Відомо, що для певної задачі керування відносним рухом космічних апаратів (КА) проводиться синтез відповідного закону управління і вибираються відповідні керуючі органи. В якості виконавчих органів при керуванні орієнтацією і стабілізацією КА використовують двигуни-маховики, геродини, електромагніти пристрої з постійними магнітами і мікрореактивні двигуни. Так, для забезпечення точної стабілізації КА в задачах дистанційного зондування Землі (ДЗЗ) найчастіше застосовують двигуни-маховики разом з електромагнітами. У свою чергу, існує ряд завдань управління відносним рухом КА, де немає необхідності в точній стабілізації КА і забезпеченні мінімальних похибок при орієнтації. До таких завдань можуть належати: завдання орієнтації КА для зарядки сонячних батарей, керування орієнтацією науково-дослідних та метеорологічних КА.

Метою дослідження є синтез закону для алгоритму керування орієнтацією КА при застосуванні виконавчих органів з постійними магнітами (ВОПМ). ВОПМ є органами керування орієнтацією КА і складаються з поворотних постійних магнітів, шагових двигунів і капсул-екранів зі стулками. Відкривання і закривання стулок капсул-екранів і поворот постійних магнітів певним чином забезпечують генерацію дискретного керуючого магнітного моменту. Слід зазначити, що ВОПМ не забезпечують точної стабілізації КА, а звідси не підходять для завдань ДЗЗ. Однак ВОПМ споживають меншу кількість бортової енергії, ніж інші системи керування орієнтацією КА, і доцільні для застосування в задачах, що потребують менш точної стабілізації.

Проведено синтез закону керування для КА з ВОПМ із застосуванням нелінійного регулятора і широтно імпульсного модулятора. Визначено межі ефективного застосування ВОПМ для різних космічних завдань, однією з яких є орієнтація і стабілізація аеродинамічного елементу перпендикулярно до динамічному потоку атмосфери, що набігає. Показано переваги використання ВОПМ в порівнянні з електромагнітними виконавчими органами в задачах стабілізації аеродинамічних елементів аеромагнітної системи відведення відпрацьованих КА з низьких навколоземних орбіт

Ключові слова: синтез закону керування, пристрої з постійними магнітами, космічний апарат, нелінійний регулятор

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SYNTHESIZING AN ALGORITHM TO CONTROL THE ANGULAR MOTION OF SPACECRAFT EQUIPPED WITH AN AEROMAGNETIC DEORBITING SYSTEM

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1. Introduction

Search for effective means of orientation and stabilization control of spacecraft is one of major research challenges in the field of space-rocket hardware. Control system effectiveness criteria are chosen in accordance with the tasks of space missions to be solved by a certain spacecraft. For example, to solve problems of precision navigation and remote Earth monitoring (REM) from satellites, spacecraft relative motion control systems are used. They provide the high quality of orientation and stabilization [1, 2]. Today, gyroscopic devices (flywheels and control moment gyroscopes) used in conjunction with electromagnetic devices serve as the executive devices that provide high-precision stabilization. They perform functions of relieving flywheels. One of the classifications concerning the accuracy of gyroscopic satellite devices is given in Table 1 [3].

Table 1

Classification of gyroscopic satellite devices

Gyroscopic devices	Random gyroscope angle deviation
Commercial	>1 degree per second
Tactical	~1 degree per hour
Navigational	0.01 degree per hour
Strategical	~0.001 degree per hour

At the same time, there is a series of space missions where there is no need to provide precision spacecraft stabilization. Such space missions may include the following:

– orientation of research and metrological satellites for conducting certain environmental measurements or charging solar batteries;

– orientation of aerodynamic elements perpendicular to a dynamic flow of incoming atmosphere [4] in order to increase braking force in solving the problem of deorbiting worked-out spacecraft [5–12];

– orientation control of large-sized solar power plants;

– orientation of a spacecraft having a transceiver antenna with a wide directional pattern for communication with a ground control center.

For such tasks, the minimization of fuel and on-board energy consumption is the criterion for effective control system application. Therefore, executive devices with permanent magnets (EDPM) have been proposed. Their use reduces on-board energy consumption for orientation control [4]. In turn, minimum on-board energy consumption when using EDPM is provided only for rough stabilization. Thus, the proposed EDPMs are appropriate for application in the space-related problems that do not require precision spacecraft orientation. One such problem is the uniaxial stabilization of spacecraft equipped with an aeromagnetic deorbiting system (AMDS) [4].

In turn, the search for an effective control law is prerequisite for effective EDPM application which should meet the chosen criterion of optimality. Also, the search for an algorithm of synthesis of a required controller is an urgent issue for the use of an aeromagnetic deorbiting system with an EDPM onboard spacecraft of various classes.

2. Literature review and problem statement

The current state of development of magnetic control devices can be estimated from analysis of studies [13–19]. For example, use of electromagnetic control devices consisting of coils with hysteresis rods is proposed in [13]. A special algorithm based on the “moving control method” was proposed for implementation of three-axis orientation. However, this method of using electromagnets had a series of drawbacks associated with the development of navigational and electronic computing systems. It should be noted that the considerable stabilization time spent when using the system [13] did not allow it to be used for precision orientation of spacecraft.

Later, with the development of noise filtration algorithms and the introduction of new electromagnets, the possibility of using magnetic executive devices to achieve more precise (than in [7]) orientation was shown in [14–16]. In turn, transition time has also decreased significantly. However, despite their relatively high precision rates, these systems required high power inputs and operation of all orientation and stabilization systems which is difficult to provide in long-term missions.

In their turn, [17, 18] proposed passive orientation systems with permanent magnets that do not consume on-board energy for their functioning. However, unlike [14–16], such systems provide just a passive spacecraft stabilization along the Earth’s magnetic field (EMF) vector and are uncontrollable. Usually, such systems are used for small-size (nano or pico) spacecraft, which cannot be equipped with executive devices for active orientation.

As a part of the solution to the problem of stabilization of the aerodynamic elements of the ACADS (attitude control and aerodynamic drag sail) aerodynamic sailing system [19], it was proposed to use additional wire loops to enable backup of basic control systems. In this way, the reliability of the magnetic stabilization system was upgraded in [19] by supplying a spacecraft having an ACADS with additional magnetic executive devices. Hence, the angular motion control system in [19] is more reliable for the use in long-term missions than the systems in [13–16]. However, significant on-board energy consumption for powering the electromagnetic control system and complexity associated with the deployment of a complex sail structure with coils remain significant drawbacks of [19].

