DOI: https://doi.org/10.15407/techned2025.01.003

IMPROVE OF UNCERTAIN MICROSATELLITE MAGNETIC CLEANLINESS BASED ON MAGNETIC FIELD SPATIAL HARMONICS COMPENSATION

B.I. Kuznetsov[1*], T.B. Nikitina[2], I.V. Bovdui[1***], K.V. Chunikhin[1****], V.V. Kolomiets[2*****], B.B. Kobylianskiy[2******]**
[1] Anatolii Pidhornyi Institute of Power Machines And Systems of the National Academy of Sciences of Ukraine, 2/10, Komunalnykiv str., Kharkiv, 61046, Ukraine,
e-mail: kuznetsov.boris.i@gmail.com.
[2] Educational scientific professional pedagogical Institute V.N. Karazin Kharkiv National University, 9a, Nosakov str., Bakhmut, 84511, Ukraine,
e-mail: nnppiuipa@ukr.net.

Problem of microsatellite magnetic cleanliness (MMC) improving by magnetic field (MF) spatial harmonics compensation and magnetic characteristics uncertainty (MCU) sensitivity reducing considered. Prediction and control by uncertain microsatellite MC design are geometric inverse magneto static problem (GIMSP) reduced to vector game solution. Vector payoff calculated based on development method for analytical calculation of magnetostatic field induction of spherical sources in the Cartesian coordinate system (CCS) using Wolfram Mathematica ® software. Both vector game solution calculated based on particles multi-swarm optimization (PMSO) algorithms from Pareto optimal solutions taking into account binary preference relations. Prediction model and location of compensating units in spherical coordinates as well as multipole harmonic coefficients of dipoles, quadrupoles and octupoles are calculated during prediction and control of uncertain microsatellite MC. Results of MC improving for microsatellite «Sich» family by compensation of dipoles, quadrupoles and octupoles components of initial MF spatial harmonics and reducing sensitivity to MCU are given. References 17, figures 2.

Keywords: microsatellite magnetic cleanliness, magnetic characteristics uncertainty, prediction and control, geometric inverse magneto static problem, computer simulation.

Introduction. Ukraine is space power state [1, 2]. Satellites magnetic characteristics are subject to strict requirements [3]. To meet these requirements all Ukrainian satellites undergo measurement and standardization of technical characteristics at magnetodynamic complex of Anatolii Pidhornyi Institute of Power Machines And Systems (IPMS) of the National Academy of Sciences of Ukraine [4]. The requirements for spacecraft MC are usually presented in restrictions form on total microsatellite magnetic moment (MMM) and of the MF strength magnitude at on-board magnetometer installation point, which specified in following regulatory documents and microsatellite design guidelines [1, 3].

Microsatellite MC solving problems accuracy ensuring largely calculated by microsatellite model MF sources for prediction magnetic field mathematical model (MFMM) adequacy to actually measured microsatellite MF characteristics values in near zone. Microsatellite MFMM usually adopted in magnetic dipoles microsatellite set units form – multiple magnetic dipole models (MMDM) [5]. However feature of microsatellite magnetic characteristics is rather small value of MMM units and, in general, of entire microsatellite. For «SICH» family spacecraft MF at on-board magnetometer installation point mainly generated by «Potential» scientific equipment set. Contributions of quadrupole and octopole spherical harmonics become close to 80 %, and dipole harmonic contributes less than 20 % of MF level [6]. Therefore, to improve microsatellites MC necessary to take into account not only dipoles, but also quadrupoles, octupoles, etc. MF model spatial characteristics [3, 6].

ORCID: * https://orcid.org/0000-0002-1100-095X; ** https://orcid.org/0000-0002-9826-1123;
*** https://orcid.org/0000-0003-3508-9781; **** https://orcid.org/0000-0001-9822-5870;
***** https://orcid.org/0000-0002-9073-5793; ****** https://orcid.org/0000-0003-3226-5997

GIMSP is a typical task of ensuring the microsatellites MC [5]. Moreover, GIMSP used to solve two problems – prediction geometric inverse magneto static problem (PGIMSP) and control geometric inverse magneto static problem (CGIMSP) [5]. First, to calculate microsatellites initial MFMM based on real measurements in near zone, it is necessary to solve PGIMSP [5].

Then, based on PGIMSP solution it is necessary to calculate real microsatellite MF values in far zone that required – total MMM value and MF value at on-board magnetometer location point.

If actual values of these microsatellite MF do not meet MC requirements, then it is necessary to perform work on initial MF compensation for which it is necessary to solve CGIMSP [5]. CGIMSP solution calculated additional compensating MF sources locations and their MMM magnitude to compensate initial microsatellite MF. As result of CGIMSP solution, it is necessary calculated such compensating MF sources in microsatellite space, which compensated initial MF generated by microsatellite in far zone. In general CGIMSP is compensation system design problem for microsatellite output MF – system of active shielding of initial microsatellite MF in far zone.

In general terms GIMSP are incorrectly set tasks. Forward geometric magneto static problem (FGMSP) calculates MF at given space point as consequence of generation of this MF used cause – MF source located at space given point with given characteristics. When GIMSP solved – consequence is known – MF at space given point. GIMSP solution calculated cause – MF source spatial location and its characteristics. It is natural that FGMSP has unique solution. However, GIMSP solution may have several solutions. To realize consequence –given initial MF, various reasons may required - different locations and different characteristics of MF sources – causes that realized consequence – given MF at given space point. Such ambiguity GIMSP solution especially characteristic when GIMSP solution calculated based on optimization algorithms.

