UDK 629.73

DOI: https://doi.org/10.20535/0203-3771442022284617

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MICRO-SATELLITE ORIENTATION CONTROL SYSTEM WITH ROTATION WHEELS

Ua Розглядається задача розробки системи керування орієнтацією мікросупутника двигунами – маховиками з обмеженими моментами керування. Для синтезу законів керування методом аналітичного конструювання оптимальних регуляторів мінімізацією інтегрально-квадратичного функціоналу динамічні рівняння обертального руху супутника лінеаризуються. Керуючими

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органами супутника є три двигуни-маховики та магнітні котушки. Розроблені алгоритми керування супутником при заспокоєнні, розвороті та стабілізації кутового положення. Алгоритми налаштовуються в залежності від параметрів супутника та забезпечують його стійкий рух на всіх режимах. Розглянуті приклади імітаційного моделювання руху супутника за повними нелінійними моделями, які показали ефективність та універсальність алгоритмів. Порівнюється ефективність алгоритмів керування використанням двигунів – маховиків та магнітних котушок.

En The task of developing a microsatellite orientation control system using rotation wheels with limited control moments is under consideration. For the synthesis of control laws by the method of analytical construction of optimal regulators by minimization of the integral-quadratic functional, the dynamic equations of the rotational motion of the satellite are linearized. The governing bodies of the satellite are three rotation wheels and magnetic coils. Algorithms for controlling the satellite during stabilization, turning and stabilization of the angular position have been developed. Algorithms are tuned depending on the parameters of the satellite and ensure its stable movement in all modes. Considered examples of simulation the satellite movement using full nonlinear models, which showed the effectiveness and universality of the algorithms. The effectiveness of control algorithms for the use of the rotation wheels and magnetic coils is compared.

Introduction

A large number of publications [1 - 4] are devoted to the research of satellite orientation and orientation control systems. They provide an overview of the main recent achievements in the field of algorithms for active magnetic orientation of satellites. The damping of the angular velocity of the satellite is considered. The promising topic of using a purely magnetic orientation system, which provides an arbitrarily specified three-axis orientation of the spacecraft, is analyzed. The possibility of implementing any mode of movement of the apparatus is shown, but the accuracy and speed of the orientation system are small. The all-magnetic orientation system has not yet been tested in flight tests, and research is far from complete.

When controlling with feedback in a magnetic orientation system, a careful selection of gain coefficients, a general limitation of the magnitude of the control moment, and the accuracy of knowledge of the inertia tensor are necessary [5]. The stabilization of a satellite with a pitch flywheel, stabilization with flywheel engines is considered [3]. In these cases, practically important modes of motion are achieved – orbital orientation and inertial stabilization.

In the vast majority, the problems of theoretical research of microsatellite orientation control systems have been solved. But there are no practical recommendations for the use of certain algorithms. It is shown that active systems allow implementing any orientation and high speed at the cost of increasing the complexity, volume, mass and cost of equipment, power consumption, which significantly limits the possibility of using such systems for small satellites. It is shown that feedback control is convenient for implementation on an on-board computer, but its implementation is complicated by control limitations [6]. This control, because of its simplicity and the large amount of completed research, is a good option for flight practice.

Research into the possibilities of controlling the orientation of microsatellites by flywheel motors and comparing it with a magnetic control system is relevant.

Formulation of the problem

We will consider the task of developing a system for controlling the orientation of a microsatellite with motors - flywheels and evaluate its effectiveness with limited control moments.

Mathematical model of the satellite's rotational motion development

Consider the equation of the dynamics of the rotational movement of the satellite relative to the axes of the connected coordinate system, which coincide with the main central axes of inertia:

$$\dot{\omega}_x = \frac{J_y - J_z}{J_x}\omega_y\omega_z + \frac{M_x}{J_x}; \qquad \dot{\omega}_y = \frac{J_z - J_x}{J_y}\omega_x\omega_z + \frac{M_y}{J_y};$$
$$\dot{\omega}_z = \frac{J_x - J_y}{J_z}\omega_x\omega_y + \frac{M_z}{J_z}, \tag{1}$$

where J_x, J_y, J_z are the main central moments of inertia of the satellite, $\omega_z, \omega_x, \omega_y$ are the projections of the angular velocity of the satellite on the axis of the linked coordinate system; M_x, M_y, M_z – projections of the main moment of external forces on the same axes.