Taking these shortcomings into account, a new design scheme of an aeromagnetic deorbiting system with executive devices based on permanent magnets was proposed in [4]. This system was proposed for deorbiting worked-out spacecraft from low Earth orbits as a part of the solution to the global problem of choking of the near-Earth space. The results of studies using a nonlinear discrete controller in [4] have shown its performance and advantages compared to the electromagnetic systems. However, no complete analysis and synthesis of the law of angular motion control were provided.

Thus, the problem of synthesizing the law of controlling the angular motion of spacecraft with on-board AMDS taking into account optimization criteria is urgent.

3. The aim and objectives of the study

The study objective is to synthesize an algorithm to control the angular motion of spacecraft, equipped with AMDS, when using EDPM.

To achieve this objective, the following tasks were set:

– to synthesize the law of control of relative motion of spacecraft equipped with AMDS when using EDPM;

– to model the process of angular stabilization of spacecraft equipped with AMDS when using EDPM and evaluate stability and quality of control;

– to develop an algorithm for choosing optimal controller parameters.

4. The model of dynamics of a spacecraft with an aeromagnetic deorbiting system for studying controllability and stability of the system

To study the orbital motion of a spacecraft, introduce an inertial coordinate system (ICS) and an orbital coordinate system (OCS). The ICS has the origins $O_I x_I y_I z_I$ at the center of Earth masses, the $O_I y_I$ axis is directed along the Earth rotation axis, the $O_I z_I$ axis is directed at the point of the spring equinox and the $O_I x_I$ axis complements the system to the right one. $O_O x_O y_O z_O$ is the OCS origin, the O_O point coincides with the spacecraft center of masses, the $O_O z_O$ axis is directed along the radius vector of the spacecraft at the current point of the orbit, the axis $O_O y_O$ is selected in the orbit plane and forms an acute angle with the spacecraft velocity, the $O_O x_O$ axis complements the system to the right one.

Orbital spacecraft motion is described by a system of the Lagrange differential equations in osculating elements [20]:

$$\left.\begin{aligned}
&\frac{da}{dt}=\frac{2\cdot a^2}{h}\left(e\cdot\sin\vartheta\cdot S+\frac{p}{r_{SC}}T\right),\\
&\frac{de}{dt}=\frac{1}{h}\left\{p\cdot\sin\vartheta\cdot S+\left[\left(p+r_{SC}\right)\cos\vartheta+r_{SC}\cdot e\right]T\right\},\\
&\frac{di}{dt}=\frac{r_{SC}}{h}\cos(\vartheta+\omega)\cdot W,\\
&\frac{d\Omega}{dt}=\frac{r_{SC}\sin(\vartheta+\omega)}{h\cdot\sin i}W,\\
&\frac{d\omega}{dt}=\frac{1}{h\cdot e}\left\{-p\cdot\cos\vartheta\cdot S+\left(p+r_{SC}\right)\cdot\sin\vartheta T\right\}-\\
&-\cos i\frac{r_{SC}\sin(\vartheta+\omega)}{h\cdot\sin i}W,\\
&\frac{d\vartheta}{dt}=\frac{h}{r_{SC}^2}+\frac{1}{h\cdot e}\left(p\cdot\cos\vartheta\cdot S-\left(p+r_{SC}\right)\cdot\sin\vartheta\cdot T\right),
\end{aligned}\right\}\qquad(1)$$

where

– a is the large half-axis of the orbit;
– e is the eccentricity of the orbit;
– Ω is the direct ascent of the ascending node;
– ω is the argument of perigee;
– μ is the gravitation constant, μ=3.986·10^5 km^3/s^2;
– r_{SC} is the spacecraft radius vector, $r_{SC}=\dfrac{a\left(1-e^2\right)}{1+e\cos\vartheta}$;
– p is the focal parameter of the orbit, $p=a\left(1-e^2\right)$;
– i is the inclination of the orbit;
– ϑ is the true anomaly;
– t is the time of orbital motion;
– S, T, W are projections of radial, transversal, and normal perturbing accelerations on the OCS axis.

In turn, for the problem of orbits close to a circular one, an adapted version of the system of differential equations (1) [21] or the mathematical model of orbital motion presented in [22] is proposed to use this problem. An atmosphere model [23] and the first six zonal harmonics of gravitational potential [20] are used in modeling.

To describe rotational spacecraft motion, a coordinate system linked (LCS) with the center of the spacecraft mass with axes coinciding with the main central axes of the spacecraft inertia was proposed. Mathematical model of spacecraft motion relative to the center of mass is described by the Euler dynamic equations:

$$\left.\begin{aligned}
&J_x\frac{d\omega_x}{dt}+\omega_y\omega_z\left(J_z-J_y\right)=\mathrm{M}_{x.\mathrm{ctrl.}}+\sum M_{x.\mathrm{pert.}}\\
&J_y\frac{d\omega_y}{dt}+\omega_x\omega_z\left(J_x-J_z\right)=\mathrm{M}_{y.\mathrm{ctrl.}}+\sum M_{y.\mathrm{pert.}}\\
&J_z\frac{d\omega_z}{dt}+\omega_y\omega_x\left(J_y-J_x\right)=\mathrm{M}_{z.\mathrm{ctrl.}}+\sum M_{z.\mathrm{pert.}}
\end{aligned}\right\},\qquad(2)$$

where

– J_x, J_y, J_z are the main central moments of inertia of a spacecraft with AMDS;
– ω_x, ω_y, ω_z are the projections of the absolute angular velocity of a spacecraft on the axes of the linked coordinate system (LCS);
– $M_{x.\mathrm{ctrl.}}$, $M_{y.\mathrm{ctrl.}}$, $M_{z.\mathrm{ctrl.}}$ are the control torque projections on the LCS axes;
– $M_{x.\mathrm{pert.}}$, $M_{y.\mathrm{pert.}}$, $M_{z.\mathrm{pert.}}$ are the projections of disturbance moments on the LCS axes.

Aerodynamic and gravitational forces and the moments perturbating spacecraft motion are taken into account in the models.

Equations of the kinematics of relative spacecraft motion can be represented in the following form:

$$\begin{bmatrix}\dot\psi\\ \dot\phi\\ \dot\theta\end{bmatrix}=\frac{1}{\cos\phi}\begin{bmatrix}\cos\phi & \sin\phi\sin\psi & \sin\phi\cos\psi\\ 0 & \cos\phi\cos\psi & -\sin\psi\cos\phi\\ 0 & \sin\psi & \cos\psi\end{bmatrix}\begin{bmatrix}\omega_x^F\\ \omega_y^F\\ \omega_z^F\end{bmatrix},\qquad(3)$$

where

– ϕ, θ, ψ are the Krylov angles (roll, pitch, yaw);
– ω_x^F, ω_y^F, ω_z^F are the projections of the angular spacecraft velocity on the LCS axes relative to the OCS.

