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Method for control by orbital spacecraft magnetic cleanliness based on multiple magnetic dipole models with consideration of their uncertainty

Aim. *Development of method for control by orbital spacecraft magnetic cleanliness based on multiple magnetic dipole models using compensation of the initial magnetic field with consideration of magnetic characteristics uncertainty.* ***Methodology.*** *Orbital spacecraft multiple magnetic dipole models calculated as solution of nonlinear minimax optimization problem based on near field measurements for prediction orbital spacecraft far magnetic field magnitude. Nonlinear objective function calculated as the weighted sum of squared residuals between the measured and predicted magnetic field. Weight matrix calculated as inverse covariance matrix of random errors vector. Values of magnetic moments and coordinates of placement of compensating magnetic dipoles for compensation of the orbital spacecraft initial magnetic field also calculated as solution of nonlinear minimax optimization problem. Both solutions of this nonlinear minimax optimization problems calculated based on particle swarm nonlinear optimization algorithms.* ***Results.*** *Results of prediction spacecraft far magnetic field magnitude based on orbital spacecraft multiple magnetic dipole models using near field measurements and compensation of the initial magnetic field with consideration of orbital spacecraft magnetic characteristics uncertainty for ensuring the orbital spacecraft magnetic cleanliness.* ***Originality.*** *The method for control by orbital spacecraft magnetic cleanliness based on multiple magnetic dipole models using compensation of the initial magnetic field with consideration of magnetic characteristics uncertainty is developed.* ***Practical value.*** *An important practical problem of ensuring orbital spacecraft magnetic cleanliness based on orbital spacecraft multiple magnetic dipole models using near field measurements and compensation of the initial magnetic field with consideration of orbital spacecraft magnetic characteristics uncertainty solved.* References 50, figures 2.

Key words: **orbital spacecraft, magnetic cleanliness, multiple magnetic dipole models, near magnetic field, far magnetic field, magnitude prediction, measurements, uncertainty.**

Мета. *Розробка методу управління магнітною чистотою орбітального космічного апарату на основі багатодипольної моделі магнітного поля з використанням компенсації вихідного магнітного поля та з урахуванням невизначеності магнітних характеристик.* ***Методологія***. *Багатодипольна модель магнітного поля орбітального космічного апарату розрахована як рішення задачі нелінійної мінімаксної оптимізації на основі вимірювань ближнього магнітного поля для прогнозування величини дальнього магнітного поля. Нелінійна цільова функція обчислена у вигляді зваженої суми квадратів залишків між виміряним і прогнозованим магнітним полем. Вагова матриця розрахована у вигляді оберненої коваріаційної матриці вектора випадкових помилок. Значення магнітних моментів і координати розміщення компенсуючих магнітних диполів для компенсації початкового магнітного поля орбітального космічного апарату також розраховані як рішення нелінійної задачі мінімаксної оптимізації. Рішення обох задач нелінійної мінімаксної оптимізації розраховані на основі алгоритмів нелінійної оптимізації роєм частинок.* ***Результати.*** *Результати прогнозування величини дальнього магнітного поля орбітального космічного апарату на основі багатодипольної моделі магнітного диполя з використанням вимірювань ближнього поля та компенсації вихідного магнітного поля з урахуванням невизначеності магнітних характеристик для забезпечення магнітної чистоти орбітального космічного апарату.* ***Оригінальність***. *Розроблено метод управління магнітною чистотою орбітального космічного апарату на основі багатодипольної моделі магнітного поля з використанням компенсації вихідного магнітного поля та з урахуванням невизначеності магнітних характеристик.* ***Практична цінність.*** *Вирішено важливу практичну задачу забезпечення магнітної чистоти орбітального космічного апарату на основі багатодипольної моделі магнітного диполя з використанням вимірювань ближнього поля та компенсації вихідного магнітного поля з урахуванням невизначеності магнітних характеристик орбітального космічного апарату.* Бібл. 50, рис. 2.

Ключові слова: **орбітальний космічний апарат, магнітна чистота, багатодипольна модель магнітного поля, ближнє магнітне поле, дальнє магнітне поле, прогнозування, вимірювання, невизначеність.**

Introduction. The problem of creating technical objects with a given distribution of the generated magnetic field is an urgent problem for many branches of science and industry. The strictest requirements for the accuracy of the spatial distribution of the magnetic field imposed when ensuring the magnetic cleanliness of orbital spacecraft [1, 2], the development of anti-mine magnetic protection of ships [3], the creation of magnetometry devices, including for medical diagnostic devices. Modern trends in the reduction of spacecraft mass set strictest requirements for magnetic systems by control their orientation [4, 5]. The fulfillment of these requirements requires the maximum minimization of the spacecraft's magnetic moment, which is one of the main destabilizing factors during its movement in near-Earth orbit and requires high accuracy of its experimental measurements [6]. So the level of the magnetic moment of a spacecraft weighing up to 100 kg should be within 0.1 A·m^2, and its experimental determination should preferably be performed with a resolution of less than 0.02 A·m^2 [5]. The main result of the work on ensuring the magnetic purity of the spacecraft is the reduction to a predetermined level of the spacecraft magnetic moment and the magnetic field induction at the location of the onboard magnetometer [6].