Microsatellites MFMM usually considered known accurately [1–6]. However, microsatellite units magnetic characteristics significantly depend on microsatellite operating modes and change during operation. Sources of such MCU are changes in microsatellite elements MMM values when microsatellite operating modes changed. In particular, MMM change most during follows operation modes: polarized relays in "on" and "off" positions, when battery in "charge" or "discharge" mode, during operation of high-frequency valves, electromagnets operation for opening hatches of astro sensors, etc. Antennas and radio frequency components used latch springs, control valves, and other moving parts. From initial cycles of their design their MMC values taken into account. In addition, entire technological branch of production of these parts involves monitoring magnetic characteristics of their material and conducting (if necessary) its demagnetization procedure. All units with magnetic drive (motors, linear motion converters, and all other mechanisms) require independent development to ensure their MMC. In particular, MMM of MPS 8S3P battery installed on “Sich 2-1” microsatellite changes within ±0.17 $A*m^2$, when discharge current changes from minus 8 A to charge current 8 A. Naturally, that this MMM must be pre-compensated with active compensation system as battery charge-discharge current function to ensure specified battery MMM level of $\pm (0.3\div 6.2)*10^{-3}$ $A*m^2$.

Note that for such microsatellite, taking into account MCU of their magnetic characteristics, terminology «uncertain microsatellite magnetic cleanliness» widely used [7–14]. Term "uncertain microsatellite magnetic cleanliness" denotes initial microsatellite MCU and their change during different operating modes microsatellite operation. According to latest standards of European Space Agency ECSS-E-HB-20-07A during space equipment testing, it is necessary to take into account test conditions, input data tolerances and measurements uncertainty [3]. Therefore designed system for controlling microsatellite MC must be robust to changes in parameters and possibly structure of microsatellite MFMM [15, 16].

In uncertainty conditions of microsatellite magnetic characteristics, when robust multispheroidal MFMM designed standard approach calculation of spatial location coordinates and spatial harmonics magnitude based on conditions of minimizing vector discrepancy between measured MF vector and predicted MFMM vector. However MCU vector calculated for "worst case" MMC from conditions of maximization same vector of discrepancy between measured MF vector and MFMM predicted vector [16]. This approach is standard for ensuring robustness of microsatellite MFMM design relative to microsatellite MCU [14].

Such GIMSP solution under uncertainty conditions is vector game solution [16]. To calculate such games solution Particle Swarm Optimization" (PSO) algorithm is used, which simulates social behavior of solution individuals in flock, and has higher speed of convergence to optimum [17]. Basic approach to vector game solution Pareto set calculation includes all solutions and that are not dominated by other solutions. To adapt PSO algorithm to Pareto-optimal solutions calculation for possible vector gain values set binary preference relations used that individual solutions Pareto-dominance determined [16].

The goal of this work is developed the method for prediction and control by microsatellite MC taking into account the uncertainties of microsatellite magnetic characteristics based on prediction geometric inverse magneto static problem and control geometric inverse magneto static problem solutions for calculation and compensation MF spatial spherical harmonics in order to improve uncertain microsatellite MC by compensation initial MF spatial harmonics and for reduced sensitivity to magnetic characteristics uncertainty.

Definition of FGMSP. Microsatellites MC problem solution success largely determined external microsatellites MFMM adequacy to microsatellites MF real values measurements in near zone [2, 3]. MF point sources most widely common approach. In this case MFMM described in spherical coordinate system (SCS). Microsatellites MFMM often adopted in MMDM form [5]. Parameters of this dipoles and their location coordinates in microsatellites space calculated in PGIMSP solution from condition of minimizing error between measured and MFMM predicted values of external MF at measurement microsatellites space points. On magnetodynamic stands microsatellites MF usually measured in Cartesian coordinate systems (CCS) related to microsatellites center. In microsatellites MMDM dipole sources positions also calculated in CCS related to microsatellites center. In addition, on magnetodynamic stands microsatellites electrical equipment component units MF often measured in CCS related to of these component units center of electrical equipment.

However, MFMM of these microsatellites component units calculated in SCS associated with these MF sources centers. In classical works on electrodynamics [5] Laplace equation solutions for MF scalar potential in SCS known [5]. This Laplace equation solution in SCS for outside region sphere $r>R_0$ calculated in form [2]:

$$U=\frac{1}{4\pi}\sum_{n=1}^{\infty}\frac{1}{r^{n+1}}\sum_{m=0}^{n}\left(g_n^m\cos m\varphi+h_n^m\sin m\varphi\right)P_n^m\left(\cos\theta\right), \tag{1}$$

where $P_n^m(\cos\theta)$ Legendre polynomials are associated with first kind of degree n and order m; r, θ, φ are the spherical coordinates of observation point; g_n^m and h_n^m are the multipole harmonic coefficients in SCS.