Thus, the mathematical model of dynamics of a spacecraft with AMDS (1) to (3) is used in this study to elucidate the basic parameters of orientation, φ, θ, ψ, which are the main indicators of quality of orientation and stabilization of a spacecraft with an AMDS.

5. Synthesis of the law of control of relative motion of a spacecraft with an AMDS

EDPMs consist of rotary permanent magnets housed in special capsule-screens with flaps, stepper motors and a control system for opening and closing the capsule-screen flaps and rotation of permanent magnets. The EDPM design scheme and principle of action are given in [4] and the algorithm of EDPM control for stabilization of aerodynamic elements of the aerodynamic deorbiting system of the spacecraft is shown. To synthesize the controller, it is convenient to represent the nonlinear mathematical model of relative spacecraft motion (3) in the form of a state space in the following discrete form using the feedback linearization method:

$$\mathbf{X}_{k+1}=A\mathbf{X}_k+B\mathbf{U}_k+C\xi_k,\qquad(4)$$

where

$$\mathbf{X}_k=\left[\psi,\phi,\theta,\dot\psi,\dot\phi,\dot\theta\right]^T$$

is the vector of state at the k-th control tact;

$$\mathbf{U}_k=\left[M_{x.\mathrm{ctrl.}},M_{y.\mathrm{ctrl.}},M_{z.\mathrm{ctrl.}}\right]^T$$

is the vector of control at the k-th tact;

$$\xi_k=\left[\sum M_{x.\text{pert.}},\sum M_{y.\text{pert.}},\sum M_{z.\text{pert.}}\right]^T$$

is the vector or perturbation at the k-th tact;

$$A=\begin{bmatrix}0&0&0&1&0&0\\0&0&0&0&1&0\\0&0&0&0&0&1\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{bmatrix}$$

is the matrix of state;

$$B=\begin{bmatrix}J_x^{-1}&0&0\\0&J_y^{-1}&0\\0&0&J_z^{-1}\end{bmatrix}$$

is the matrix of control;

$$C=\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$$

is the matrix of perturbation.

However, it should be noted that in the synthesis of the modal controller, matrix and perturbation vector are not taken into account. At the same time, models (1) to (3) take into account aerodynamic and gravitational perturbations. The controller efficiency is determined by a pass bandwidth and the ability to compensate for disturbance.

In addition, control can be represented as follows:

$$\mathbf{U}_k^L=-K\mathbf{X}_k, \tag{5}$$

where K is the matrix of gain coefficients.

It is proposed to find the matrix of gain coefficients by the pole placement method (PPM) to provide the required control quality [24]. For example, performance ω_0 of a closed system is related to the time T_{tt}^m of the transient process of the modal controller as follows:

$$T_{tt}^m\cong\frac{3}{\omega_0}. \tag{6}$$

In turn, using the pole placement method [25], the matrix of gain coefficients is presented as follows

$$K=\begin{bmatrix}K_1&0&0&K_2&0&0\\0&K_1&0&0&K_2&0\\0&0&K_1&0&0&K_2\end{bmatrix}, \tag{7}$$

where $K_1=\omega_0^2$; $K_2=2\cdot\omega_0$.

Then, taking into account (5) to (7), the control moments being the components of the $\mathbf{U}_k^L$, vector will be written as follows:

$$M_{x.\text{ctrl.l.}}=-J_x\left(K_1\psi+K_2\dot{\psi}\right),$$

$$M_{y.\text{ctrl.l.}}=-J_y\left(K_1\phi+K_2\dot{\phi}\right),$$

$$M_{z.\text{ctrl.l.}}=-J_z\left(K_1\theta+K_2\dot{\theta}\right), \tag{8}$$

where $M_{x.\text{ctrl.l.}}$, $M_{y.\text{ctrl.l.}}$, $M_{z.\text{ctrl.l.}}$ are the control moments generated by means of a linear controller.

Taking into account the nonlinearity of mathematical model (2), (3), it is proposed to apply transition from a linear model to a nonlinear one using the following transformation:

$$\mathbf{U}_k^N=\left(JF_kJ^{-1}\right)^{-1}\left(\mathbf{U}_k^L-J\dot{F}_k\omega_k^T\right)+\omega_k\times J\omega_k^T, \tag{9}$$

where J is the diagonal matrix of spacecraft inertia with components J_x, J_y, J_z; $\omega_k=\left[\omega_x^F,\omega_y^F,\omega_z^F\right]$;

$$F_k=\begin{bmatrix}1&\tan\phi_k\sin\psi_k&\tan\phi_k\cos\psi_k\\0&\cos\psi_k&-\sin\psi_k\\0&\sec\phi_k\sin\psi_k&\sec\phi_k\cos\psi_k\end{bmatrix};$$

$$\dot{F}_k=\begin{bmatrix}0&\begin{bmatrix}\sec^2\phi_k\sin\psi_k\dot{\phi}_k+\\+\cos\psi_k\tan\phi_k\dot{\psi}_k\end{bmatrix}&\begin{bmatrix}\sec^2\cos\psi_k\phi_k\dot{\phi}_k-\\-\sin\psi_k\tan\phi_k\dot{\psi}_k\end{bmatrix}\\0&-\sin\phi_k\dot{\phi}_k&-\cos\psi_k\dot{\psi}_k\\0&\left[\sec\phi_k\begin{pmatrix}\sin\psi_k\tan\phi_k\dot{\phi}_k+\\+\cos\psi_k\dot{\psi}_k\end{pmatrix}\right]&\left[\sec\phi_k\begin{pmatrix}\cos\psi_k\tan\phi_k\dot{\phi}_k-\\-\sin\psi_k\dot{\psi}_k\end{pmatrix}\right]\end{bmatrix}.$$

Thus, the synthesized control moments for the nonlinear control law are the vector $\mathbf{U}_k^N$ components

$$\mathbf{U}_k^N=\left[M_{x.\text{ctrl.nl.}},M_{y.\text{ctrl.nl.}},M_{z.\text{ctrl.nl.}}\right]^T.$$

In accordance with the principle of EDPM action [4], the discrete magnetic moment generated in the interaction of permanent magnets with the Earth's magnetic field (EMF) is the control action. In a general case, the magnetic moment arising from the interaction of the spacecraft magnetic field with the EMF is written as follows:

$$\bar{M}_{\text{magn.}}=\bar{p}_m\times\bar{B}_{\text{EMF}}, \tag{10}$$

where $\bar{M}_{\text{magn.}}$ is the vector of magnetic moment acting on the spacecraft; $\bar{p}_m$ is the vector of a magnetic dipole moment of the spacecraft; $\bar{B}_{\text{EMF}}$ is the vector of magnetic induction of EMF.

