UDC621.317:006-91 DOI: 10.30837/2663–9564.2025.2.05

A STUDY OF THE METROLOGICAL CHARACTERISTICS OF MULTISENSOR SYSTEMS FOR MEASURING EXTERNAL MAGNETIC FIELDS

O.V. Degtiarov, I.I. Klyuchnyk, I.E. Khoroshailo, V.O. Lutsenko.

Kharkiv National University of Radio Electronics, Kharkiv,Ukraine

Abstract

The paper investigates the metrological characteristics of instruments for spatial harmonic analysis of external magnetic fields generated by technical objects. Mathematical models of signal conversion are presented, along with relations for calculating the conversion function, sensitivity, linear-angular, and multipole measurement errors. The influence of the spatial configuration of the distributed converter system on measurement accuracy and interference immunity is analyzed. The obtained dependencies can be used to evaluate accuracy and optimize the parameters of spatial harmonic analysis instruments.

Keywords: external magnetic field; spatial harmonic analysis; metrological characteristics; distributed converter system; conversion function; sensitivity; measurement error; interference immunity.

1. Introduction

Measurement of parameters of external magnetic fields of technical objects is an important direction of modern metrology, since magnetic fields accompany the operation of most electrical, energy and transport systems. Their control allows to assess electromagnetic compatibility, equipment condition and impact on the environment. The increase in the density of electronic devices, the use of powerful power supplies and automation systems leads to the need for high-precision methods of spatial analysis of magnetic fields. This determines the relevance of creating measuring instruments with improved metrological characteristics, capable of selectively determining the parameters of individual spatial harmonics.

The application of multipole field theory [1,6,7] to the study of external magnetic fields generated by technical objects in the surrounding space – according to which the source field represents a spatial spectrum of individual harmonics or multipoles – has led to the creation of new magnetometric methods and measuring instruments designed for the selective measurement of spatial harmonic parameters. It is the provision of spatial filtering capability, i.e., the isolation of any individual component from the entire multipole spectrum and the determination of its parameters, that allows these measurement tools to be classified into a separate group and defined as tools for spatial harmonic analysis. The issues of assessing and improving the accuracy of measurement data are urgent, which requires the study of metrological characteristics. This issue is a narrow field of measurement and is not sufficiently covered in publications.

A review of recent publications shows that considerable attention is given to improving the accuracy of magnetic parameter measurements for technical objects, particularly small satellites and elements of electrical equipment. In study [1], a methodological error of 2% and a total stand error of 13% were achieved, confirming the complexity of ensuring high accuracy when reproducing magnetic moments. In [2], the measurement errors of magnetic parameters of satellite components were analyzed, but the methodological error and its estimation procedure were not specified. The authors of [3, 4] proposed measurement techniques limited by the geometry of the objects under test – coil-type or disk-shaped. Paper [5] focuses on the methodology for evaluating the uncertainties of magnetic moment measurements, confirming the need to improve metrological support in this area. Therefore, the comprehensive analysis of metrological characteristics of spatial harmonic analysis instruments remains an insufficiently studied research direction.

The purpose of the study is to determine and analyze the metrological characteristics of instruments for spatial harmonic analysis of external magnetic fields generated by technical objects, as well as to develop mathematical models describing their conversion function, sensitivity, measurement errors, and interference immunity.

To achieve this purpose, the following objectives were set:

1) To develop mathematical models of transformations for distributed converter systems used in spatial harmonic analysis instruments.

2) To determine the main metrological characteristics, including the conversion function, sensitivity, multipole, and linear-angular errors.

3) To assess the influence of the spatial configuration of converter systems on measurement results and interference immunity.

4) To generalize the obtained results for further optimization of the design and parameters of spatial harmonic analysis instruments.

2. Research results

The main magnetic parameters of multipoles, which determine the spatial image inherent only to a given object and generally constitute its information field, include, firstly, multipole magnetic moments, which are considered as sources of the corresponding spatial harmonics, and, secondly, the level and distribution of the intensity of the total magnetic field of the source and each of the multipoles that make it up.

