are placed, respectively;

φ – angular coordinate.

The magnetic field strength H_R affects the magnetic axes of the sensor coils 1...4 and 5...8, located on the circles of radii R_1 and R_2, and brings electrical signals into them. The effective value of the electrical signals for the measuring channels *X*, *Y*, *Z* is described by the expressions (5), (6).

$$E_{x(y)}(R_1)=\frac{1}{2k_f}\sum_{n=1}^{\infty}\frac{1-(-1)^n}{R_1^{n+2}}(n+1)M_{x(y)n},$$

$$E_{x(y)}(R_2)=\frac{1}{2k_f}\sum_{n=1}^{\infty}\frac{1-(-1)^n}{R_2^{n+2}}(n+1)M_{x(y)n}, \tag{5}$$

$$E_z(R_1)=-\frac{1}{2k_f}\sum_{n=1}^{\infty}\frac{1-(-1)^n}{R_1^{n+2}}M_{zn},$$

$$E_z(R_2)=-\frac{1}{2k_f}\sum_{n=1}^{\infty}\frac{1-(-1)^n}{R_2^{n+2}}M_{zn}, \tag{6}$$

where k_f – the sensor coil constant; M_{in} – resultant magnetic moment of elementary multipoles of the spatial *n*-th harmonic of the radial strength of the source magnetic field along the coordinate direction *X*, *Y*, *Z*.

The arrangement of the sensors 1–8 around the tested source of the EMF and the coordination of their coils according to a useful signal is ensured, and the zonal and sectorial harmonics are delimited by the dipole component of the magnetic field, proportional to the measured components of the dipole moment M_x, M_y, M_z of the field source, from the harmonic of the EMF of even order. Therefore, the structure of the resulting signal, given by the radial, tangential and axial components of the source magnetic field strength in the measuring circuits of the sensor system coils, consists of a useful harmonic signal $n=1$ and multipole interference of odd harmonics (5), (6).

The structure of the resulting electrical signals $E(R_1)$ and $E(R_2)$ of channels *X*, *Y*, *Z* consists of a useful signal of the first harmonic $n=1$ and signals of odd harmonics $n=3,5,7$ ..., introducing a methodical error in the results of measuring the dipole magnetic moment. Therefore, in order to improve the accuracy of measuring dipole magnetic moments M_x, M_y, M_z, it is first of all necessary to exclude $E(R_1)$ and $E(R_2)$ from the structure of the signals and the most significant minterference of the harmonics $n=3$. This is done analytically by solving the system of equations (5), (6). As a result, let's obtain an algorithm for determining the resulting signals E of the measuring channels *X*, *Y*, *Z*:

$$E=k_{1E}E(R_2)-k_{2E}E(R_2), \tag{7}$$

where k_{1E}, k_{2E} – the coefficients which values for a given ratio of radii R_2/R_1 on which the sensor groups 1...4 and 5...8 are arranged according to the scheme in Fig. 1 are calculated by the formulas:

$$k_{1E}=\frac{2}{(R_2^2/R_1^2)-1},\ k_{1E}=\frac{2(R_2^5/R_1^5)}{(R_2^2/R_1^2)-1}. \tag{8}$$

To display the structure of the resulting signal E of the *X*, *Y*, *Z* channels, let's substitute the signal values in a harmonic series $E(R_1)$ and $E(R_2)$, as described by the expressions (5), (6), taking into account the value M_{in} in the expression (7) and obtain expressions of the form:

$$E_x=\frac{8\sqrt{2}g_{11}}{k_f R^3}+\frac{4}{k_f}\sum_{n=5}^{\infty}\frac{1-(-1)^n}{R^{n+2}}\frac{(R_2/R_1)^{3-n}-1}{(R_2^2/R_1^2)-1}(n+1)\times$$
$$\times\sum_{m=1}^{n}g_{nm}\sin m45^\circ\sin^3 m90^\circ P_n^m(\theta=90^\circ), \quad (9)$$

$$E_y=\frac{8\sqrt{2}}{k_f R^3}h_{11}+\frac{4}{k_f}\sum_{n=5}^{\infty}\frac{1-(-1)^n}{R^{n+2}}\frac{(R_2/R_1)^{3-n}-1}{(R_2^2/R_1^2)-1}(n+1)\times$$
$$\times\sum_{m=1}^{n}h_{nm}\cos m45^\circ\sin^3 m90^\circ P_n^m(\theta=90^\circ), \quad (10)$$

$$E_z=\frac{8}{k_f R^3}g_{10}-\frac{4}{k_f}\sum_{n=5}^{\infty}\frac{1-(-1)^n}{R^{n+2}}\frac{(R_2/R_1)^{3-n}-1}{(R_2^2/R_1^2)-1}\times$$
$$\times\sum_{m=1}^{n}g_{nm}\cos m45^\circ\sin^3 m90^\circ\frac{\partial P_n^m(\theta=90^\circ)}{\partial\theta}, \quad (11)$$

where $R=R_1$ – the distance, is taken as the base one when measuring the dipole magnetic moments of the EMF sources.