Control algorithms for active magnetic systems consisting of electromagnets are given in [4, 13–16]. Let us consider the problem of the uniaxial orientation of an aerodynamically unstable space system (spacecraft+AMDS) by means of EDPM [4] according to the following algorithm:

$$M_{\text{magn}.x}=p_{my}\cdot B_z-p_{mz}\cdot B_y,$$

$$M_{y.\text{ctrl.nl.}}=M_{\text{ctrl.magn}.y}=sign\left(\delta_y\right)\cdot p_{mz}\cdot B_x,$$

$$M_{z.\text{ctrl.nl.}}=M_{\text{ctrl.magn}.z}=sign\left(\delta_z\right)\cdot\left(-p_{my}\cdot B_x\right), \tag{11}$$

where $M_{\text{magn}.x}$ is the moment of roll perturbation rotating the spacecraft with an AMDS (the roll channel is uncontrollable); $M_{\text{ctrl.magn}.y}$, $M_{\text{ctrl.magn}.z}$ are the discrete yaw and pitch control moments generated by a non-linear controller (9); p_{my}, p_{mz} are the magnetic dipole moments of permanent magnets placed along the LCS z and y axes; B_x, B_y, B_z are the projections of $\bar{B}_{\text{EMF}}$ on the LCS axes; δ_y, δ_z are the sign functions (change in the magnet polarity, rotation by 180 degrees with the help of a stepper motor).

Thus, the following calculation of theoretical dipole moments $p_{my.\text{ther.}}$, $p_{mz.\text{ther.}}$, satisfying the values of synthesized control moments $\mathbf{U}_k^N$ is proposed with the use of algorithm (11) and nonlinear control law:

$$p_{my.\text{ther.}} = \frac{-M_{z.\text{ctrl.nl.}}}{B_x},$$

$$p_{mz.\text{ther.}} = \frac{M_{y.\text{ctrl.nl.}}}{B_x}. \qquad (12)$$

It should be noted that values of $p_{my.\text{ther.}}$, $p_{mz.\text{ther.}}$, change continuously depending on the changes in a magnetic induction component B_x and theoretical values of $M_{z.\text{ctrl.nl.}}$, $M_{y.\text{ctrl.nl.}}$. However, unlike electromagnetic devices where a smooth change of electromagnet feeding voltage allows smooth change of values $p_{my.\text{ther.}}$, $p_{mz.\text{ther.}}$, the values of p_{my}, p_{mz} for permanent magnets are constant. Thus, to synthesize the control law according to algorithm (12), it is necessary to use a pulse-width modulator (PWM).

To obtain the required pulse length, it is first proposed to apply the discretization of calculated theoretical dipole moments $p_{my.\text{ther.}}(t)$, $p_{mz.\text{ther.}}(t)$, which are functions of time t (control interval). Discretization is implemented by a classical method with the use of lattice functions and the following formulas:

$$p_{my.\text{ther.D.}}(t) = p_{my.\text{ther.}}(t) \cdot \sum_{k=0}^{n} \sigma(t - k \cdot \Delta t),$$

$$p_{mz.\text{ther.D.}}(t) = p_{mz.\text{ther.}}(t) \cdot \sum_{k=0}^{n} \sigma(t - k \cdot \Delta t), \qquad (13)$$

where $p_{my.\text{ther.D.}}(t)$, $p_{mz.\text{ther.D.}}(t)$ are the functions of discrete dipole moments; Δt is the discretization period of the controller to generate $p_{my.\text{ther.}}(t)$, $p_{mz.\text{ther.}}(t)$; k is the number of pulses in the control interval t; $\sigma(t)$ is the Dirac delta function.

Upon discretization of theoretical dipole moments using PWM, the pulse widths necessary for synthesizing discrete control moments (11) are obtained using the formulas proposed in [4, 26]:

$$\mathrm{d}t_y = \frac{|p_{my.\text{ther.D.}}(t)|}{p_{my}} \Delta t,$$

$$\mathrm{d}t_z = \frac{|p_{mz.\text{ther.D.}}(t)|}{p_{mz}} \Delta t, \qquad (14)$$

where $\mathrm{d}t_y$, $\mathrm{d}t_z$ are the corresponding pulse widths in the control channels, $M_{\text{ctrl.magn.}y}$, $M_{\text{ctrl.magn.}z}$.

Next, taking into account the possible negative theoretical values of functions $p_{my.\text{ther.D.}}(t)$, $p_{mz.\text{ther.D.}}(t)$, related to providing required polarity to dipole moments, the function of the reversing sign of the magnetic dipole moment will be written as follows:

$$\delta_y = \frac{p_{my.\text{ther.D.}}(t)}{p_{my}} \Delta t,$$

$$\delta_z = \frac{p_{mz.\text{ther.D.}}(t)}{p_{mz}} \Delta t. \qquad (15)$$

Thus, using the synthesis of a linear modal controller (4) to (8), conversion to a nonlinear control law (9), algorithm (11), discretization of design $p_{my.\text{ther.}}$, $p_{mz.\text{ther.}}$ and PWM, necessary EDPM control laws were obtained. Also, necessary discrete laws for controlling the opening and closing of the capsule-screens (14) and rotation of permanent magnets to change polarity (15) were synthesized.

6. Modeling the process of angular stabilization of a spacecraft equipped with AMDS using the synthesized control law

To analyze the main quality indices of the EDPM control system, perform modeling of the uniaxial orientation of a spacecraft equipped with AMDS possessing the following characteristics (Table 1).