To analyze constant and low-frequency magnetic fields, under condition $\mathrm{rot}\overline{H} = 0$, the mathematical apparatus of multipole field theory can be applied in the form of spatial series, which for the components of the tension in the spherical coordinate system R, φ, θ have the form (1-3):

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

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

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

where g_{nm}, h_{nm} are multipole magnetic moments, $\mathrm{A\cdot м}^{n+1}$; n is the multipole order or harmonic number, m is the elementary multipole of the n^{th} order; $P_n^m(\cos\theta)$ is the adjoint Legendre polynomials.

The solution of the spatial filtering problem became possible through the application of the principle of spatial arrangement of sensors, when a certain number of sensors are simultaneously placed at the control points around the source of an external magnetic field (EMF), which are electrically combined into a system. Such a system of transducers with a certain spatial configuration is a functionally complete technical means – a distributed transducer system (DTS). Since it is the DTS that provides the necessary functional conversion of magnetic parameters into an electrical signal, its metrological characteristics (MCh) determine the properties of a particular means of spatial harmonic analysis (SHA) as a whole.

Research in this direction has revealed that the characteristic intended for determining the measurement results – the conversion function, as well as the characteristics of the errors of the tool are entirely determined by the structure of the DTS and the switching algorithms of the system's converters. Therefore, further, using the example of analyzing a DTS consisting of eight sensors located in the equatorial plane around the studied EMF source evenly on two circles, the axes of which coincide and the radii R differ, we will determine such basic MCh of this SHA tool as the conversion function, sensitivity to the measured magnetic parameters, noise immunity, multipole and linear-angular errors.

Expressions (1-3) are initial for obtaining mathematical models of DTS, creation of new DTS tools and obtaining metrological characteristics noted above.

The eight-point DTS under consideration excludes the influence on the measurement result of all paired multipoles of the spectrum (1-3), as well as the third and some components of the fifth-order multipole and provides measurement of the parameters of the first spatial harmonic – dipole magnetic moments.

The three-component DTS sensors are divided into two bodies of four in each so that sensors 1-4 are located on a circle with radius R, sensors 5-8 on a circle with radius $R_1 > R$. The distances R and R_1 are related to the sensitivity S to the magnetic field strength of sensors 1-4 and the sensitivity S_1 of sensors 5-8 by the ratio

$$\frac{R_1}{R} = \left(\frac{S_1}{S}\right)^{1/5}. \quad (4)$$

To obtain the conversion function, we give an expression for the useful signal E_x at the output of channel X of the eight-point DTS, which represents a mathematical model of the conversion:

$$\begin{aligned} E_x &= S_x(H_1 + H_2 - H_3 - H_4) - S_{1x}(H_5 + H_6 - H_7 - H_8) = \\ &= S_x(H_{R(R,\varphi=0^\circ)} + H_{\varphi(R,\varphi=90^\circ)} - H_{R(R,\varphi=180^\circ)} - H_{\varphi(R,\varphi=270^\circ)}) - \\ &- S_{1x}(H_{R(R_1,\varphi=0^\circ)} + H_{\varphi(R_1,\varphi=90^\circ)} - H_{R(R_1,\varphi=180^\circ)} - H_{\varphi(R_1,\varphi=270^\circ)}), \end{aligned}$$

where S_x, mV/mOe is sensitivity of sensors 1-4, S_{1x} is sensitivity of sensors 5-8 of measuring channel X.

Summing up the radial and tangential components of the EMF intensity determined at the control points using this algorithm, under condition (4) and without taking into account the insignificant fraction of non-excluded multipoles of higher odd orders (n=5, 7...), leads to the following result:

$$E_x = 6g_{11}\frac{S_x}{R^3}(1 - k_s^{5/2}), \quad (5)$$

where $k_s = S_1/S$.