It is not scalar potential that practically important, but MF strength projections. Microsatellite overall dimensions in different directions approximately same MF strength of elements and entire microsatellite MFMM calculated based on Laplace equation solutions for scalar magnetic field potential (1) in spherical spatial harmonics (SSH) strengths sum form with corresponding multipole coefficients:

$$H_r=\sum_{n=1}^{\infty}\sum_{m=0}^{n}\frac{n+1}{r^{n+2}}\left\{g_n^m\cos m\varphi+h_n^m\sin m\varphi\right\}\cdot P_n^m\left(\cos\theta\right), \tag{2}$$

$$H_\theta=-\sum_{n=1}^{\infty}\sum_{m=0}^{n}\frac{1}{r^{n+2}}\left\{g_n^m\cos m\varphi+h_n^m\sin m\varphi\right\}\frac{dP_n^m\left(\cos\theta\right)}{d\theta}, \tag{3}$$

$$H_\phi=\sum_{n=1}^{\infty}\sum_{m=0}^{n}\frac{m}{r^{n+2}}\left\{g_n^m\sin m\varphi-h_n^m\cos m\varphi\right\}\frac{P_n^m\left(\cos\theta\right)}{\sin\theta}. \tag{4}$$

Spatial harmonic analysis application based on MF harmonic composition study. This application result transition from MF measured values to MF integral characteristics namely harmonics multipole coefficients. Then MF calculated based on obtained multipole coefficients values in entire region. Description accuracy depends both on calculated multipole coefficients accuracy and on spatial harmonics number used source function expansion. This FGMSP microsatellite MF calculated using expressions (2) – (4) based on known MF sources coordinates and MF multipole coefficients values of these sources.

In modern works, for example, related to microsatellites MC [6–13] based on Laplace equation solutions for scalar potential for outside MF source analytical equations for magnetic induction projections in SCS obtained [6]. Moreover, these equations obtained only for several first spherical harmonics (up to 4) and for these equations associated Legendre polynomials written out by obtaining rather cumbersome equations [6]. However, to date there is no generalization of formula for case of n-harmonic. Additional it is often necessary to work in CCS [14] and in addition to transform coordinates from CCS to SCS, and then magnetic induction projections calculated from SCS to CCS.

Therefore, consider method for simplification of mathematical modeling of uncertain microsatellites MF based on analytical calculation of MF induction of spherical MF sources in CCS. Consider analytical equations for magnetic induction projections using spherical harmonics. We obtain equation for B_x:

$$B_x\left(x,y,z\right)=-\frac{\mu_0}{4\pi}\sum_{n=1}^{\infty}\frac{1}{r^{n+2}}\times$$

$$\times\sum_{m=0}^{n}\left\{\begin{aligned}&\left[m\varphi_x^{'}r\left(h_n^m\cos m\varphi-g_n^m\sin m\varphi\right)-\left(n+1\right)\left(r_x^{'}+\frac{\left(\cos\theta\right)_x^{'}r\cos\theta}{\cos^2\theta-1}\right)\left(g_n^m\cos m\varphi+h_n^m\sin m\varphi\right)\right]\times\\&\times P_n^m\left(\cos\theta\right)+\left(n-m+1\right)\frac{\left(\cos\theta\right)_x^{'}r}{\cos^2\theta-1}\left(g_n^m\cos m\varphi+h_n^m\sin m\varphi\right)P_{n+1}^m\left(\cos\theta\right)\end{aligned}\right\}. \quad (5)$$

Similarly, we obtain equations for B_y, B_z (note in case of B_z since $\varphi_z^{'}=0$ first term in curly brackets is zero

$$B_y\left(x,y,z\right)=-\frac{\mu_0}{4\pi}\sum_{n=1}^{\infty}\frac{1}{r^{n+2}}\times$$

$$\times\sum_{m=0}^{n}\left\{\begin{aligned}&\left[m\varphi_y^{'}r\left(h_n^m\cos m\varphi-g_n^m\sin m\varphi\right)-\left(n+1\right)\left(r_y^{'}+\frac{\left(\cos\theta\right)_y^{'}r\cos\theta}{\cos^2\theta-1}\right)\left(g_n^m\cos m\varphi+h_n^m\sin m\varphi\right)\right]\times\\&\times P_n^m\left(\cos\theta\right)+\left(n-m+1\right)\frac{\left(\cos\theta\right)_y^{'}r}{\cos^2\theta-1}\left(g_n^m\cos m\varphi+h_n^m\sin m\varphi\right)P_{n+1}^m\left(\cos\theta\right)\end{aligned}\right\}. \quad (6)$$

$$B_z\left(x,y,z\right)=-\frac{\mu_0}{4\pi}\sum_{n=1}^{\infty}\frac{1}{r^{n+2}}\times$$

$$\times\sum_{m=0}^{n}\left\{\begin{aligned}&\left[-\left(n+1\right)\left(r_z^{'}+\frac{\left(\cos\theta\right)_z^{'}r\cos\theta}{\cos^2\theta-1}\right)\left(g_n^m\cos m\varphi+h_n^m\sin m\varphi\right)\right]\times P_n^m\left(\cos\theta\right)+\\&+\left(n-m+1\right)\frac{\left(\cos\theta\right)_z^{'}r}{\cos^2\theta-1}\left(g_n^m\cos m\varphi+h_n^m\sin m\varphi\right)P_{n+1}^m\left(\cos\theta\right)\end{aligned}\right\}. \quad (7)$$

It is quite simple to MF created by several, for example N_1, spheroidal MF sources with coordinates x_i, y_i, z_i relative to microsatellites center $\{x_0, y_0, z_0\}=\{0, 0, 0\}$ and several, for example N_2, spherical MF sources that compensate for MF in given area, with coordinates x_j, y_j, z_j relative to microsatellites center. For this used superposition principle and obtain, for example, for x-projection

$$B_x^{result}\left(x_P,y_P,z_P\right)=\sum_{i=1}^{N_1}B_{xi}\left(x_P-x_i,y_P-y_i,z_P-z_i\right)+\sum_{j=1}^{N_2}B_{xj}\left(x_P-x_j,y_P-y_j,z_P-z_j\right), \quad (8)$$

where B_{xi} calculated by equation (8) with its parameters g_n^m and h_n^m and B_{xj} calculated by equation (12) with its parameters g_{nj}^m, h_{nj}^m. The same is true for other projections.