Table 1

Characteristics of a spacecraft equipped with AMDS

Spacecraft mass, m_{SC}	180 kg
J_x	75 kg·m^2
J_y	100 kg·m^2
J_z	67 kg·m^2
Spacecraft midsection area, S_m	1.69 m^2
AECB aerodynamic element section, S_{AMDS}	5 m^2
AECB mass (including magnetic control devices), m_{AMDS}	5 kg
Magnetic dipole moment of constant magnets, p_{my} and p_{mz}	20 A·m^2
Distance between the mass center and the pressure center r_b	0.5 m

For example, it is proposed to model stabilization of a spacecraft equipped with AMDS and having characteristics given in Table 2 for an altitude of 600 km (close to a circular orbit) with orbit eccentricity e=0.0001 for a period of motion of 32,400 s (approximately 3 turns). Uniaxial yaw and pitch stabilization is performed for given initial deviations of yaw $\psi = 70^\circ$ and pitch $\theta = 55^\circ$. Modeling of orbital motion taking into account aerodynamic and gravitational forces and moments of perturbation and control magnetic moment is realized using mathematical models (1) to (3) and the synthesized control law (4) to (15). The following software environments have been selected for calculations: SciLab application package and Visual Studio C++. Graphs obtained in modeling the stabilization and necessary control moments for its implementation are presented in Fig. 1–4.

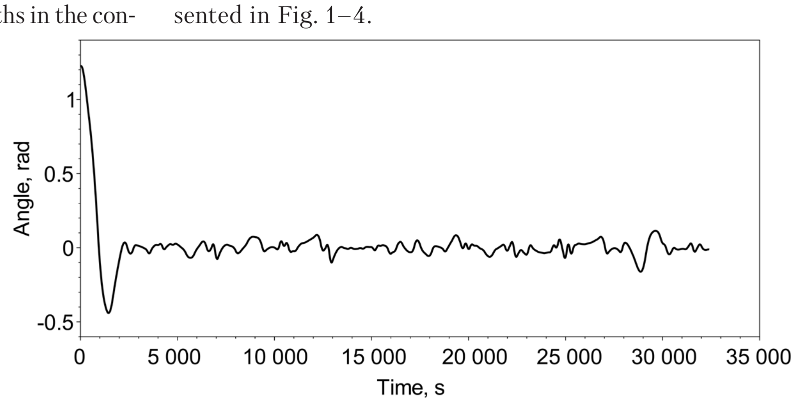

Fig. 1. Yaw stabilization

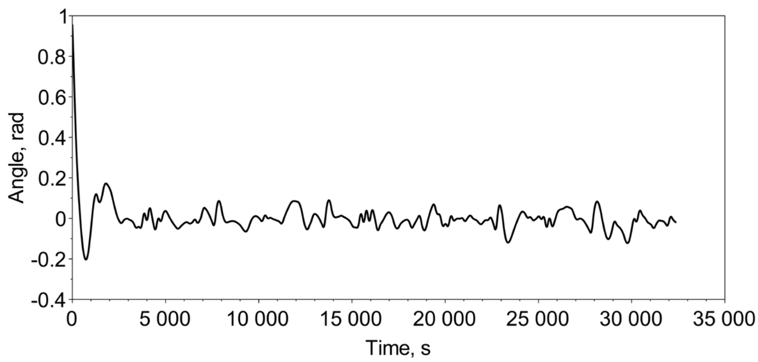

Fig. 2. Pitch stabilization

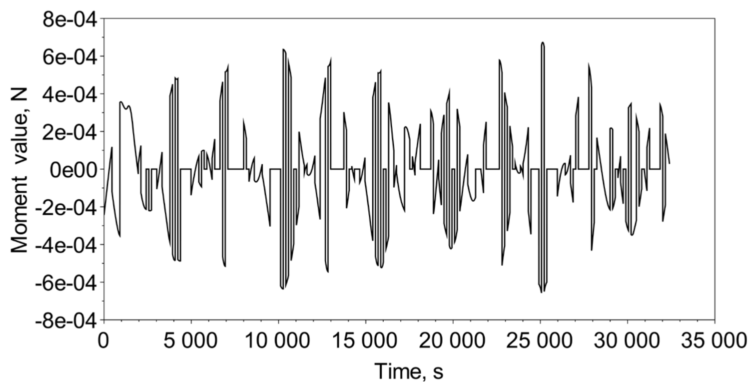

Fig. 3. Control moment to ensure yaw stabilization

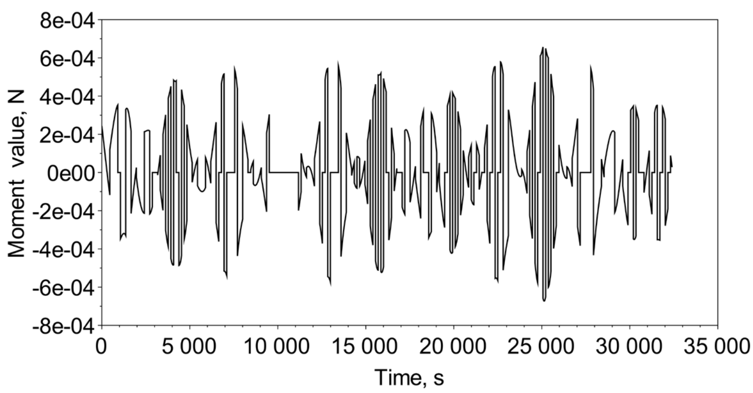

Fig. 4. Control moment to ensure pitch stabilization

Modeling shows that the system with permanent magnetic executive devices provides control stability for a specified period (Fig. 1, 2) where the maximum permissible error of control does not exceed $\varepsilon \leq 0.15$ rad. It is shown in [4] that the error of $\varepsilon \leq 0.15$ rad satisfies control requirements in the stabilization of the AMDS aerodynamic element. This allows us to conclude that the object is controllable. Besides, the speed of operation of the non-linear controller selected using the PPM method is $\omega_0 = 0.012\,\text{s}^{-1}$, Hence, according to formula (7), the time of the transient process of the modal controller is $T_{tt}^{m} = 250\,\text{s}$. To ensure the system stability, ω_0 is placed in the left part of the complex plane. It should also be noted that ω_0 and T_{tt}^{m} are key parameters in the control law synthesis because they indicate the controller's ability to compensate for the effects of disturbances. As for the transient process time T_{tt}^{r} of an actual discrete nonlinear controller, according to the graphs (Fig. 1, 2) its average value in both channels is approximately 2000 s. This value of T_{tt}^{r} satisfies requirements to stabilization of aerodynamic elements in long-term missions when deorbiting the worked-out spacecrafts.