The analysis of expressions (9)–(11) shows that the signal structure E_x, E_y, E_z consists of the useful signals of the harmonic $n=1$, which is proportional to the coefficients $g_{11}=M_x, h_{11}=M_y, g_{10}=M_z$ and multipole interference $n=5,7,9...$ of the odd harmonics, the order of the elementary multipole interference of which $m=0,4,8,12...$ is smaller n. In this case, the resulting signals E_x, E_y, E_z (9)–(11) can be described as a useful signal E_{x1}, E_{y1}, E_{z1} of the dipole component of the magnetic field to within a multipole interference of the harmonic $n=5$, which makes the main contribution to the methodical error in measuring the components of the dipole magnetic moment M_x, M_y, M_z for EMF sources. As a result, let's obtain the expressions:

$$E_x\approx E_{x1}=\frac{8\sqrt{2}g_{11}}{k_f R^3},$$

$$E_y\approx E_{y1}=\frac{8\sqrt{2}h_{11}}{k_f R^3},\quad E_z\approx E_{z1}=\frac{8g_{10}}{k_f R^3},$$

from which it follows that the measured dipole magnetic moments of the source of the magnetic field are determined by the expressions:

$$M_x=g_{11}=\frac{E_x k_f R^3}{8\sqrt{2}},\quad M_y=h_{11}=\frac{E_y k_f R^3}{8\sqrt{2}},$$

$$M_z=g_{10}=\frac{E_z k_f R^3}{8}.$$

The sensitivity of the channels X, Y, Z of the measuring system to the useful signal of the dipole component of the EMF source is determined by expressions:

$$S_x=\frac{8\sqrt{2}}{k_f},\quad S_y=\frac{8\sqrt{2}}{k_f},\quad S_z=\frac{8}{k_f}.$$

According to the results of measuring the components of the magnetic moment M_x, M_y, M_z of magnetic field of the black-box type source, it is possible to calculate the level of the magnetic field strength of the source in any zones of the surrounding space. It is also possible to determine the spatial configuration of the external magnetic field of the source by using expressions (2)–(4) and made computer simulation [17].Practical implementation of the method for measuring the dipole magnetic moments of EMF sources is carried out by a three-channel measuring system, the structural diagram of which is shown in Fig. 2.

Electrical signals, indicated by the magnetic field of the investigated source, in the circles of the radial and axial coils of the sensors are fed into the switching device SD. SD generates the resulting electrical signals $E_x(R_1)$, $E_x(R_2)$ in the measuring channel X, $E_y(R_1)$, $E_y(R_2)$ – in the measuring channel Y, $E_z(R_1)$, $E_z(R_2)$ – in the measuring channel Z by appropriate commutation of the radial and axial coils. The resultant electrical signals of the measuring channels X, Y, Z are fed to the three-position switch of the CS, which sets the preset mode of operation of the three-channel measuring system to alternately measure the dipole magnetic moments M_x, M_y, M_z of the EMF sources. After the set measurement mode has been established, the resulting signals $E(R_1)$ and $E(R_2)$ of the measuring circuit of the corresponding channel of the measuring system are fed to the amplifiers A1 and PA2 to amplify them in accordance with (7) in k_{1E} and k_{2E} time, respectively (8). The amplified signals $E(R_1)_E=k_{1E}E(R_1)$ and $E(R_2)_E=k_{2E}E(R_2)$ are then coupled with the compensating signal U_k of the external interference compensator and the external interference signal E_P to the input of the adder AD and the measuring device MD for displaying the measurement result.