Thus, based on superposition principle, it is possible calculated MF at an arbitrary point in region outside spherical sources using equations (5) – (7). The advantage of these formulas over known ones [6] is: 1) magnetic induction projections in CCS explicitly written due to taking direct derivatives with respect to CCS coordinates; 2) their generalization to n-harmonic case; 3) there is no need to transform from one coordinate system to another, which is especially important in case of MF calculated from several spherical and sources; 4) equations relative compactness. Correctness of equations (5) – (7) confirmed by comparison with results calculated numerical partial derivatives with respect to coordinates x, y, z. Another check made using COMSOL® modeling by ellipsoid MF of revolution. COMSOL® model has ability to specify direction of ellipsoid magnetization, which made it possible to check correctness of equations (5) – (7) for first harmonics case.

Most microsatellite units MF sources are point type MF sources MFMM of which calculated in SCS. However number of microsatellite MF sources have extended shapes, for example electrical energy distributors. Initial MFMM of such extended MF sources are calculated in prolate elongated spheroidal coordinate system. For calculated MFMM of such extended MF sources in CCS it is necessary to obtain new equations for magnetic induction projections in CCS similar to (5) – (8). Magnetic induction projections in CCS are calculated based on analytical calculation of MF induction of extended MF sources in prolate elongated spheroidal coordinate system.

Definition of PGIMSP. To ensure MMC it is necessary solved two inverse problems: PGIMSP and CGIMSP. First, consider definition of PGIMSP microsatellites MC. For measured MF values generated by microsatellites it is necessary calculated MF sources geometric coordinates location in microsatellites space in such a way that these sources generate MF with magnitude at measurement points in microsatellites near zone is equal to experimentally measured MF values on magnetodynamic stand. Naturally, this is GIMSP [5]. As result of PGIMSP solution, it is necessary calculated such MF sources in microsatellites space, which generated real MF in microsatellites near zone. PGIMSP solution is approximating problem of original MF in predictive MFMM form and therefore PGIMSP solution is MFMM designing and identifying problem based on experimental measurements.

Microsatellites prediction MFMM as a result of PGIMSP solution are calculated based on measured MF in near zone. But then this prediction MFMM used for calculated MF in far zone. For MMC control this prediction MFMM used for calculated microsatellites initial MMM and magnetic induction level at on-board magnetometer installation point.

In contrast to [1, 2] consider microsatellite units magnetic characteristics uncertainty vector $\vec{G}$ in various operation modes. Also we consider microsatellite MF MM generated not only by dipoles, but also by quadrupoles and octupoles of microsatellite units.

Consider PGIMSP required parameters vector $\vec{X}_P$ with spherical coordinates r_n, φ_n and θ_n of model units location in microsatellite space as well as multipole harmonic coefficients values of dipoles $g_{n1}^{0}(\vec{G})$, $g_{n1}^{1}(\vec{G})$, $h_{n1}^{1}(\vec{G})$, quadrupoles $g_{n2}^{2}(\vec{G})$, $h_{n2}^{1}(\vec{G})$, $h_{n2}^{2}(\vec{G})$ and octupoles $g_{n3}^{1}(\vec{G})$, $g_{n3}^{2}(\vec{G})$, $g_{n3}^{3}(\vec{G})$, $h_{n3}^{1}(\vec{G})$, $h_{n3}^{2}(\vec{G})$, $h_{n3}^{3}(\vec{G})$ of these units. Then vector $\vec{Y}_C(\vec{X}_P,\vec{G})$ with magnetic field predicted values at near field given points calculated based on (1) – (3). Consider vector $\vec{E}(\vec{X}_P,\vec{G})$ with difference between vector $\vec{Y}_C(\vec{X}_P,\vec{G})$ calculated based on (1) – (3) and microsatellite MF measured values vector $\vec{Y}_M(\vec{G})$ at near field given points

$$\boldsymbol{E(X_P,G)=Y_M(G)-Y_C(X_P,G)}. \tag{9}$$

Then PGIMSP solution reduced to game $\vec{E}(\vec{X}_P,\vec{G})$ solution calculated by minimizing payoff vector on required parameters vector $\vec{X}_P$, but maximizing same payoff vector on uncertainties vector $\vec{G}$.

Note that PGIMSP solution is ambiguous. Microsatellite units MMC measured during their manufacture and strictly regulated. Their location coordinates in microsatellite space are also precisely known. Therefore, for microsatellite units MMC given values and for their location given coordinates in microsatellite space FGMSP is solved and microsatellite MF magnitudes in near zone are calculated. Based on these MF values calculated in microsatellite near zone PGIMSP is solved. Naturally magnetic characteristics of microsatellite MF model sources and their microsatellite space location coordinates calculated during PGIMSP solution is not correspond to microsatellite real unit's magnetic characteristics. Model MF sources location coordinates in microsatellite space will also not be correspond to the real units location coordinates in microsatellite space. However, such correspondence between real units and model MF sources not required. Based on PGIMSP solution it is necessary to calculate only MF magnitudes in microsatellite near zone corresponding to MF actual values in near zone.