To obtain the laws governing the satellite's rotational motion, equation (1) must be linearized. We also linearize the Euler equation for orientation angles [7]. After the transformations, we will obtain the differential equations of the rotational motion of the satellite in deviations:

$$\begin{aligned}
&\Delta\dot{\gamma} = a_\gamma^\gamma\Delta\gamma + a_\gamma^\psi\Delta\psi + a_\gamma^\vartheta\Delta\vartheta + a_\gamma^{\omega x}\Delta\omega_x + a_\gamma^{\omega y}\Delta\omega_y + a_\gamma^{\omega z}\Delta\omega_z;\\
&\Delta\dot{\psi} = a_\psi^\gamma\Delta\gamma + a_\psi^\psi\Delta\psi + a_\psi^\vartheta\Delta\vartheta + a_\psi^{\omega y}\Delta\omega_y + a_\psi^{\omega z}\Delta\omega_z;\\
&\Delta\dot{\vartheta} = a_\vartheta^\gamma\Delta\gamma + a_\vartheta^\psi\Delta\psi + a_\vartheta^{\omega y}\Delta\omega_y + a_\vartheta^{\omega z}\Delta\omega_z;\\
&\Delta\dot{\omega}_x = a_{\omega x}^{\omega y}\Delta\omega_y + a_{\omega x}^{\omega z}\Delta\omega_z + b_{\omega x}^{Mx}\Delta M_x;\\
&\Delta\dot{\omega}_y = a_{\omega y}^{\omega x}\Delta\omega_x + a_{\omega y}^{\omega z}\Delta\omega_z + b_{\omega y}^{My}\Delta M_y;\\
&\Delta\dot{\omega}_y = a_{\omega z}^{\omega x}\Delta\omega_x + a_{\omega z}^{\omega y}\Delta\omega_y + b_{\omega z}^{Mz}\Delta M_z,
\end{aligned} \tag{2}$$

Here, the symbol Δ indicates the deviations of the satellite motion parameters from their program values at the linearization point, a_i^j, b_i^j are coefficients depending on the program values of the angles ϑ, γ, ψ and angular velocities $\omega_z, \omega_x, \omega_y$.

From the linearized equations (2), we will create a mathematical model of the rotational motion of the satellite in the state space:

$$\dot{X} = AX + BU, \tag{3}$$

where the state vector $X = \left(\Delta\gamma, \Delta\psi, \Delta\vartheta, \Delta\omega_x, \Delta\omega_y, \Delta\omega_z\right)^T$; control vector $U = \left(\Delta M_x, \Delta M_y, \Delta M_z\right)^T$.

Equations (3) are integrated in the Simulink package. A comparison of the simulation results of model (3) and the nonlinear one confirmed the correctness of the performed linearization.

Algorithms for controlling the orientation of satellites during the settling stage. The synthesis of the laws of controlling the angular motion of the satellite will be carried out by the method of analytical design of optimal regulators [8] by minimizing the integral-quadratic functional

$$I = \int_0^\infty (X^T QX + U^T RU)dt \tag{4}$$

by control

$$U = -K \cdot X \tag{5}$$

with the optimal matrix of gain coefficients of the regulator

$$K = R^{-1}B^T P. \tag{6}$$

The iterative synthesis process results in positively defined matrices of weighting coefficients Q and R, and the required control quality is achieved. We will use information about its angular velocity to form a controlling influence at the satellite's stabilization stage. Then in (4), (5) is a vector will look like $X = \left(\Delta\omega_x, \Delta\omega_y, \Delta\omega_z\right)^T$; $U = \left(\Delta M_x, \Delta M_y, \Delta M_z\right)^T$.