The next key parameters in synthesis of the control law for EDPM include discretization period Δt of the controller and pulse widths dt_y and dt_z. These parameters indicate frequency of opening and closure of the capsule-screens which in turn influences on-board energy consumption by stepping motors to perform above operations. Maximization of minimum pulse widths $dt_{y.\min}$, $dt_{z.\min}$ in both channels is used to reduce frequency of opening the capsule-screens while maintaining the control quality. This means that the controller does not generate pulses smaller than $dt_{y.\min}$, $dt_{z.\min}$ and the system does not open flaps of the capsule-screens to save on-board energy. For example, when modeling, $dt_{y.\min}$ and $dt_{z.\min}$ were chosen equal to 150 s. The obtained graphs of the modeled pulses required for the synthesis of control moments are shown in Fig. 5, 6. In turn, the total running time of stepper motors was 108 s for opening the capsule-screens in both channels and 150 s for rotation of permanent magnets.

For example, computer modeling was used to analyze the stability and controllability of a spacecraft equipped with AMDS when using EDPM to stabilize the aerodynamic element perpendicular to the flow of the incoming atmosphere. Based on the results obtained in modeling, it can be concluded that when applying the derived law of control of aerodynamically unstable space objects by means of EDPM, the system maintains stability at a specified maximum error satisfying the stabilization requirements. It was also found that a height of not less than 580 km where the system maintains stability and the controller can compensate for disturbances is the limit of effective use of EDPM for spacecraft with specified characteristics (Table 2). For aerodynamically unstable spacecraft having no sail elements, the height of not less than 480 km is the limit of effective application of EDPM for spacecraft with these parameters and ballistic coefficient depending on geometric parameters and spacecraft shape. Thus, it is possible to formulate an algorithm for selecting EDPM controller parameters.

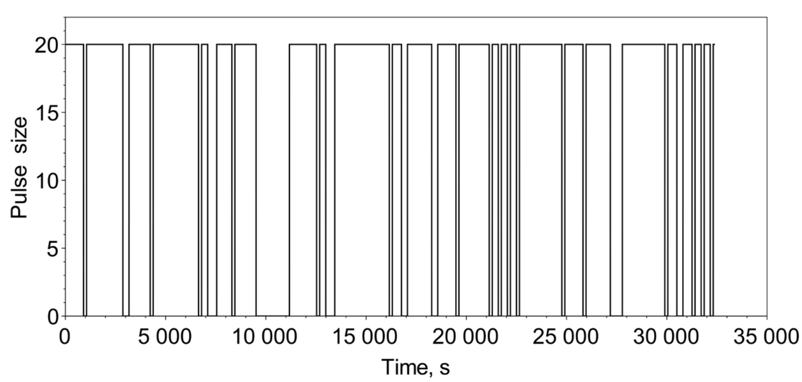

Fig. 5. Number of pulses for the generation of control moment $M_{y.\text{ctrl.}}$

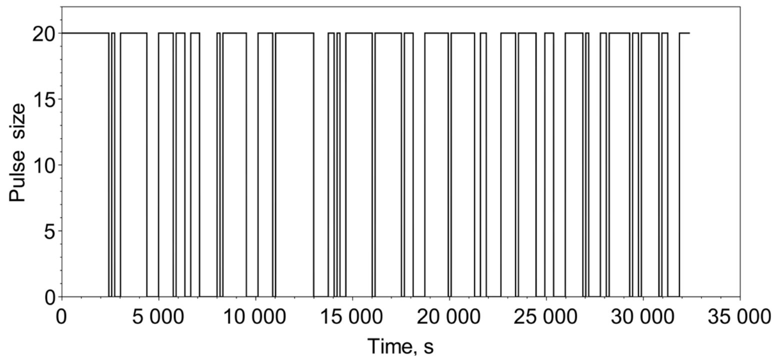

Fig. 6. Number of pulses for generating control torque

7. Algorithm for selecting controller parameters for spacecraft equipped with AMDS and EDPM taking into account the optimization criteria

An algorithm of selecting controller parameters is proposed for various aerodynamically unstable space objects taking into account optimization criteria. Considering the fact that EDPMs provide just rough stabilization and stepper motors spend much less on-board energy than electromagnets [4], a criterion of optimal use of EDPM is proposed. Its essence is to minimize on-board energy consumption. This optimization criterion can be written as follows:

$$Q = \sum_{k=0}^{n} \int_{0}^{T_1} k \cdot U_k I_k dt + \sum_{k_1=0}^{n_1} \int_{0}^{T_2} k_1 \cdot U_{k_1} I_{k_1} \mathrm{d}t \to \min, \tag{16}$$

where Q is the total consumption of on-board energy by stepping motors of EDPM; U_k, U_{k_1} are the supply voltages of stepper motors for opening flaps of capsule-screens and rotation of permanent magnets; I_k, I_{k_1} are the supply currents of stepper motors for opening flaps of capsule-screens and rotation of permanent magnets; k is the number of capsule-screen openings (number of pulses in both control channels); k_1 is the number of turns of permanent magnets in both control channels (number of transitions through 0 in graphs of functions of the control moments $M_{\text{ctrl.magn.}y}$, $M_{\text{ctrl.magn.}z}$); T_1 is the time of running of the stepper motor, which opens flaps of capsule-screens; T_2 is the time of running of a stepper motor that rotates permanent magnets.

It should also be noted that parameters k and k_1 are the functions of performance ω_0, of a specified maximum permissible control error ε and minimum pulse widths $\mathrm{d}t_{y.\min}$, $\mathrm{d}t_{z.\min}$. Thus, the conditions for fulfilling criterion (16) can be written in the following form:

$$k, k_1 = f\left(\omega_0, \varepsilon, \mathrm{d}t_{y.\min}, \mathrm{d}t_{z.\min}\right),$$

$$\omega_0 = \omega_{\text{nom.}},$$

$$\varepsilon \le \varepsilon_{\text{nom.}},$$

$$\mathrm{d}t_{y.\min}, \mathrm{d}t_{z.\min} \to \max, \tag{17}$$

where $\omega_{\text{nom.}}$ is the rated value of the controller performance for a concrete space mission; $\varepsilon_{\text{nom.}}$ is the specified rated value of the maximum permissible control error for the concrete mission.

The on-board energy consumption for uniaxial stabilization of a spacecraft equipped with AMDS when modeling orbital motion in the problem described in the previous paragraph can be estimated by criterion (17). For example, when applying stepping motors in the EDPM mentioned in [4], total consumption of on-board energy for opening and closing capsule-screens and rotation of permanent magnets was $Q = 0.0016185\,\text{kWh}$. In turn, when using four electromagnets of ZARM Technik MT15-1 class which have dipole moments $10\,\text{A}\cdot\text{m}^2$, supply voltage $U = 10\,\text{V}$ and supply current $I = 1\,A$ total energy consumption for control are much higher. For example, to maintain stability at a condition of $\varepsilon \le 0.15\,\text{rad}$, at constant stabilization, energy consumption is $Q_{EM} = 0.072\,\text{kWh}$. Proceeding from the obtained values of consumption of on-board energy for a given period of motion, use of EDPM for ensuring rough stabilization is more effective than the use of electromagnetic devices.