The coefficient g_{11} is in this expression is a constant value for a given EMF source and is equal to the dipole moment M_x. The value of the electrical signal at the output of channel X (5) determines the dipole moment M_x,

$$M_x = E_x = \frac{1}{(1 - k_s^{5/2})}\cdot\frac{R^3}{6S_x}. \quad (6)$$

Then, based on the obtained expressions for E_x and M_x, for channel X, we can conclude that expression (5) is the eight-point DTS transformation function, and expression (6) is the working measurement formula implemented by the SHA tool as a whole.

From expression (6) the sensitivity S_M^x of channel X to the dipole magnetic moment M_x is determined, which depends on the sensitivity of DTS converters:

$$S_M^x = 6S_x(1 - k_s^{2/5}),$$

Thus, the conversion function and channel sensitivity can be represented as dependencies:

$$M_x = f(R, E_x);\ S_M^x = f(S_x, S_{1x}).$$

The above dependencies also fully apply to channels Y, Z of the eight-point DTS. The considered characteristics are the same for channels X and Y, differ for channel Z, but have the same structure.

The use of SHA tools is associated with the procedure of placing transducers at control points in space with specified coordinates, which, according to the type of DTS, depend on the selected measurement method.

Due to the fact that the SHA means transformation function in the form (6), where $E_x = S_x \cdot H(R, \varphi)$, is essentially a mathematical model for solving the inverse magnetostatics problem regarding the determination of the moment M_x, the field source, which by formulation belongs to the class of incorrect ones, the question arises about the stability of its solution, that is, whether small perturbations in the magnetic field strength, which arise due to inaccurate placement of sensors, correspond to small deviations of the solution of the problem regarding the magnetic moment.

Research in this direction has shown that the problem is stable and errors in installing sensors at points with given coordinates $\pm\Delta R, \pm\Delta\varphi, \pm\Delta\theta$ lead to the appearance of a random linear-angular error. For the eight-point SHA tool, this error depends on the values of the distances *R* and R_1 to the EMF source, at which the sensors are installed, and on the magnitudes of the displacements of each of the spherical coordinates of the sensor installation points, which are respectively given by the boundaries $\pm\Delta R, \pm\Delta\varphi, \pm\Delta\theta$.

When finding the limits of the linear-angular error, its root-mean-square value in relative form for the measuring instrument under consideration, assuming a uniform law of deviation distribution, $\pm\Delta R, \pm\Delta\varphi, \pm\Delta\theta$ will be determined by the following formula:

$$\sigma_0 = \frac{\sqrt{\sum_{i=1}^{8} \Delta E_{ix}^2}}{1{,}73 \cdot E_{ix}}, \qquad (7)$$

where ΔE_{ix} is the absolute error of measurement of the useful electrical signal by the i^{th} sensor of channel X; E_{ix} is the effective value of the useful electrical signal, which is given in the i^{th} sensor of channel X, determined by formula (5).

The X and Y channels of this device are identical, so we will now focus on determining the limits of the linear-angular error of the inaccuracy of the sensor installation for the SHA device under consideration only when measuring the moment M_x.

When measuring the moment M_x with this device, the sensors of the X channel, the direction of the magnetic axes of which coincide with or are parallel to the X coordinate axis, will be affected by the radial H_{1R} (1) and tangential $H_{1\varphi}$ (2) components of the dipole component of the magnetic field strength.

Due to the fact that it is planned to use SHA tools to measure the EMF of electrical equipment that has different overall dimensions and is in different operating conditions, i.e. R=var, there is a practical need for an equation that will allow for a priori calculation of the standard deviation of the desired error at permissible deviation values $\pm\Delta R, \pm\Delta\varphi, \pm\Delta\theta$ for different values of the control distance R. Thus, such an equation, which is an important MCh, would be convenient to present in the form of a functional dependence $\sigma_0 = f(\Delta R / R, \Delta\alpha)$ with its subsequent generalization to other multipointSHA means. Deviations $\Delta\varphi, \Delta\theta$ as quantities of one order of magnitude, within which the angular coordinates of the sensor installation point can be located with equal probability, are denoted as $\Delta\alpha$, i.e. $\Delta\alpha = \Delta\varphi = \Delta\theta$..