In addition, usually MF values in microsatellite near zone calculated based on FGMSP solution do not correspond to real MF values experimentally measured on magnetodynamic stand. This discrepancy is primarily due to mutual influence of magnetic fields of individual microsatellite units on each other. In addition, during microsatellite design individual satellite units, for example, electromagnetic relays, high-frequency valves, are arranged in this way that these units MMM directed oppositely to each other and initial individual units MMM compensated. Moreover, such individual units MMM compensation leads to quadrupole, octupole and higher order MF sources appearance.

Therefore reality PGIMSP solved based not on MF values in microsatellite near zone calculated during solving FGMSP, but based on experimentally measured microsatellite MF values on magnetic measuring stand. In addition, when PGIMSP solving based on experimentally measured MF values, task is to simplify MFMM by reducing of model MF sources number. Naturally, in this case, there can be no question of any correspondence between of real microsatellite units magnetic characteristics and model MF sources, as well as spatial location coordinates of microsatellite units and model MF sources.

Definition of CGIMSP. Consider definition of CGIMSP microsatellites MC [5]. It consists in fact, that for calculated values of MMM and for magnetic induction level at on-board magnetometer installation point, it is necessary calculated compensating MF sources MMM and their spatial location geometric coordinates in microsatellites space in such a way that these MF sources generate such compensating MF that microsatellites resulting MMM values and resulting MF magnetic induction level at on-board magnetometer installation point meet microsatellites MC requirements. This is also GIMSP. As CGIMSP solution result it is necessary to find such compensating MF sources in microsatellites space, which generated compensating MF in outer microsatellites space. In fact, CGIMSP is compensation system design problem for microsatellites output MF – system of active shielding of microsatellites own MF.

Unlike [1, 2] to improve microsatellite MC introduced compensating units, consisting not only of compensating dipoles, but also of compensating quadrupoles and compensating octupoles generated compensating MF opposite initial microsatellite MF. Consider required parameters vector $\vec{X}_C$ of this CGIMSP with spherical coordinates r_c, φ_c and θ_c of compensating units location in microsatellite space as well as multipole harmonic coefficients values of dipoles g_{C1}^0, g_{C1}^1, h_{C1}^1, quadrupoles g_{C2}^0, g_{C2}^1, g_{C2}^2, h_{C2}^1, h_{C2}^2 and octupoles g_{C3}^0, g_{C3}^1, g_{C3}^2, g_{C3}^3, h_{C3}^1, h_{C3}^2, h_{C3}^3 of these compensating units . Then, based on (1) – (3) calculated vector $\vec{B}_C(\vec{X}_C, G)$ with compensating MF predicted values at near field given points. Consider vector $\vec{B}_R(\vec{X}_C, \vec{G})$ with sum vector $\vec{B}_C(\vec{X}_C, G)$ compensating MF calculated based on (1) – (3) and microsatellite initial MF vector $\vec{B}(\vec{G})$ calculated as PGIMSP solution

$$\vec{B}_R(\vec{X}_C, \vec{G}_C) = \vec{B}(\vec{G}_C) + \vec{B}_C(\vec{X}_C). \tag{10}$$

Then CGIMSP solution for uncertain microsatellite MC reduced to game $\vec{B}_R(\vec{X}_C, \vec{G})$ solution calculated by minimizing payoff vector on required parameters vector $\vec{X}_C$ of compensating units, but maximizing same payoff vector on uncertainties vector $\vec{G}_C$.

Naturally CGIMSP solution is also controversial. Apparently most effective compensation of microsatellite initial MF can be achieved by compensating MF sources locating in model MF sources locations calculated during PGIMSP solution. However in practice, attempts are made to reduced compensating MF sources number. In this case, naturally there can be no question of any correspondence between CGIMSP and PGIMSP solutions.

In addition, to simplify technical implementation, permanent magnets usually used as microsatellite compensating MF sources. Electromagnets used potentially makes it possible MMC increased by units magnetic characteristics compensated for microsatellite different modes operation changed.

Solution method. Initial expansion coefficients values for spherical harmonics for PGIMSP solution and for CGIMSP solution calculated as GIMSP solution taking into account these real uncertainties of characteristics of microsatellite MC. Moreover, GIMSP solutions based on conditions of minimization of deviation vector of experimentally measured microsatellites MF values relative to calculated values of magnetic induction based on designed microsatellites MFMM, but at the same time on conditions of maximization same vector of deviations relative to microsatellites MC uncertainties vector. This approach is standard for ensuring robustness of designed microsatellites MMMF relative to uncertainties vector of microsatellites magnetic characteristics [16]. Both PGIMSP and CGIMSP for uncertain microsatellite MC reduced to vector game solutions minimized on initial parameters vector, including spherical coordinates and dipole, quadrupole and octopole harmonics of initial or compensating units but maximized on uncertainty vector of microsatellite magnetic characteristics. Both game vector payoff calculated based on Laplace equation solutions of scalar microsatellite magnetic field potential (2) – (4) using Wolfram Mathematica ® software. Both vector games calculated from Pareto optimal solutions taking into account binary preference relations based on multiswarm stochastic multiagent optimization algorithms [7].