NASA and ESA developed a regulatory framework that summarizes their rich experience on this issue [5, 6]. Thus for «Pioneer-6» spacecraft magnetic field level at the magnetometer installation point [4] did not exceed 0.3 nT. On the Danish satellite «Oersted» for the Earth magnetic field measuring a boom is 8 m. The modern level of ensuring magnetic cleanliness considered the «Swarm» spacecraft for researching the Earth magnetic field. Its magnetometric equipment measurements the Earth magnetic field with an error of ±0.1 nT [5].

According to the requirements [2] for the «MikroSAT» spacecraft the magnetic field level at the place of installation of the scientific apparatus was limited to 1 nT with a length of the extension boom of –2.5 m. During the development of the «Sich-2» spacecraft, a limitation was set on the characteristics of the magnetic field of its equipment – the magnetic field strength magnitude of each of the nodes and blocks should not exceed 20 A/m at 0.1 m distance from their surface. On a later «EqyptSAT» spacecraft - this limitation was already more «hard» – 10 A/m at 0.1 m distance from the surface of his equipment [2].

Currently, the experimental measurements of the magnetic characteristics of all Ukrainian spacecraft is carried out exclusively at the magnetic measuring stand of the Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, which is a unique Magnetodynamic Complex in Ukraine and included in the list of scientific objects that constitute the national heritage of Ukraine.

Technologies for ensuring the magnetic cleanliness of spacecraft managed by NASA, ESA and CAST include interrelated works of an organizational, technical and metrological nature [6]. The foundation of this technology is the calculation models of the spacecraft, which allow analytical or numerical prediction of the magnetic characteristics of the spacecraft, based on the knowledge of the magnetic field of its constituent parts [7–10]. The angular displacement of the spacecraft occurs due to the interaction of the magnetic moment of the included electromagnet of magnetic spacecraft attitude control and stabilization systems with the Earth magnetic field. The accuracy of this movement determined by the reliability of current measurements of the on-board magnetometer and the error of calculating the magnetic moment of the spacecraft with its correspondingly activated electromagnets [11].

Analytical description of the distribution of the magnetic field of spacecraft traditionally carried out using the multipole model proposed by K. Gauss in the study of the Earth magnetism [12]. However to date the methods that would allow in practice to use the integral characteristics of the magnetic field – spatial harmonics, and associate them with the parameters of the spacecraft – remain insufficiently developed. The need to develop such methods confirmed by one of the latest standards of the European Space Agency ECSS-E-HB-20-07A [11], which recommends using its spherical harmonics as integral characteristics of the spatial distribution of the magnetic field to ensure the spacecraft magnetic cleanliness [12].

For most electrical equipment, the magnetic field at distances is greater than three of its maximum overall dimensions are determined mainly by members of the first degree series, i.e. the first three multipole coefficients [13–15]. Therefore, if the measurement of the magnetic field of the technical object performed at a distance greater than three of its maximum overall dimensions, then it can be limited to the construction of the mathematical model of the spacecraft in the form of a multidipole model [16, 17].

The magnetic test requirements in accordance to European cooperation for space standardization during space engineering testing it is necessary to take into account test conditions, input tolerances and measurement uncertainties [18–21]. The main uncertainties of the spacecraft magnetic cleanliness calculated are the changing values of the magnetic moments of the spacecraft elements when the spacecraft operating modes changing [6, 11]. In particular, the magnetic moments change most strongly when the polarization relays operate in the «on» and «off» positions, when the battery operates in the «charge» or «discharge» mode, during operation of high-frequency valves etc. The values of these uncertainties of the magnetic moments of the spacecraft elements during the operation of the spacecraft change within certain limits. In addition, strict restrictions are imposed on these changes in the values of the magnetic moments of the spacecraft elements to ensure the magnetic cleanliness of the entire spacecraft.

Therefore, an urgent problem is the develop of method for design of a model for predicting the far spacecraft magnetic field from measurements of the near magnetic field, which is robust to the spacecraft elements magnetic moments uncertainties and based on this model to calculate the parameters of compensating magnetic dipoles to improve the spacecraft magnetic cleanliness and its controllability in orbit.

The aim of the work is to develop the method for control by orbital spacecraft magnetic cleanliness based on multiple magnetic dipole models using compensation of the initial magnetic field with consideration of magnetic characteristics uncertainty to improve the spacecraft magnetic cleanliness and its controllability in orbit.

Statement of the problem. Consider as an example the general view of the «MicroSAT» spacecraft with the «Ionosat-Micro» instrumentation [2] shown in Fig. 1. On-board magnetometer FGM and three wave probes WP are fixed on the rods. Rod lengths are 2 m, the size of the spacecraft side is about 1 m. For this spacecraft the distance between the spacecraft and the installation point of the onboard magnetometer is more than three times greater than the size of the spacecraft, which makes it possible to adequately describe the spacecraft magnetic field using the multiple magnetic dipole models [11, 12].

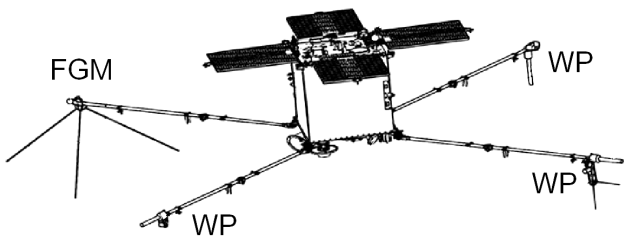

Fig. 1. Spacecraft «MicroSAT» with «Ionosat-Micro» instrumentation

The three-axis system of magnetic spacecraft attitude control and stabilization systems in the Earth orbit includes a three-component magnetic sensor (on-board magnetometer for the orientation of the spacecraft according to the Earth magnetic field and three special executive bodies – electromagnets for the formation of magnetic moments of the spacecraft of a certain magnitude and direction.