To simplify further calculations, let us consider a real case for a certain DTS configuration, when $k_S = 2$. In this case, the distances at which the sensors are located are related as R_1=1,15·*R*. Then, under the specified conditions and the corresponding transformations of expression (7), after substituting the components of the intensity of the first spatial harmonic from the series (1), (2) and taking into account the deviations $\pm\Delta R, \pm\Delta\varphi, \pm\Delta\theta$, we obtain:

$$\sigma_0 = 0{,}43 \left\{ \frac{4[-\sin^2\Delta\alpha \pm 3(\Delta R/R)]^2}{[1 \pm 3(\Delta R/R)]^2} + \frac{[-\sin^2(\Delta\alpha/2) \pm 3(\Delta R/R)]^2}{[1 \pm 3(\Delta R/R)]^2} + \frac{7[-\sin^2\Delta\alpha \pm 2{,}61(\Delta R/R)]^2}{[1 \pm 3(\Delta R/R)]^2} + \frac{1{,}74[-2\sin^2(\Delta\alpha/2) \pm 2{,}61(\Delta R/R)]^2}{[1 \pm 3(\Delta R/R)]^2} \right\}^{1/2}.$$

It was noted above that the eight-point DTS according to the given transformation model (5) provides measurement of the parameters of the first spatial harmonic with an error caused by the non-excluded elementary harmonics of the fifth order multipole. This error is defined as multipole and is the error of the measurement method implemented by the eight-point DTS.

The noted methodological multipole measurement error M_x, M_y, M_z in relative form is equal to

$$\delta_x = \frac{E_{x5}}{E_{x1}} 100\,\% = -\frac{40}{g_{11}R^4}\left(\frac{1}{12}g_{51} - g_{53} + 66 g_{55}\right) \cdot 100\,\%;$$

$$\delta_y = \frac{E_{y5}}{E_{y1}} 100\,\% = -\frac{40}{h_{11}R^4}\left(\frac{1}{12}h_{51} - h_{53} + 66 h_{55}\right) \cdot 100\,\%;$$

$$\delta_z = \frac{E_{z5}}{E_{z1}} 100\,\% = -\frac{1.43}{g_{10}R^4} g_{50} \cdot 100\,\%.$$

where g_{5m}, $h_{5m}\,(m = 0,1,3,5)$ are the fifth harmonic magnetic moments caused by the displacement of the magnetic dipole to coordinates x_0, y_0, z_0.

After substituting the values g_{5m}, h_{5m} associated with the overall dimensions of the investigated EMF source, which is largely convenient from the point of view of practical evaluation, for the limiting value of the methodological error of measuring dipole moments, we can write:

$$\delta_x = -0.62\left(\tfrac{L_x}{R}\right)^4 \cdot 100\%;$$

$$\delta_y = -0.62\left(\tfrac{L_y}{R}\right)^4 \cdot 100\%;$$

$$\delta_z = -0.44\left(\tfrac{L_z}{R}\right)^4 \cdot 100\%;$$

where L_x, L_y, L_z are the overall dimensions of the EMF source in the coordinate directions X, Y, Z of the adopted coordinate system, respectively.

The use of distributed systems of transducers with different sensor configurations in space as part of SHA tools allows for quite flexible coverage of EMF sources with different geometries, and, in addition, provides the opportunity to perform research under operating conditions of the sources.

In such a formulation, the solution of the problem of spatial selection of parameters of individual multipoles is directly correlated with the problem of ensuring the reliability of measurements under the influence of magnetic interference fields created by extraneous sources. The property of SHA means with DTS of a particular configuration, which characterizes the degree of influence of interference fields on the results of spatial measurements, is determined by such an important MCh as interference immunity. Through this MCh, the additive component of the error due to the action of magnetic interference fields can also be determined.