To solve vector game solutions stochastic multi-agent optimization algorithm used. Based on set of particles swarms, the number of which equal number of components of payoff vector game. In the standard particle swarm optimization (PSO) algorithm particle velocities change according to linear laws. In order to increase speed of global solution finding, special nonlinear algorithms of stochastic multi-agent optimization used, in which movement of particle i of swarm j described by following expressions

$$v_{ij}(t+1) = w_{1j} v_{ij}(t) + c_{1j} r_{1j}(t) H\big(p_{1ij}(\mathrm{t}) - \varepsilon_{1ij}(t)\big)\big[y_{ij}(t) - x_{ij}(t)\big] + c_{2j} r_{2j}(t) H\big(p_{2ij}(t) - \ldots$$
$$\ldots - \varepsilon_{2ij}(t)\big)\big[y_j^*(t) - x_{ij}(t)\big] \quad (11)$$

$$u_{ij}(t+1) = w_{2j} u_{ij}(t) + c_{3j} r_{3j}(t) H\big(p_{3ij}(t) - \varepsilon_{3ij}(t)\big)\big[z_{ij}(t) - \delta_{ij}(t)\big] + \ldots$$
$$\ldots + c_{4j} r_{4j}(t) H\big(p_{4ij}(t) - \varepsilon_{4ij}(t)\big)\big[z_j^*(t) - \delta_{ij}(t)\big], \quad (12)$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1), \quad g_{ij}(t+1) = \delta_{ij}(t) + u_{ij}(t+1), \quad (13)$$

where position $x_{ij}(t)$ and velocity $v_{ij}(t)$ particle i swarm j calculated required parameters variables vectors $\vec{X}_P$ and $\vec{X}_C$ when minimizing payoff vector games (9) – (10), position $g_{ij}(t)$ and velocity $u_{ij}(t)$ particle i swarm j calculated required parameters variables vectors $\vec{G}$ and $\vec{G}_C$ when maximizing payoff same vector games (9) – (10).

Optimization problems of scalar game solution, which are components of vector game payoff solved with individual swarms help. In order to find global vector game solution, individual swarms exchange information among themselves during calculated optimal solutions of local criteria. Information about global optimum obtained by particles of another swarm used to calculate movement velocities of particles of one swarm, which allows all potential Pareto-optimal solutions identified. For this purpose, at each step of movement of particle i of swarm j preference relationship functions of local solutions advantages used. In fact, this approach implements main idea of successively narrowing method trade-offs – from area initial set of possible solutions, based on information about relative importance of local solutions, all Pareto-optimal solutions cannot chosen according to available information about advantages of attitudes successively removed. Deletion carried out until globally optimal solution obtained. As a result of this approach, no potentially optimal solution will be removed at each narrowing step.

Simulation results. Basis of metrological support for determination in multi-magnetodipole format of magnetic characteristics of microsatellite units is work performed on specialized magnetic measuring stands. Main provisions of work organization for microsatellite magnetic characteristics reducing implemented by such leading developers of NASA, ESA, etc. space industry. IPMS has powerful specialized experimental base "Magnetodynamic Complex", Fig. 1, included in list of scientific objects constituted national property of Ukraine [4]. At IPMS magnetodynamic complex experimental part of fundamental studies of various technical objects magnetism and their physical models (spacecraft, ships, electric power equipment, building structures, pipelines) carried out. Analysis of MF spatio-temporal structure of these objects performed (including an ultra-small level with a self-induction lower than 10^{-8} *T*). At IPMS stand experimental studies of developed methods and means aimed at purposefully changing magnetic characteristics of various technical objects carried out. Since 2003 magnetodynamic stand tested all orbital spacecraft launched into Earth orbit in Ukraine, namely “Microsat” (2003), “EgiptSat-1” (2007), “Sich-2” (2011), “Sich-2-30" (2022).

Fig. 1

Consider developed method used for prediction and control by uncertain microsatellite MC based on spatial harmonic analysis for MF at LEMI-016 magnetometer installation point generated by KPNCP space plasma sensor «Potential» scientific complex microsatellites «Sich» family [6] diagram of which shown in Fig. 2.

Microsatellite initial MF [6] spherical harmonic coefficients $g_1^0 = 4.1*10^{-3}$, $g_1^1 = -8.4*10^{-2}$, $h_1^1 = 4.2*10^{-2}$, $g_2^0 = 1.411*10^{-3}$, $g_3^0 = 2.5*10^{-4}$. Dipole harmonic (magnetic moment field) relative contribution to initial MF less than 20 % and quadrupole and octupole spherical harmonics contribution to initial MF about 80% [18]. CGIMSP solution calculated spherical coordinates of compensating unit spatial location r_k = =0.0768617; φ_k = 0.163995; θ_k = 3.90015, compensating quadrupole g_2^0 = 0.0249959, g_2^1 = 0.981453,

g_2^2 = 0.271729, h_2^1 = 0.62818, h_2^2 = 0.620474 and compensating octopole g_3^0 = 0.00160516, g_3^1 = 0.0282545, g_3^2 = 0.651052, g_3^3 = –0.704719, h_3^1 = 0.0031692, h_3^2 = 0.175824, h_3^3 = –1.11672. Due to compensating quadrupoles and octupoles installation possible microsatellite initial MF reduce by more than hundred times.