Magnetic orientation of spacecraft in the Earth orbit performed by the position control of the spacecraft only by the lines of force of the Earth magnetic field [1]

$$T = MB, \tag{1}$$

where T is the mechanical torque; M is the magnetic moment of the spacecraft; B is the Earth magnetic field.

The spacecraft magnetic moment M include the magnetic moment M_C of the actuator (electromagnet) of the spacecraft and its own magnetic moment M_S of the spacecraft

$$M = M_C + M_S. \quad (2)$$

The characteristics of the accuracy of electromagnetic systems are negatively affected by orientation magnetic moment M_S of the spacecraft itself and the magnetic field generated by spacecraft at the on-board magnetometer location point.

All technical objects elements undergo strict control for magnetic cleanliness and, as a rule, their preliminary demagnetization is performed. The components M_{nx}, M_{ny}, M_{nz} of the magnetic moment of all technical objects elements are measured before installation and meet the stringent requirements of magnetic cleanliness.

Then, the components B_{KX}, B_{KY}, B_{KZ} of technical object magnetic field at any point P_k of space with coordinates x_k, y_k, z_k in the form of the multiple magnetic dipole models of the technical object with the magnetic moment M_{nx}, M_{ny}, M_{nz} of N dipole located at the points of the space of the technical object with coordinates (x_n, y_n, z_n), can be calculated [17]

$$\begin{bmatrix} B_{KX} \\ B_{KY} \\ B_{KZ} \end{bmatrix} = \mu_0 \sum_{n=1}^{N} \frac{1}{4\pi r'^5} \begin{bmatrix} 2x'^2 - y'^2 - z'^2 & \ldots \\ 3x'y' & \ldots \\ 3x'z' & \end{bmatrix}$$

$$\ldots \begin{matrix} 3x'y' & 3x'z' \\ 2y'^2 - x'^2 - z'^2 & 3y'z' \\ 3y'z' & 2z'^2 - y'^2 - x'^2 \end{matrix} \Bigg] \cdot \begin{bmatrix} M_{nx} \\ M_{ny} \\ M_{nz} \end{bmatrix}. \quad (3)$$

Here the designations are introduced

$$x^i = x_k - x_n\,, \quad y^i = y_k - y_n\,,$$

$$z^i = z_k - z_n\,,$$

$$r' = ((x_k - x_n)^2 + (y_k - y_n)^2 + (z_k - z_n)^2)^{1/2}\,.$$

Then, for the known magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles and the coordinates of their location (x_n, y_n, z_n) in the space of technical object, one can calculate magnetic moment of the spacecraft [1]

$$M_x = \sum_{I=1}^{N} M_{nx}\,, \quad M_y = \sum_{I=1}^{N} M_{ny}\,, \quad M_z = \sum_{I=1}^{N} M_{nz} \quad (4)$$

and the magnetic field B_{KX}, B_{KY}, B_{KZ} at any point of space with coordinates x_k, y_k, z_k including the installation point of the technical object onboard magnetometer.

All Ukrainian spacecraft after installing all the elements are examined for magnetic cleanliness at the magnetic measuring stand Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine. According to real measurements, the spacecraft magnetic moment and the magnetic field at the installation point of the onboard magnetometer are calculated. For this purpose, according to the data of measurements of the magnetic field in the near zone of the spacecraft, the real values of the moment vectors of the dipoles of the received M_n are restored. In this case, it is assumed that the coordinates of the location of the dipoles in the space of the spacecraft remain unchanged.

Let us introduce the vector X of the desired parameters, the components of which are the components M_{nx}, M_{ny}, M_{nz} – of the magnetic moment vectors M_n of dipoles located at the given points P_n of the technical object with coordinates (x_n, y_n, z_n).

For the given coordinates (x_n, y_n, z_n) of the location of the N dipoles based on (3), we calculate the vector of the Y_C prediction values of the magnetic field at the given measurement points with the coordinates x_k, y_k, z_k in the form of the following linear dependence

$$Y_C = AX\,, \quad (5)$$

where the elements of the matrix A are the elements of the matrix from expression (3) calculated for the given coordinates x_n, y_n, z_n of the location of the dipoles in the space of technical object and for the given coordinates x_k, y_k, z_k of the location of the measurement points.

Let us introduce the vector Y_M of measurements of the magnetic field, the components of which are measurements components B_{KX}, B_{KY}, B_{KZ} at the given points P_K of the space with coordinates (x_k, y_k, z_k).

The mathematical model (5) should predict the magnetic field at the measurement points

$$Y_M = AX\,. \quad (6)$$

The number of unknown components of the vector X in (6) is equal to three times the number of dipoles, and the number of equations (dimension of vector Y_M) is equal to three times the number of measurement points. Usually, the number of equations in (6) exceeds the number of unknowns. To calculate this over determined system of linear equations, we use the generalized least squares method. Let us introduce the E vector of the discrepancy between the vector Y_M of the measured magnetic field and the vector Y_C of the predicted by model (5) magnetic field

$$E = Y_M - Y_C = Y_M - AX\,. \quad (7)$$

We write the objective function as the weighted sum of squared residuals between the measured Y_M and predicted Y_C by the model (5) values of the magnetic field

$$f(X) = E(X)^T WE(X) = (Y_M - AX)^T \times \ldots$$
$$\ldots \times W(Y_M - AX). \quad (8)$$

The minimum of this quadratic objective function (8), based on the necessary minimum condition

$$\partial f(X)/\partial X = 0 \quad (9)$$

calculated based on the expression

$$X = (A^T WA)^{-1} A^T WY_M\,. \quad (10)$$

The weight matrix W takes into account the different importance of the error components between the measured Y_M and the predicted Y_C model (5) magnetic field values. If the inverse covariance matrix V of random errors vector E use as weight matrix W than generalized least squares method is the most effective in the class of linear unbiased estimates. If the components of the magnetic field measurement vector Y_M are not correlated with each other, then the weight matrix W diagonal. Then the generalized least squares method becomes the weighted least squares method.