The interference immunity of an eight-point system and in general of any DTS consisting of a total number of transducers n, which are located around the investigated source of the MMF, is defined as the deviation of the resulting interference signal

$$E_{I\tau} = S_\tau \sum_{i=1}^{n} H_{iI\tau},$$

where $H_{iI\tau}$ is the magnetic field strength of the interference, which affects the magnetic axes of the transducers of the corresponding channel) at the channel $\tau = X, Y, Z$ output from the basic interference signal $E_{I\tau 0} = S_\tau H_{I\tau 0}$, , which is proportional to the interference strength $H_{I\tau 0}$ in the center of the DTS:

$$\Delta_{I\tau}^{n} = \frac{E_{I\tau 0} - E_{I\tau}}{E_{I\tau}} 100\%. \qquad (8)$$

Given the dipole nature of the interference magnetic field, we will determine the interference immunity of the eight-point DTS for channel X. Let us assume that the dipole magnetic moment of the external interference $M_{DI} = M_{DI\,X}$ is located on the X axis and is distant R_C from the geometric center SHZ and oriented in the direction of the component M_x. Then the magnetic potential of the interference dipole will be equal to

$$U = \frac{\overline{M}_{DI}\overline{R}}{4\pi R^3}, \qquad (9)$$

where $\overline{R} = \overline{i}x + \overline{j}k + \overline{k}z$; x, y, z are current coordinates of the observation point.

To determine the noise immunity Δ_{Ix}^{8} of an eight-point DTS, it will be convenient to expand the potential (9) in the Cartesian coordinate system:

$$U = \frac{M_{DIx}x + M_{DIx}y + M_{DIx}z}{4\pi R^3}. \qquad (10)$$

Based on (10) and taking into account the connection $H_x = -\partial U / \partial x$, the x-component of the magnetic field strength of the interference H_{Ix}, which affects the magnetic axes of the converters of channel X, is found:

$$H_{Ix} = H_{Ix0} \frac{R_C^3 (2x^2 - y^2)}{2(x^2 - y^2)^{5/2}},$$

where $H_{Ix0} = M_{DIx} / 2\pi R_C^3$ is the magnetic field strength of the interference in the centre of the SHA, the level of which is taken as the baseline.

The coordinates of points 1-8 of the sensor location in the form $i(x_i, y_i)$ are equal to

$$1(R_C + R, 0);\ 2(R_C + R);\ 3(R_C - R, 0); 4(R_C - R);$$
$$5(R_C + R_1, 0);\ 6(R_C + R_1);\ 7(R_C - R_1, 0); 8(R_C - R_1).$$

After performing the summation according to the DTS transformation model of the components in the form $S_X H_{iIx}$, where $S_X = S_x, S_{1x}$; i is the sensor number, which is proportional to the interference signal in each of the converters, we obtain E_{Ix}, based on (8), we find Δ_{Ix}^{8}:

$$\Delta_{Ix}^{8} = \left\{1 - \lambda^3 \left[\frac{4\lambda(3{,}96 + \lambda^2)}{(\lambda^2 - 1{,}32)^3} + \frac{2{,}64 - 4\lambda^2}{(\lambda^2 + 1{,}32)^{5/2}} - \right.\right.$$
$$\left.\left. - \frac{2\lambda(3 + \lambda^2)}{(\lambda^2 - 1)^3} + \frac{1 - 2\lambda^2}{(\lambda^2 + 1)^{5/2}}\right]\right\}.$$

Note that the interference immunity of the channels X and Y of the DTS under consideration is the same and, given the relative remoteness of the interference source $\lambda = R_C / R \geq 10$, the interference immunity of the channels exceeds 90 %.

Provided that the dipole moments of the investigated EMF M_x source and the sources of the interference field M_{DIx} are known, the error due to the action of the magnetic fields of interference from external sources can be determined:

$$\delta_{Ix} = \frac{0{,}52 M_{DIx}}{M_x e^3}(1 - \Delta_{Ix}^{8}) \cdot 100,\ \%.$$

3 Conclusions

1) The main metrological characteristics of instruments for spatial harmonic analysis of external magnetic fields have been determined, taking into account the specifics of spatial filtering when measuring the parameters of individual harmonics.