Thus, for application of EDPM and further studies of permanent magnet drives using optimization criteria (16), (17), an algorithm of synthesis of a nonlinear discrete controller for EDPM is proposed. This is presented in Fig. 7. This algorithm can be applied to aerodynamically unstable spacecraft of various classes equipped with EDPM as well as for spacecraft that do not require precise stabilization during the flight mission.

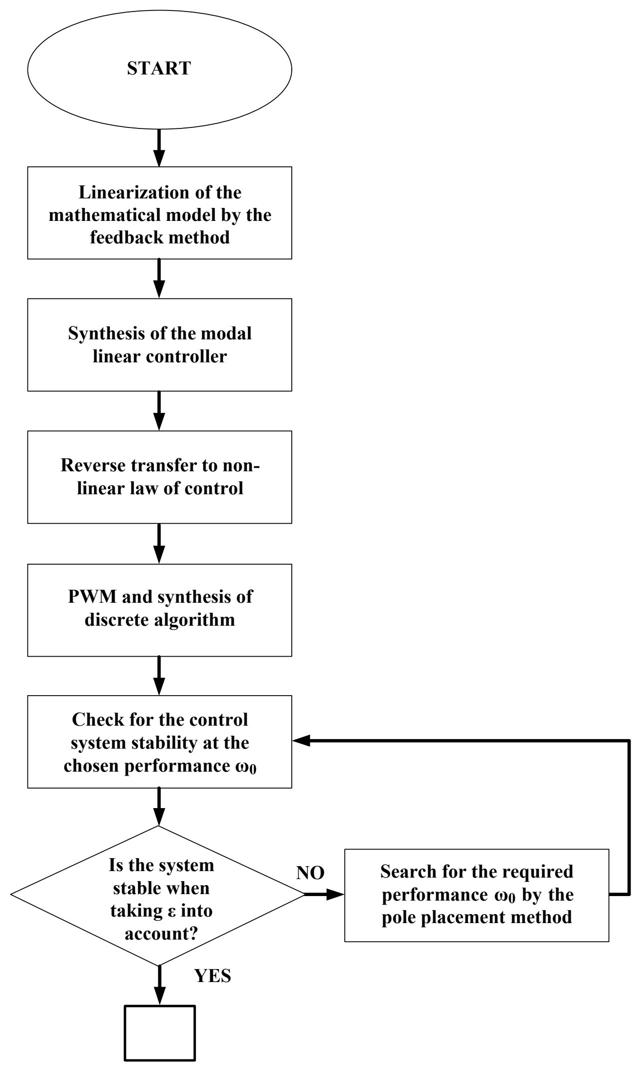

Fig. 7. Algorithm for selecting the controller parameters for a spacecraft equipped with EDPM. Part 1

The developed algorithm (Fig. 7, 8) allows us to select the necessary parameters of the controller for aerodynamically unstable spacecraft of various classes and extends limits of EDPM use.

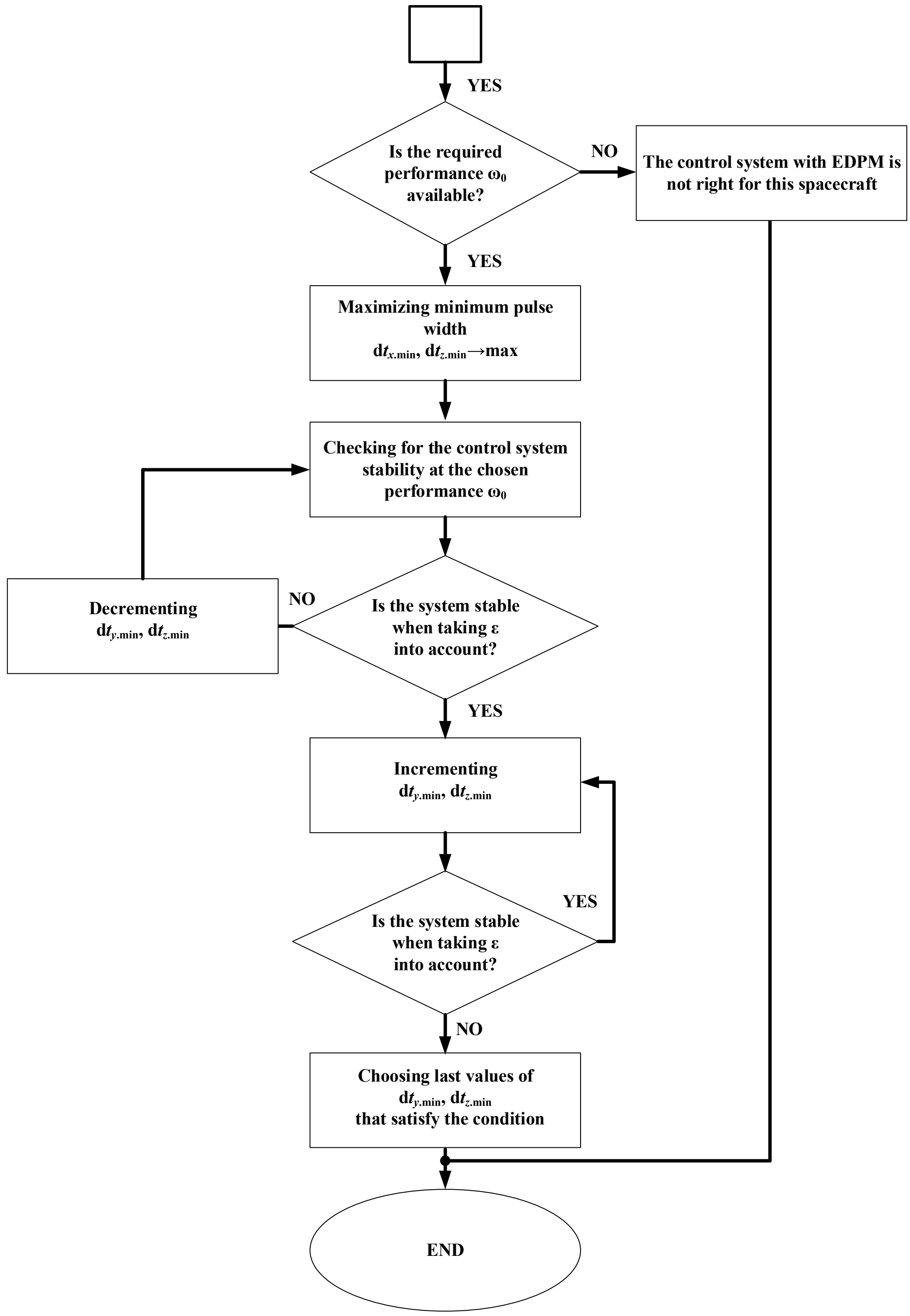

Fig. 8. Algorithm for selecting the controller parameters for a spacecraft equipped with EDPM. Part 2