If the technical object multiple magnetic dipole model (5) obtained on the basis of the vector Y_M of measured magnetic field is too rough, then on the basis of the vector Y_M of the measured magnetic field, not only the magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles, but also their position in the space of the technical object with coordinates x_n, y_n, z_n can be calculated.

Let us consider the design of the technical object multiple magnetic dipole models only on the basis of the vector Y_M of the measured magnetic field. Let us introduce the vector of desired parameters X, the components of which are the desired values magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles and coordinates x_n, y_n, z_n of their position in the space of the spacecraft.

We also introduce the vector G of uncertainty parameters of the magnetic moments of the technical object the components of which are the deviations during the operation of the technical object of the magnetic moments of the technical object elements from their central values, taken in the design of the control system for the magnetic field of the technical object. Then, based on (1), the initial nonlinear equation for the spacecraft multiple magnetic dipole model can be obtained.

$$Y_M = F(X, G) . \qquad (11).$$

Here, the vector nonlinear function $F(X, G)$ obtained on the basis of expression (3) with respect to the vector X of unknown variables, whose components are the desired values magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles and coordinates x_n, y_n, z_n of their position in the space of the spacecraft and the vector G of the parameters of the uncertainties of the magnetic moments of the elements of the technical object.

In nonlinear equation (11) the number of unknown components of the vector X equal to six times the number N of dipoles, and the number of equations is equal to three times the number K of measurement points.

Let us introduce the E vector of the discrepancy between the vector Y_M of the measured magnetic field and the vector Y_C of the predicted by model (11) magnetic field

$$E(X, G) = Y_M - Y_C(X, G) = y_M - F(X, G) . \qquad (12)$$

We write the objective nonlinear function as the weighted sum of squared residuals between the measured and predicted by the model (12) values of the magnetic field

$$f(X, G) = (E(X, G))^T WE(X, G) . \qquad (13)$$

The nonlinear objective function (13) is obtained on the basis of expression (3) with respect to the vector X of unknown variables, whose components are the desired values magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles and coordinates x_n, y_n, z_n of their position in the space of the spacecraft and the vector G of the parameters of the magnetic moments uncertainties of the spacecraft elements.

As a rule, when optimizing the nonlinear objective function (13),

$$X^{\bullet} = \arg\min f(X, G) ; \qquad (14)$$

$$G^{\bullet} = \arg\max f(X, G) , \qquad (15)$$

it is necessary to take into account restrictions on the values of magnetic moments M_{nx}, M_{ny}, M_{nz} of the dipoles and coordinates x_n, y_n, z_n of their position in the space of the spacecraft. These restrictions can usually be written as vector inequalities

$$G(X, G) \leq G_{\max} . \qquad (16)$$

Let's consider another approach to the design of spacecraft multiple magnetic dipole models. Usually the designer of the spacecraft knows the N of the elements of the technical object, which are the main sources of the initial magnetic field of the technical object. These are polarization relays, batteries and high-frequency valves. The technical object designer knows the number N of these elements, the coordinates x_n, y_n, z_n of their location in the spacecraft space, as well as the nominal values M_{nx}, M_{ny}, M_{nz} of their magnetic moments. Then the vector Y_C of the magnetic field components B_{KX}, B_{KY}, B_{KZ} at the given points P_K of the space with coordinates x_k, y_k, z_k can be calculated based on spacecraft multiple magnetic dipole model (3).

Note that the values M_{nx}, M_{ny}, M_{nz} of the magnetic moments of these N main elements of the spacecraft can be refined on the basis of the vector Y_M of the measured magnetic field according to (2)–(6).

As a rule, the technical object multiple magnetic dipole models obtained in this way is a rather rough approximation to the actual magnetic range of the technical object. To refine this model, consider the following approach. Let's introduce more M dipoles wits magnetic moment M_{mx}, M_{my}, M_{mz} located at the points P_m of the technical object with coordinates x_m, y_m, z_m. Let us introduce the vector of desired parameters X, the components of which are the desired values magnetic moments M_{mx}, M_{my}, M_{mz} of the M dipoles and coordinates x_m, y_m, z_m of their position in the space of the technical object. We also introduce the vector G of uncertainty parameters of the magnetic moments of the technical object. Then, based on the spacecraft multiple magnetic dipole models (1) can be calculated the vector $Y_A(X, G)$ of additional magnetic field, generated by only M additional dipoles at the measurement points.

$$Y_A(X, G) = F_A(X, G) . \qquad (17).$$

We introduce the vector Y_I of the initial magnetic field of the technical object, the components of which are the components of the magnetic field of the technical object calculated in this way at the measurement points generated by the main N elements of the technical object with known values of the magnetic moments and the coordinates of their location in the space of the technical object.