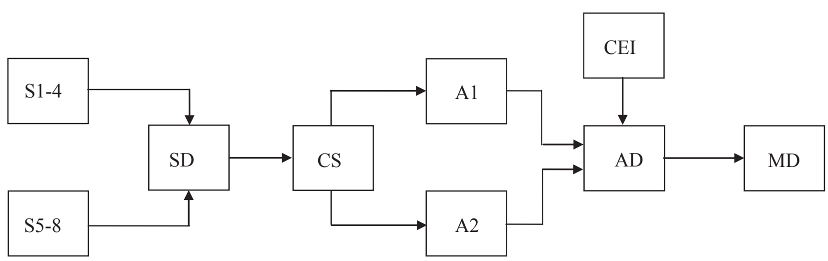

Fig. 2. Structural diagram of a three-channel measuring system measurements of dipole magnetic moments: S1-4 – sensors of the first group; S5-8 – sensors of the second group; SD – switching device; CS – channel switch; A1, A2 – amplifiers; AD – adder; CEI – compensator of external interference; MI – measuring device

6.2. Effectiveness evaluation of the developed measurement method. Determination of the value of the methodological error of the developed method and obtaining its mathematical expressions is based on the use of the multipole theory of the representation of EMF sources and the classical method of representing the source magnetic field, based on the theory of a magnetic dipole. This makes it possible to obtain reliable and convenient mathematical expressions on the basis of a comparative analysis for a methodical error in evaluating the efficiency and determining the metrological characteristics of the measuring system.

Let's determine the value of the methodical error for the first three odd harmonics $n=5,7,9$ (12)–(17) and the resulting methodical error (18), (19):

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$$\delta_{x,y5}=\frac{E_{x,y5}}{E_{x,y1}}=\frac{255R_1^2}{32R_2^2}\left(\frac{k_{x,y}}{R/L_{x,y}}\right)^4, \tag{12}$$

$$\delta_{x,y7}=\frac{E_{x,y7}}{E_{x,y1}}=\frac{161R_1^4(1+R_2^2/R_1^2)}{32R_2^4}\left(\frac{k_{x,y}}{R/L_{x,y}}\right)^4, \tag{13}$$

$$\delta_{x,y9}=\frac{E_{x,y9}}{E_{x,y1}}=\frac{37215R_1^6(R_2^6/R_1^6-1)}{2048R_2^6(R_2^2/R_1^2-1)}\left(\frac{k_{x,y}}{R/L_{x,y}}\right)^8, \tag{14}$$

$$\delta_{z5}=\frac{E_{z5}}{E_{z1}}=-\frac{75R_1^2}{8R_2^2}\left(\frac{k_z}{R/L_z}\right)^4, \tag{15}$$

$$\delta_{z7}=\frac{E_{z7}}{E_{z1}}=\frac{245R_1^4(1+R_2^2/R_1^2)}{16R_2^4}\left(\frac{k_z}{R/L_z}\right)^6, \tag{16}$$

$$\delta_{z9}=\frac{E_{z9}}{E_{z1}}=-\frac{2835R_1^6(R_2^6/R_1^6-1)}{128R_2^6(R_2^2/R_1^2-1)}\left(\frac{k_z}{R/L_z}\right)^8, \tag{17}$$

where $E_{x,y,z1}$ – useful signals of channels X, Y, Z of the measuring system, created by the dipole component of the magnetic field; $k_{x,y,z}=x_0(y_0,z_0)/L_{x,y,z}\le 1/2$ – eccentricity coefficient of the measured dipole moment M_x, M_y, M_z; $L_{x,y,z}$ – the overall size of the EMF source along the coordinate direction X, Y, Z.

$$\delta_{x(y)p}=\frac{E_{x(y)p}-E_{x(y)1}}{E_{x(y)1}}=\frac{B_{x(y)}\cdot R_2^5/R_1^5-A_{x(y)}}{4\sqrt{2}\left(R_2^2/R_1^2-1\right)}-1, \tag{18}$$

$$\delta_{zp}=\frac{E_{zp}-E_{z1}}{E_{z1}}=\frac{B_z\cdot R_2^5/R_1^5-A_z}{R_2^2/R_1^2-1}-1, \tag{19}$$

where A_i, B_i – the coefficients which values are calculated for a given k_f, R_2/R_1 and $R/L_i=\text{var}$, $i=x,y,z$.