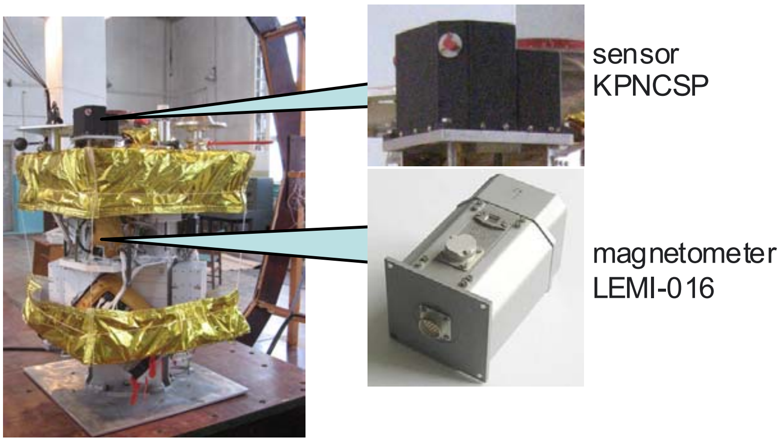

Fig. 2

Conclusions. For the first time the method for prediction and control by microsatellite MC taking into account the uncertainties of microsatellite magnetic characteristics based on prediction geometric inverse magneto static problem and control geometric inverse magneto static problem solutions for calculation and compensation MF spatial spherical harmonics for improved uncertain microsatellite MC by compensation initial MF spatial harmonics and for reduced sensitivity to magnetic characteristics uncertainty developed.

The method for mathematical modeling simplification of uncertain microsatellites MF based on analytical calculation of MF induction of spherical MF sources in Cartesian coordinate systems developed.

Prediction and control problem by uncertain microsatellite MC are geometric inverse magneto static problems. Microsatellite MF spatial spherical harmonics calculated based on Laplace equation solutions for MF scalar potential using Wolfram Mathematica® software. Both prediction geometric inverse magneto static problem and control geometric inverse magneto static problem solutions reduced to vector game solution calculated based on particles multi-swarm optimization algorithms from Pareto optimal solutions taking into account binary preference relations.

During prediction geometric inverse magneto static problem and control geometric inverse magneto static problem solutions for uncertain microsatellite MC model MF sources and compensating spherical MF sources spherical coordinates location and multipole harmonic coefficients of dipoles, quadrupoles and octupoles calculated.

Based on developed method MC of «Sich-2» microsatellite family generated by space plasma sensor KPNCP at onboard magnetometer LEMI-016 installation point improved. Compensating dipole, quadrupole and octupole reduced initial MF by more than hundred times.

Conflict of interest. The author of the article declares no conflict of interest.

1. Droughts S.A., Fedorov O.P. Space project Ionosat-Micro. Monograph. Kyiv: Akademperiodika Publ., 2013. 218 p. (Rus).

2. Rozov V.Yu., Getman A.V., Petrov S.V. Spacecraft magnetism. *Tekhnichna elektrodynamika. Tematychnyi vypusk Problemy suchasnoi elektrotekhniky.* Part 2. 2010. Pp. 144-147. (Rus).

3. ECSS-E-HB-20-07A. Space engineering: Electromagnetic compatibility hand-book. ESA-ESTEC. Noordwijk: Requirements & Standards Division, 2012. 228 p.

4. Baranov M.I., Rozov V.Yu., Sokol Ye.I. To the 100th anniversary of the National Academy of Sciences of Ukraine – the cradle of domestic science and technology. *Electrical Engineering & Electromechanics*. 2018. No 5. Pp. 3-11. DOI: https://doi.org/10.20998/2074-272X.2018.5.01.

5. Weikert S., Mehlem K., Wiegand A. Spacecrat magnetic cleanliness prediction and control. ESA Workshop on *Aerospace EMC*, Venice, Italy, May 2012. URL: http://articles.adsabs.harvard.edu/pdf/2012ESASP.702E..44W (accessed at 15.06.2024).

6. Getman A.V. Spatial harmonic analysis of the magnetic field of the sensor of the neutral plasma component. *Eastern European Journal of Advanced Technologies*. 2010. Vol. 6. No 5(48). Pp. 35-38.

7. Janani Moorthy, Visakamoorthi Balasubramani, Muthukumar Palanisamy, Sung-ho Hur. Memory sampled-data control design for attitude stabilization of uncertain spacecraft with randomly missing measurements. *Advances in Space Research*. 2024. Vol. 74. Issue 3. Pp. 1276-1287. DOI: https://doi.org/10.1016/j.asr.2024.04.047.

8. Zhiwei Hou, Xuejing Lan. Adaptive sliding mode and RBF neural network based fault tolerant attitude control for spacecraft with unknown uncertainties and disturbances. *Advances in Space Research*. 2024. Vol. 74. Issue 4. Pp. 1680-1692. DOI: https://doi.org/10.1016/j.asr.2024.05.021.

9. Matsushima M., Tsunakawa H., Iijima Yu-Ichi, Nakazawa S., Matsuoka A., Ikegami S., Ishikawa T., Shibuya H., Hisayoshi Shimizu H., Takahashi F. Magnetic Cleanliness Program Under Control of Electromagnetic Compatibility for the SELENE (Kaguya) Spacecraft. *Space Sci. Rev.* 2010. Vol. 154. Pp. 253-264. DOI: https://doi.org/10.1007/s11214-010-9655-x.

10. Boghosian M., Narvaez P., Herman R. Magnetic testing, and modeling, simulation and analysis for space applications. IEEE International Symposium on *Electromagnetic Compatibility*, Denver, CO, USA, 05–09 August 2013. Pp. 265-270. DOI: https://doi.org/10.1109/ISEMC.2013.6670421.