Then one can calculate the vector Y_R of resulting magnetic field generated by N dipoles with known magnetic moments nominal values M_{nx}, M_{ny}, M_{nz} and coordinates x_n, y_n, z_n of their location in the technical object space and generated by M additional dipoles with unknown magnetic moments M_{mx}, M_{my}, M_{mz} and unknown coordinates x_m, y_m, z_m of their location in the technical object space

$$Y_R(X, G) = Y_I + Y_A(X, G) . \qquad (18)$$

Then the problem (18) of calculated the vectors of unknown parameters of additionally introduced M dipoles can be solved similarly to the problem (13) of calculated the vector of unknown parameters of N dipoles for design of the technical object multiple magnetic dipole model.

Usually, the technical object magnetic cleanliness requirements are presented in the form of restrictions on the total magnetic moment of the technical object and the magnitude of the magnetic field at the installation point of the onboard magnetometer [6, 11]. If the magnetic properties of the spacecraft do not satisfy the overall magnetic cleanliness requirements magnetic compensation tests shall be conducted. According to the technical object multiple magnetic dipole model obtained in the form (13), it is possible to calculate the spacecraft far magnetic field components B_{KX}, B_{KY}, B_{KZ}, and in particular, at the point of installation of the onboard magnetometer and technical object magnetic moments M_{nx}, M_{ny}, M_{nz}. Let us now consider the application of the developed technical object multiple magnetic dipole model to ensure the spacecraft magnetic cleanliness by introducing additional magnetic dipoles to compensate for the far magnetic field of the technical object, in particular, at the point of the onboard magnetometer installation [22–25].

To compensate for the initial magnetic field of the technical object, we introduce C magnetic dipoles with unknown magnetic moments M_{cx}, M_{cy}, M_{cz} located at C points P_c with unknown coordinates x_c, y_c, z_c.

Let us introduce the vector X of the desired parameters for solving the problem of compensating the initial magnetic field of the technical object, whose components are the oblique values of the magnetic moments M_{cx}, M_{cy}, M_{cz} and coordinates x_c, y_c, z_c of the location of the compensating magnetic dipoles in the technical object space. Then, for a given value of the vector X of the desired parameters of the compensating dipoles, based on (1), the vector $B_C(X)$ of the compensating magnetic field generated by all compensating dipoles at the installation point of the onboard magnetometer and the vector $M_C(X)$ of the compensating magnetic moment generated by all compensating dipoles can be calculated [26–30].

Then we calculated the vector $M_R(X, G)$ of resulting magnetic moment and vector $B_R(X, G)$ of resulting magnetic field generated at the installation point of the onboard magnetometer by the technical object elements and all compensating dipoles

$$M_R(X,G) = M(G) + M_C(X)\,; \qquad (19)$$

$$B_R(X,G) = B(G) + B_C(X)\,. \qquad (20)$$

Then the problem of calculated the coordinates x_c, y_c, z_c of spatial arrangement and magnetic moments M_{cx}, M_{cy}, M_{cz} of the compensating dipoles can be reduced to solving the problem of vector minimax optimization of resulting magnetic moment of the technical object and the resulting magnetic field at the installation point of the onboard magnetometer

$$X^{\bullet} = \arg\min M_R(X,G)\,; \qquad (21)$$

$$X^{\bullet} = \arg\min B_R(X,G)\,; \qquad (22)$$

$$G^{\bullet} = \arg\max M_R(X,G)\,; \qquad (23)$$

$$G^{\bullet} = \arg\max B_R(X,G)\,. \qquad (24)$$

This six-criteria minimax problem (21)–(24) can be reduced to a single-criteria problem by the following linear trade-off scheme

$$\begin{aligned} f(X,G) = (M_R(X,G))^T W_1 (M_R(X,G)) + \ldots \\ \ldots + (B_R(X,G))^T W_2 (B_R(X,G)), \end{aligned} \qquad (25)$$

where W_1 and W_2 are weight matrices.

Note that this approach is standard when designing of robust control, when the coordinates of the spatial arrangement and the magnitudes of the magnetic moments of the compensating dipoles are found from the conditions for minimizing the modulus of technical object magnetic field at the magnetometer installation point for the «worst» values of the magnetic moments of the elements of the technical object.

The developed technical object multiple magnetic dipole model can be used to calculate the most magnetically clean point at a given distance from the technical object to onboard magnetometer point [31–37]. Let's consider this approach. Let us set a limit on the maximum distance of the technical object onboard magnetometer in the form of a sphere of radius R

$$X^2 + Y^2 + Z^2 \le R^2\,. \qquad (26)$$

Let's solve the optimization problem

$$X^{\bullet}, Y^{\bullet}, Z^{\bullet} = \arg\min B(X,Y,Z)\,. \qquad (27)$$

With constraint (26) on the required variables. In this case, the technical object multiple magnetic dipole model in the objective function (27) calculated according (10) or (14) – (15).

At present, in order to improve the magnetic cleanliness, the onboard magnetometer is mounted on a boom 1–10 m long. Naturally, the length of this rod must be taken as small as possible [38–40]. Let us consider the application of the developed spacecraft multiple magnetic dipole models to calculate the minimum length of a boom, at the end of which an onboard magnetometer installed.