On the basis of expressions (12)–(17) and (18), (19) the value of the resulting methodical error and its components, with a value of $R_2/R_1=\sqrt[3]{2}$, and $k=1/3$ are calculated. Thus, when measuring dipole magnetic moments M_x, M_y, at a distance $R=(1{,}5-2)L_{x(y)}$, the resulting methodological error $\delta_{x(y)p}=(0{,}381-1{,}154)$ %, and its main components – the errors of the fifth, seventh and ninth harmonics are, respectively:

$$\delta_{x(y)5}=(0{,}365-1{,}026)\ \%;$$

$$\delta_{x(y)7}=(0{,}011-0{,}062)\ \%;$$

$$\delta_{x(y)9}=(0{,}002-0{,}016)\ \%.$$

When measuring the axial dipole moment M_z of a magnetic field source at a distance $R=(1{,}5-2)L_z$, the resulting methodical error is $\delta_{zp}=(0{,}431-1{,}278)\%$, and its components of odd harmonics $n=5,7,9$ in this case will be equal to:

$$\delta_{z5}=(0{,}346-1{,}010)\ \%;$$

$$\delta_{z7}=(0{,}033-0{,}189)\ \%;$$

$$\delta_{z9}=(0{,}002-0{,}019)\ \%.$$

The analysis shows that the accuracy of measuring dipole magnetic moments M_x, M_y, M_z, by the proposed method, exceeds the standardized chitiorite method by 8–21 times [10, 13, 14].

7. SWOT analysis of research results

Strengths. Among the strengths of this research, it is necessary to note the results obtained for achieving high metrological characteristics of the developed method and measuring system. To this should be attributed a significant reduction in the methodological error of measurement, increasing the sensitivity of the measuring channels, the ability to measure several parameters – magnetic moment, magnetic field strength, spatial configuration. The merits include the ability to compensate for interference from external sources, small overall dimensions, low cost of used inductive sensors.

Also it should be noted the possibility of wide application of the developed measurement method, namely the solution of a number of practical problems:

– electromagnetic compatibility of various kinds of magnetosensitive external magnetic field of equipment;
– when developing protection against the negative impact of an external magnetic field on the environment;
– when creating magnetometric test stands for monitoring the parameters of the magnetic field of technical means, to which they place requirements to reduce their magnetic field level.

Weaknesses. The weaknesses of this research are related to certain difficulties in measuring the magnetic field of objects of a large elongated shape. Also, it should be noted the high requirements for the accuracy of the installation of sensors according to the proposed layout of their location, which can affect the accuracy of measurements. This circumstance imposes special requirements for the qualification of operators.

Particular attention should be given to the choice of sensors used. Since eight sensors are used, high demands are placed on the degree of homogeneity of their metrological characteristics.

Opportunities. Opportunitiesfor further research are related to the improvement of the metrological characteristics of magnetometric instruments, the development of metrological verification tools, and the automation of measurements. In particular, the effect of excluding from the useful signal spatial harmonics of higher order on the magnitude of the methodical error can be investigated. This will allow changes to be made to improve the measuring system.

The results of the implementation of the research contribute to the improvement of the quality of research results. Increase the reliability of the results of monitoring the magnetic field, carried out in testing laboratories and enterprises.

Threats. The threats in implementing the research results are related to the following factors. Additional costs are required for metrological certification and subsequent verification work. It is necessary to develop the appropriate software to automate measurements, reduce the amount of calculations.

8. Conclusions

1. A mathematical model describing an external magnetic field, which is formed by technical objects, is proposed. The application of this model provides for taking into account the geometric properties of the field source, allows to describe the field parameters in a convenient coordinate

system, ensures the interrelation of the field parameters, allows to calculate the field at any point in space.

2. A point magnetometric method has been developed for measuring the magnetic moments of the dipole component of the intensity of the external magnetic field of the source. The structural scheme of a measuring system that implements the developed method is proposed. Typical differences of this scheme is the presence of the block, it ensures the elimination of the third order harmonic from the resulting signal and the presence of a block that compensates for interference from extraneous sources.

3. The evaluation of the effectiveness of the developed method is performed. It is determined that the methodical error of measurement for the components of the magnetic moment M_x, M_y, M_z is $\delta = 0.381 - 1.278\ \%$. The measurement accuracy in two dimensions increases by an order of magnitude in comparison with the analog. The sensitivity of the measuring channels to the useful signal is increased by 2 times.

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РАЗРАБОТКА МЕТОДА ИЗМЕРЕНИЙ ПАРАМЕТРОВ ВНЕШНЕГО МАГНИТНОГО ПОЛЯ ТЕХНИЧЕСКИХ СРЕДСТВ

На основе моделирования внешнего магнитного поля технического средства в виде совокупности пространственных гармоник – мультиполей, разработан магнитометрический метод измерения величин дипольных магнитных моментов. Метод основан на измерении компонент напряженности магнитного поля с помощью системы из восьми двухкомпонентных индукционных датчиков в восьми точках окружающего пространства. Оценена методическая погрешность, дана оценка эффективности разработанного метода.

Ключевые слова: напряженность магнитного поля, дипольный магнитный момент, методическая погрешность, индукционный датчик.

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