2) It has been shown that the conversion function of spatial harmonic analysis instruments is entirely

determined by the configuration of the distributed converter system and the applied switching algorithms.

3) Relationships for calculating sensitivity, multipole, linear–angular, and interference errors have been obtained, enabling a quantitative assessment of measurement accuracy.

4) It has been established that changes in the geometry of sensor placement significantly affect metrological characteristics and can be used to optimize the design of spatial harmonic analysis instruments.

5) The obtained results provide a foundation for improving the metrological support of magnetic field measurements of technical objects under complex operating conditions.

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Надійшла(Received) 10.09.2025

Прийнята до друку (accepted for publication) 13.10.2025

ABOUTTHEAUTHORS/ ВІДОМОСТІ ПРО АВТОРІВ

Дегтярьов Олександр Валентинович – к.т.н., доцент,доцент кафедри інформаційно-вимірювальних технологій, Харківський національний університет радіоелектроніки, м. Харків, Україна; e-mail: oleksandr.degtiarov@nure.ua, ORCID: https://orcid.org/0000-0002-3187-1621.
Degtiarov Oleksandr – PhD, associate professor of Information and Measurement Technology Department of Kharkiv National University of Radio Electronics; Kharkiv, Ukraine; e-mail: oleksandr.degtiarov@nure.ua, ORCID: https://orcid.org/0000-0002-3187-1621.

Ключник Ігор Іванович – професор кафедри проектування та експлуатації електронних апаратів, кандидат технічних наук, доцент, професор університету, Харківський національний університет радіоелектроніки, e-mail: ihor.kliuchnyk@nure.ua, ORCID: https://orcid.org/0000-0002-9352-5716.
Klyuchnyk Igor – professor of the Department of Electronic Devices Design and Operation, PhD, associate professor, professor of the University, Kharkiv National University of Radio Electronics, e-mail: ihor.kliuchnyk@nure.ua, ORCID: https://orcid.org/0000-0002-9352-5716.

Хорошайло Юрій Євгенович – к.т.н., доцент, завідувач кафедри проектування та експлуатації електронних апаратів, Харківський національний університет радіоелектроніки, м. Харків, Україна; e-mail: yurii.khoroshailo@nure.ua, ORCID: 0000-0002-4239-4357.
Khoroshailo Iurii – PhD, associate professor, Head of Design and Operation of Electronic Devices Department of Kharkiv National University of Radio Electronics; Kharkiv, Ukraine; e-mail: yurii.khoroshailo@nure.ua.

Луценко Віктор Олександрович – аспірант кафедри інформаційно-вимірювальних технологій, Харківський національний університет радіоелектроніки, м. Харків, Україна; e-mail: viktor.lutsenko@nure.ua, ORCID: https://orcid.org/0000-0003-0491-3280.
LutsenkoViktor – PhD student of IMT Department, Kharkiv National University of Radio Electronics; Kharkiv, Ukraine; e-mail: viktor.lutsenko@nure.ua, ORCID: https://orcid.org/0000-0003-0491-3280.

Дослідження метрологічних характеристик мультисенсорних систем для вимірювання зовнішніх магнітних полів

О.В. Дегтярьов, І.І. Ключник, Ю.Є.Хорошайло, В.О. Луценко

Анотація:
У статті досліджено метрологічні характеристики приладів для просторового гармонічного аналізу зовнішніх магнітних полів, що генеруються технічними об'єктами. Представлено математичні моделі перетворення сигналів, а також співвідношення для розрахунку функції перетворення, чутливості, лінійно-кутової та мультипольної похибок вимірювання. Проаналізовано вплив просторової конфігурації розподіленої перетворювальної системи на точність вимірювання та завадостійкість. Отримані залежності можуть бути використані для оцінки точності та оптимізації параметрів приладів просторового гармонічного аналізу.

Ключові слова: зовнішнє магнітне поле; просторовий гармонічний аналіз; метрологічні характеристики; розподілена система перетворювачів; функція перетворення; чутливість; похибка вимірювання; завадостійкість.