Let us set the installation direction of the onboard magnetometer in the spherical coordinate system in the form of the length of the radius R and two angles φ and θ. Then the X, Y, Z coordinates of the onboard magnetometer location in the orthogonal coordinate system associated with the spacecraft are calculated

$$\begin{aligned} Z = R\cos(\theta), \quad X = R\cos(\varphi)\sin(\theta), \\ Y = R\sin(\theta)\sin(\varphi). \end{aligned} \qquad (28)$$

Then, in order to calculate the minimum boom length R, at the end of which an on-board magnetometer is installed, it is necessary to solve a one-parameter optimization problem

$$R^{\bullet} = \arg\min B(R) R\cos(\varphi) \qquad (29)$$

with restriction

$$B(R) \le B_{\max}\,, \qquad (30)$$

where $B_{\max}$ is the maximum value of the magnetic field at the installation point of the on-board magnetometer.

The method for problem solving. The problem (10) is usually solved by finding the pseudo inverse matrix or LU decomposition of a matrix or the very effective Cholesky method [15]. If it is necessary to take into account the restrictions type (16) on the values of the magnetic moments of the dipoles, then this problem solved [41–44] as an optimization problem (14) – (15) with restrictions (16). A feature of this optimization problem is the quadratic objective function (8) and linear constraints. To solve such an optimization problem, an algorithm for sequential quadratic programming developed.

Let us represent (8) in the following form

$$f(x) = \frac{1}{2}\sum_{i=1}^{l} f_i(x)^2\,. \qquad (31)$$

Gradient of this objective function represented as follows

$$\nabla f(x) = \nabla F(x) F(x)\,, \qquad (32)$$

where the Jacobian $\nabla F(x) = (\nabla f_1(x), \ldots, \nabla f_l(x))$ of this function is indicated and it is assumed that the components of the objective function can be differentiated twice. Then the matrix of second derivatives of the objective function – the Hesse matrix can be written in the following form

$$\nabla^2 f(x) = \nabla F(x) \nabla F(x)^T + B(x), \tag{33}$$

where

$$B(x) = \sum_{i=1}^{l} f_i(x) \nabla^2 f_i(x) \nabla^2 f_i(x). \tag{34}$$

Then the iterative procedure for choosing the direction $d_k \in R^n$ of motion using the Newton method reduced to solving the linear system

$$\nabla^2 f(x_k) d + \nabla f(x_k) = 0, \tag{35}$$

or to the solution of an equivalent system in the following form

$$\nabla F(x_k) \nabla F(x_k)^T d + B(x_k) d + \nabla F(x_k) F(x_k) = 0. \tag{36}$$

At the optimal solution point x^* the following condition is satisfied

$$F(x^*) = \left(f_1(x^*), \ldots, f_l(x^*)\right)^T = 0, \tag{37}$$

therefore, finding the motion step d can be reduced to solving the normal equation of the least squares problem

$$\min_{d \in R^n} \left\| \nabla F(x_k)^T d + F(x_k) \right\|, \tag{38}$$

from which a recursive equation can be obtained for iteratively finding the vector of desired parameters,

$$x_{k+1} = x_k + \alpha_k d_k, \tag{39}$$

in which d_k is the solution of the optimization problem, and α_k is an experimentally determined parameter.

This algorithm uses the Gauss–Newton method, which is a traditional algorithm for solving the problem of the nonlinear least squares method, to calculate the direction of movement. In the general case, the Gauss–Newton method allows one to obtain a solution to the problem of sequential quadratic programming using only first-order derivatives, but in real situations it often cannot obtain a solution. Therefore, to improve convergence, second-order methods are used, in which the matrix of second derivatives of the objective function is used – the Hesse matrix when solving optimization problems without restrictions. Second-order algorithms, compared to first-order methods, make it possible to effectively obtain a solution in a region close to the optimal point, when the components of the gradient vector have sufficiently small values.

Recently, methods using Levenberg-Marquardt algorithms have become widespread in quasi-Newtonian methods. The idea of these methods is to replace the Hesse matrix with some matrix $\lambda_k I$ with a positive coefficient λ_k. Then we get the following linear equations system

$$\nabla F(x_k) \nabla F(x_k)^T d + \lambda_k d + \nabla F(x_k) F(x_k) = 0. \tag{40}$$

One of the most promising methods of solving problems of this class is the use of stochastic multi-agent algorithms, which do not require the calculation of derivatives of the objective function, and are also much more effective than the simple multi-start method, since they use special heuristic methods to search for the optimum [45, 46]. Genetic algorithms, which are a universal tool for finding an optimal solution close to the global one, deserve special attention, and they work equally well for both discrete and continuous parameter values. The particle swarm optimization method, which simulates the social behavior of individuals in a flock, has a higher speed of convergence to the optimum, but when the number of varied parameters increases, as practice shows, the probability of stopping the search near one of the local optima increases. To date, a large number of particle swarm optimization algorithms have been developed – PSO algorithms based on the basic ideas of the collective intelligence of particle swarms, such as the gbest PSO and lbest PSO algorithms. Practically all these algorithms described by the following expression for changing the position and speed of movement of that particle

$$\begin{aligned} v_{ij}(t+1) &= v_{ij}(t) + c_1 r_{1j}(t)\left[y_{ij}(t) - x_{ij}(t)\right] + \ldots \\ &\ldots + c_2 r_{2j}(t)\left[y_j^*(t) - x_{ij}(t)\right]; \end{aligned} \tag{41}$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1), \tag{42}$$

where $x_{ij}(t)$, $v_{ij}(t)$ are the position and speed of the particle i in the swarm j; c_1 and c_2 are positive constants that determine the weights of the cognitive and social components of the speed of particle movement; $r_{1j}(t)$ and $r_{2j}(t)$ are random numbers from the range [0, 1], which determine the stochastic component of the particle speed component.