8. Discussion of results obtained in the synthesis of the law of control over spacecraft equipped with AMDS using EDPM

As a result of our study, the analysis and synthesis of the law of control over spacecraft equipped with AMDS using the EDPM were performed. A system of differential equations in osculating elements (1) was chosen for studying the orbital motion of a spacecraft equipped with AMDS. Motion relative to the center of mass of the system consisting of a spacecraft and AMDS is described by Euler dynamic equations (2). These mathematical models of spacecraft dynamics are used for computer modeling of the process of spacecraft stabilization when applying the relevant control law.

For example, feedback linearization (4) was applied to a nonlinear model of the motion of a spacecraft relative to the center of mass (2) in the first stage of synthesis of the law of control of a spacecraft equipped with AMDS. Using this linearization, a modal linear controller (5) to (8) was synthesized. Considering the limitation of using the linear controllers only by small deviation angles, the transition to a nonlinear controller was made using transformation (9). Transformation (9), in turn, allows us to model control of angular spacecraft orientation at significant angles of yaw, roll or pitch deviation. Based on the fact that EDPMs are control devices for spacecraft equipped with AMDS, an appropriate algorithm (11) was selected for uniaxial stabilization at two angles: yaw and pitch. In turn, EDPM magnetic devices are in the form of permanent magnets [4] rotating by 180 degrees to change polarity by means of small-power stepping motors. Considering this, unlike electromagnets, there is no possibility of continuous control of current in coils to adjust required magnetic dipole moments when using permanent magnets. On this basis, it was proposed to use theoretical discretization of calculated theoretical $p_{my.\text{ther.}}$, $p_{mz.\text{ther.}}$ and their pulse-width modulation which allows one to calculate the tacts necessary to close and open capsule-screens and rotate permanent magnets of the EDPM. Opening and closing of the capsule-screens and rotation of permanent magnets make it possible to generate discrete control moments.

This enables compensation for perturbations and provides required stabilization of spacecraft equipped with AMDS.

Thus, the EDPM control law (4) to (15) was developed with the specified optimization criterion (16), (17) using the nonlinear discrete controller. The optimization criterion implies minimizing the consumption of on-board energy in long-term missions (16). Also, orbital motion modeling has shown the efficiency of using the EDPM with uniaxial two-channel stabilization of the aerodynamic element perpendicular to the flow of incoming atmosphere. Based on the results obtained in modeling uniaxial stabilization at two angles (Fig. 1, 2), the possibility of using EDPM for implementation of rough stabilization of spacecraft equipped with AMDS at a maximum permissible error of $\varepsilon \leq 0.15$ rad was shown. The value of the maximum permissible error of $\varepsilon \leq 0.15$ rad was chosen based on previous studies and calculations of the force of aerodynamic braking depending on the orientation of the aerodynamic flat sailing element [4]. For example, it has been determined that when using EDPM to provide stabilization at a specified error, significantly less on-board electricity is consumed than in the case of using electromagnetic control devices. This is explained by the use of low-power stepping motors for EDPM and synthesized discrete control law (14), (15) which makes it possible to minimize the number of openings and closures of the screen-capsules in the specified period at a specified maximum error. Minimization of the number of openings and closures of the capsule-screens and turns of permanent magnets minimizes the consumption of on-board electrical energy of the spacecraft which meets the established criteria (16), (17).

However, it should be noted that minimum consumption of on-board energy is observed only when providing rough spacecraft stabilization which is explained by the minimum number of pulses required (Fig. 5, 6) to generate discrete control moments (11). In the case of precise stabilization, pulse frequency grows and the on-board energy consumption by EDPM associated with frequency of openings and closures of the capsule-screens is close to that of other electromagnetic control devices. Thus, EDPMs are effective for the use in space missions where there are no requirements of high-precision stabilization and orientation and angular stabilization of spacecraft equipped with AMDSs.

Based on the study results, an algorithm of synthesis of a controller for spacecraft (Fig. 7) equipped with EDPMs was developed taking into account the specified optimization criteria (16), (17). This algorithm enables the synthesis of control laws for aerodynamically unstable spacecraft having EDPM to provide rough stabilization. The algorithm allows one to select the required controller speed based on the mass and dimensional parameters of the spacecraft and the requirements to the precision of stabilization and orientation in a specific space mission. Thus, this algorithm makes it possible to extend limits of application of the synthesized law for various space missions where there is no need for precise stabilization.

9. Conclusions

1. Analysis and synthesis of the law of control over the angular motion of a system consisting of a spacecraft and an AMDS with the help of EDPM were performed. The purpose of EDPM use for an aerodynamically unstable system (spacecraft+AMDS) consists in providing rough uniaxial stabilization in order to orient an aerodynamic planar element to the maximum area of incident aerodynamic flow. The synthesized nonlinear discrete control law makes it possible to select required EDPM controller parameters for certain mass and dimensional characteristics of the spacecraft and control quality requirements.

2. The results of modeling obtained for application of the synthesized low have shown sufficient control quality satisfying requirements to rough stabilization of the aerodynamic element perpendicular to the dynamic flow of the incoming atmosphere. With the selected maximum permissible deviation in each channel of $\varepsilon \leq 0.15$ rad, there was a much lower on-board energy consumption when using EDPM compared to electromagnets. On this basis, one can distinguish the benefits of using EDPM in long-term space missions. However, the benefits are only observed when providing rough stabilization of spacecraft equipped with AMDS where the number of control pulses is minimal.

3. To extend areas of EDPM application, an algorithm of synthesis of a nonlinear discrete control law was developed for various spacecraft equipped with EDPM that do not require precise stabilization. This algorithm makes it possible to select required parameters of the controller performance by the method of placing poles for spacecraft of any class based on the spacecraft characteristics and control requirements. Thus, when applying this algorithm, it becomes possible to conveniently synthesize EDPM control laws for various aerodynamically unstable spacecraft and space systems such as solar power plants, flat sails, etc.

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