11. Mehlem K., Wiegand A. Magnetostatic cleanliness of spacecraft. Asia-Pacific International Symposium on *Electromagnetic Compatibility*, Beijing, China, 12–16 April 2010. Pp. 936-944. DOI: https://doi.org/10.1109/APEMC.2010.5475692.

12. Chen X., Liu S., Sheng T., Zhao Y., Yao W. The satellite layout optimization design approach for minimizing the residual magnetic flux density of micro- and nano-satellites. *Acta Astronautica*. 2019. Vol. 163. Part B. Pp. 299-306. DOI: https://doi.org/10.1016/j.actaastro.2018.12.006.

13. Yao W., Chen X., Luo W., Van Tooren M., Guo J. Review of uncertainty-based multidisciplinary design optimization methods for aerospace vehicles. *Progress in Aerospace Sciences.* 2011. Vol. 47. Issue 6. Pp. 450-479. DOI: https://doi.org/10.1016/j.paerosci.2011.05.001.

14. Walton MA. *Managing uncertainty in space systems conceptual design using portfolio theory*. PhD dissertation, Massachusetts Institute of Technology, 2002. 242 p.

15. Junge A., Marliani F. Prediction of DC Magnetic Fields for Magnetic Cleanliness on Spacecraft. *IEEE Int. Symp. EMC*, Long Beach, California, 14–18 August 2011. Pp. 834-839. DOI: https://doi.org/10.1109/ISEMC.2011.6038424.

16. Sushchenko O., Averyanova Y., Ostroumov I., Kuzmenko N., Zaliskyi M., Solomentsev O., Kuznetsov B., Nikitina T., Havrylenko O., Popov A., Volosyuk V., Shmatko O., Ruzhentsev N., Zhyla S., Pavlikov V., Dergachov K., Tserne E. Algorithms for Design of Robust Stabilization Systems. *Computational Science and Its Applications – ICCSA 2022.* 2022. Vol. 13375. Pp. 198-213. DOI: https://doi.org/10.1007/978-3-031-10522-7_15.

17. Hashim F.A., Hussain K., Houssein E.H., Mabrouk M.S., Al-Atabany W. Archimedes optimization algorithm: a new metaheuristic algorithm for solving optimization problems. *Applied Intelligence*. 2021. Vol. 51. Pp. 1531-1551. DOI: https://doi.org/10.1007/s10489-020-01893-z.

УДК 621.3.01

ПОКРАЩЕННЯ МАГНІТНОЇ ЧИСТОТИ МІКРОСУПУТНИКА ІЗ НЕВИЗНАЧЕНОСТЯМИ НА ОСНОВІ КОМПЕНСАЦІЇ ПРОСТОРОВИХ ГАРМОНІК МАГНІТНОГО ПОЛЯ

Б.І. Кузнецов[1], докт. техн. наук, **Т.Б. Нікітіна**[2], докт. техн. наук, **І.В. Бовдуй**[1], канд. техн. наук, **К.В. Чуніхін**[1], канд. техн. наук, **В.В.Коломієць**[2], канд. техн. наук, **Б.Б. Кобилянський**[2], канд. техн. наук

[1] **Інститут енергетичних машин і систем ім. А. М. Підгорного НАН України,**
вул. Комунальників, 2/10, Харків, 61046, Україна, e-mail: kuznetsov.boris.i@gmail.com.

[2] **Навчально-науковий професійно-педагогічний інститут УІПА,**
вул. Носакова, 9а, Бахмут, 84511, Україна, e-mail: nnppiuipa@ukr.net.

Вступ. *Розглянуто вирішення проблеми підвищення магнітної чистоти мікросупутників шляхом компенсації просторових гармонік магнітного поля та зменшення чутливості до невизначеності магнітних характеристик.* ***Мета****. Розробка методу прогнозування та контролю магнітної чистоти мікросупутників із невизначеностями, який є геометричною оберненою проблемою магнітостатики мікросупутників, рішення якої зведено до розв'язання векторної гри. Векторний виграш розрахований на основі розробленого методу аналітичного розрахунку індукції магнітостатичного поля сферичних джерел у декартовій системі координат за допомогою програмного забезпечення Wolfram Mathematica ®.* ***Методологія.*** *Обидва рішення векторних ігор розраховані на основі алгоритмів оптимізації багатьох роїв частинок з Парето-оптимальних рішень з урахуванням бінарних відносин переваги.* ***Оригінальність.*** *Під час проектування прогнозу та контролю магнітної чистоти мікросупутника із невизначеностями розраховано сферичні координати просторового розташування модельних і компенсаційних модулів та мультипольні гармонічні коефіцієнти диполів, квадруполів та октуполів.* ***Результати.*** *Наведено результати підвищення магнітної чистоти мікросупутників сімейства «Січ» шляхом компенсації дипольних, квадрупольних та октупольних складових просторових гармонік вихідного магнітного поля датчика космічної плазми KPNCP в точці встановлення бортового магнітометра LEMI-016 та зменшення чутливості до невизначеності магнітних характеристик.* Бібл. 17, рис. 2.

Ключові слова: магнітна чистота мікросупутника, невизначеність магнітних характеристик, прогнозування та керування, геометрична обернена задача магнітостатики, комп'ютерне моделювання.

Надійшла 24.06.2024
Остаточний варіант 05.09.2024