Here $y_{ij}(t)$ and y_j^* the best local and global positions of that particle i are found, respectively, by only one particle and all swarm particles, which are analogs of the local optimum determined by that particle and the global optimum determined by all swarm particles.

In the standard particle swarm optimization algorithm [45, 46] particle velocities change according to linear laws [47, 48]. To increase the speed of finding a global solution, special nonlinear stochastic multi-agent optimization algorithms [49, 50], in which the movement of a particle i of a swarm j is described by the following expressions

$$\begin{aligned} v_{ij}(t+1) &= w_j v_{ij}(t) + \ldots \\ &\ldots + c_{1j} r_{1j}(t) H\left(p_{1j} - \varepsilon_{1j}(t)\right)\left[y_{ij}(t) - x_{ij}(t)\right] + \ldots \\ &\ldots + c_{2j} r_{2j}(t) H\left(p_{2j} - \varepsilon_{2j}(t)\right)\left[y_j^*(t) - x_{ij}(t)\right]. \end{aligned} \tag{43}$$

Heaviside function H is used as an option for switching the particle motion according to the local $y_{ij}(t)$ and global $y_j^*(t)$ optimum.

Parameters of switching the cognitive p_{1j} and social p_{2j} components of the speed of particle movement in accordance with the local and global optimum; $\varepsilon_{1j}(t)$ and $\varepsilon_{2j}(t)$ random numbers and determine the parameters of switching the particle motion according to the local and global optimum. If $p_{1j} < \varepsilon_{1j}(t)$ and $p_{2j} < \varepsilon_{2j}(t)$ then the speed of movement of particle i of swarm j does not change at a step and the particle moves in the same direction as in the previous optimization step.

During their movement, the particles try to improve the solution they found earlier and exchange information with their neighbors, due to which they find the global optimum in a smaller number of iterations. The advantage of these methods over classical gradient optimization methods is also that they do not require the calculation of the derivatives of the objective function, they are practically insensitive to the proximity of the initial approximation to the desired solution, and allow for easier consideration of various restrictions when finding global optimum.

Note that the search algorithm for the vector G that maximizes the objective function (15) is described by the same expressions (42). However, in contrast to the search for the vector X, which minimizes the objective function (7), $y_{ij}(t)$ and y_j^* are the best local and global positions, which maximizes the objective function (15).

Optimization results. Let us consider the application of the developed method for solving the problem of ensuring the magnetic cleanliness of the «Sich-2-1» spacecraft. Based on the experimental measured magnetic field generated by «Sich-2-1» spacecraft, performed in 2021 by researchers Sergey Petrov and Anatoliy Erisov of the Department of Magnetism of Technical Objects, calculations of the characteristics of the spacecraft magnetic cleanliness carried out.

The experimentally measured value of the total magnetic moment of spacecraft is equal M = [0.24, 0.5, 0.4]. The dispersion of the magnetic field prediction error in this case is D = 7560.6. The value of the experimentally measured magnetic moment of the spacecraft implies the presence of several dipoles located in the space of the spacecraft. In the calculation it is assumed that the model of the magnetic field of the spacecraft represents one dipole located at the origin of the spacecraft.

Based on the experimental measured magnetic field at first the spacecraft magnetic field model was presented as a single dipole located in the center of the spacecraft. To calculate the vector of moments of this dipole on the basis of (6), the inverse matrix of 3×3 size was calculated. Based on the vector of the measured magnetic field of the spacecraft Y_M, the moments of this single dipole M = [0.2400, 0.5000, 0.4000] were calculated. The dispersion of the magnetic field prediction error in this case is D = 7272.7.

Then the magnitude of the magnetic moment of this single dipole, located at the center of the spacecraft, calculated by solving the problem of unconstrained optimization (9) unlimited (12). The values of the magnetic moments of the spacecraft, calculated by the expression (6) using the inverse matrix, and those calculated in the course of solving the optimization problem (9) coincide.

Note that when calculating the magnetic moment of the spacecraft in the form of a solution to the optimization problem (9), one can also take into account the restrictions on the values of the components of the vector of the magnetic moments of the spacecraft.

Let us now consider the mathematical model of the magnetic field of the spacecraft in the form of a single dipole, the location coordinates of which in the space of the spacecraft also need to be calculated. For the calculated value of the moment M = [0.2664, 0.1641, 0.1434] and coordinates P = [0.2158, –0.4136, 0.0859] of the location of such a single dipole, the prediction error variance is D = 3239.8. Note that the location of the only dipole not at the origin of the coordinates, but at the point with the optimal coordinates made it possible to reduce the dispersion of the magnetic field prediction by a factor of 2.3337.

If, when solving the problem of optimizing the values of the magnetic moments and the coordinates of the location of one dipole, we introduce restrictions on the magnitude of the dipole moments in the form of restrictions [–0.8, –0.8, –0.8] ≤ M ≤ [0.8, 0.8, 0.8], optimal values of the moments M = [0.2388, 0.1921, 0.1258] and coordinates P = [0.2056, –0.4146, 0] of the location of such a single dipole, the prediction error variance is D = 3325.1. Thus, under restrictions on the magnitude of the dipole moments, the optimum values of the magnetic moments are at the limits and, in this case, the dispersion increases by a factor of 2.2738.

Let us now consider the model of the spacecraft magnetic field in the form of two dipoles. If, when solving the problem of optimizing the values of the magnetic moments and the coordinates of the location of two dipoles, we introduce restrictions on the magnitude of the dipole moments in the form of restrictions [–0.8, –0.8, –0.8] ≤ M ≤ [0.8, 0.8, 0.8], optimal values of the moments $M1$ = [0.3538, –0.0326, –0.0345] and $M2$ = [–0.6137, 0.6695, –0.2802] and the coordinates $P1$ = [0.3090, –0.3080, 0.0867] and $P2$ = [–0.0657, –0.0789, –0.3908] of the location of two dipoles, the dispersion the prediction error is D = 1203.4. Thus, under restrictions on the magnitude of the two dipoles moments, the optimum values of the magnetic moments are at the limits and, in this case, the dispersion increases by a factor of 6.2827.

Let us now consider the design of the spacecraft magnetic field model for the most common case, when the coordinates and magnetic moments of the magnetic field sources, which are the main sources of the initial spacecraft magnetic field, are preliminarily set. In particular, consider an example in the form of six dipoles,

$M1$ = [–0.6119, 0.6682, –0.2796],
$M2$ = [0.0787, –0.0356, –0.0337],
$M3$ = [0.0915, –0.0015, –0.0137],
$M4$ = [0.0893, –0.0322, –0.0104],
$M5$ = [0.0314, 0.0137, –0.0076],
$M6$ = [0.0621, 0.0233, 0.0312],
$P1$ = [–0.0664, –0.0790, –0.3903],
$P2$ = [0, 0, 0],
$P3$ = [0, 0, 0],
$P4$ = [0, 0, 0],
$P5$ = [0, 0, 0],
$P6$ = [0.3092, –0.3083, 0.0870].

For these six dipoles, the dispersion of the prediction error is D = 1203.4.

Figure 2 shows the spatial arrangement of the modules of the measured and predicted magnetic field and the deviation between the measured and predicted magnetic field for six dipoles.

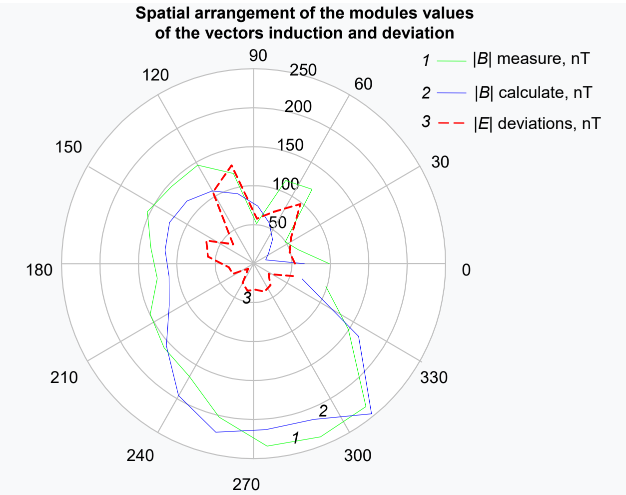

Fig. 2. The spatial arrangement of the modules of the measured, predicted and deviation magnetic field

Using the developed spacecraft magnetic field model, the spacecraft magnetic moment M = [–0.2619, 0.6356, –0.3112] was calculated and the magnetic field B = [5.0638, 13.7326, 2.5545] was predicted at the installation point of the onboard magnetometer. As a result of solving the problem of compensation for the initial magnetic field of the spacecraft, the magnetic moments $M1$ = = [0.6119, –0.6682, 0.2796] and $M2$ = [–0.0621, –0.0233, –0.0312] and coordinates $P1$ = [–0.0664, –0.0790, –0.3903] and $P2$ = [0.3092, –0.3083, 0.0870] of two compensation dipoles were calculated.

The calculated value of the resulting spacecraft magnetic moment M = [0.0246, –0.0566, 0.0363] and the predicted resulting magnetic field B = [1.3506, –3.702, 0.6872] at the installation point of the onboard magnetometer show that due to the introduction of two compensating dipoles, it was possible to reduce the magnitude of the resulting spacecraft magnetic moment by a factor of 6.21 and also to reduce the value of the predicted resulting magnetic field at the point of installation of the onboard magnetometer by a factor of 3.7.

Conclusions.

1. Method for control by orbital spacecraft magnetic cleanliness based on multiple magnetic dipole models using compensation of the initial magnetic field with consideration of magnetic characteristics uncertainty developed.

2. Magnetic moments and coordinates values of orbital spacecraft multiple magnetic dipole models calculated based the solution of nonlinear minimax optimization problem. Nonlinear objective function calculated as the weighted sum of squared residuals between the measured and predicted magnetic field. Values of magnetic moments and coordinates of placement of compensating magnetic dipoles for compensation of the orbital spacecraft initial magnetic field also calculated as solution of nonlinear minimax optimization problem. Solutions of this both nonlinear minimax optimization problems calculated based on particle swarm nonlinear optimization algorithms.

3. The developed method for control by orbital spacecraft magnetic cleanliness allows at the design stage to calculate the multiple magnetic dipole models and based on its to calculate the parameters of compensating magnetic dipoles to improve the spacecraft magnetic cleanliness and its controllability in orbit.

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Conflict of interest. The authors declare that they have no conflicts of interest.

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