As a result of solving the Riccati equation for a microsatellite with the inertia tensor

$$I = \begin{pmatrix} 0,5741 & -0,028 & -0,0144 \\ -0,028 & 0,6115 & -0,0246 \\ -0,0144 & -0,0246 & 0,572 \end{pmatrix} \tag{7}$$

we will get the optimal matrix of gain coefficients

$$K = \begin{pmatrix} 0,0018 & 0,0023 & -0,000096 \\ 0,00217 & 0,0085 & -0,0015 \\ -0,000097 & -0,0016 & 0,0029 \end{pmatrix}. \qquad (8)$$

Let's assume that the executive control bodies of the satellite are three flywheel motors and three magnetic coils. When the satellite rotates, the kinetic moments of the rotors of the flywheel engines create variable gyroscopic moments, which must be taken into account in the control laws (5). Then the control laws will have the form

$$\begin{aligned} M_x &= K_x^{\omega x}\omega_x + K_x^{\omega y}\omega_y + K_x^{\omega z}\omega_z - I_m\omega_{my}\omega_z + I_m\omega_{mz}\omega_y; \\ M_y &= K_y^{\omega x}\omega_x + K_y^{\omega y}\omega_y + K_y^{\omega z}\omega_z - I_m\omega_{mz}\omega_x + I_m\omega_{mx}\omega_z; \\ M_z &= K_z^{\omega x}\omega_x + K_z^{\omega y}\omega_y + K_z^{\omega z}\omega_z - I_m\omega_{mx}\omega_y + I_m\omega_{my}\omega_x, \end{aligned} \qquad (9)$$

and with numerical values (8) for parameters (7)

$$\begin{aligned} M_x &= 0.0018\omega_x + 0.0023\omega_y - 0.000096\omega_z - I_m\omega_{my}\omega_z + I_m\omega_{mz}\omega_y; \\ M_y &= 0.00217\omega_x + 0.0085\omega_y - 0.0015\omega_z - I_m\omega_{mz}\omega_x + I_m\omega_{mx}\omega_z; \\ M_z &= -0.000097\omega_x - 0.0016\omega_y + 0.0029\omega_z - I_m\omega_{mx}\omega_y + I_m\omega_{my}\omega_x, \end{aligned} \qquad (10)$$

where I_m is the moment of inertia of rotation wheel; M_x, M_y, M_z are controlling torques; $\omega_{mx}, \omega_{my}, \omega_{mz}$ are angular velocities of engines.

At the calming stage (Fig. 1) the gyroscope unit (RG) of the orientation system determines the angular velocities of the satellite $\omega_x, \omega_y, \omega_z$. Using their scores $\hat{\omega}_x, \hat{\omega}_y, \hat{\omega}_z$, as well as angular velocities $\omega_{mx}, \omega_{my}, \omega_{mz}$ the rotation wheels, the control algorithm forms control signals U_x, U_y, U_z for feeding to the inputs of rotation wheels. According to these signals, the rotation wheels create the necessary control torques M_x, M_y, M_z; $U_i k_i = M_i$; k_i is the coefficient of the conversion function of the *i*-th rotation wheel.

Taking into account (10) and Fig. 1 the appeasement control algorithm will take the final form:

$$\begin{aligned} U_x &= \frac{1}{k_x}\left(0.0018\omega_x + 0.0023\omega_y - 0.000096\omega_z - I_m\omega_{my}\omega_z + I_m\omega_{mz}\omega_y\right); \\ U_y &= \frac{1}{k_y}\left(0.00217\omega_x + 0.0085\omega_y - 0.0015\omega_z - I_m\omega_{mz}\omega_x + I_m\omega_{mx}\omega_z\right); \\ U_z &= \frac{1}{k_y}\left(-0.000097\omega_x - 0.0016\omega_y + 0.0029\omega_z - I_m\omega_{mx}\omega_y + I_m\omega_{my}\omega_x\right), \end{aligned} \qquad (11)$$

To determine the requirements for the level of control torques, we will assume that the initial angular velocity of the satellite in absolute value does not exceed 0,3 rad/s. Preliminary calculations show that for this, the maximum moment of force created by the control bodies should be at least $4{,}4\cdot10^{-3}$ N·m. Rotation wheels in this case must provide a maximum kinetic moment of at least 0б2 kg·m^2/s.

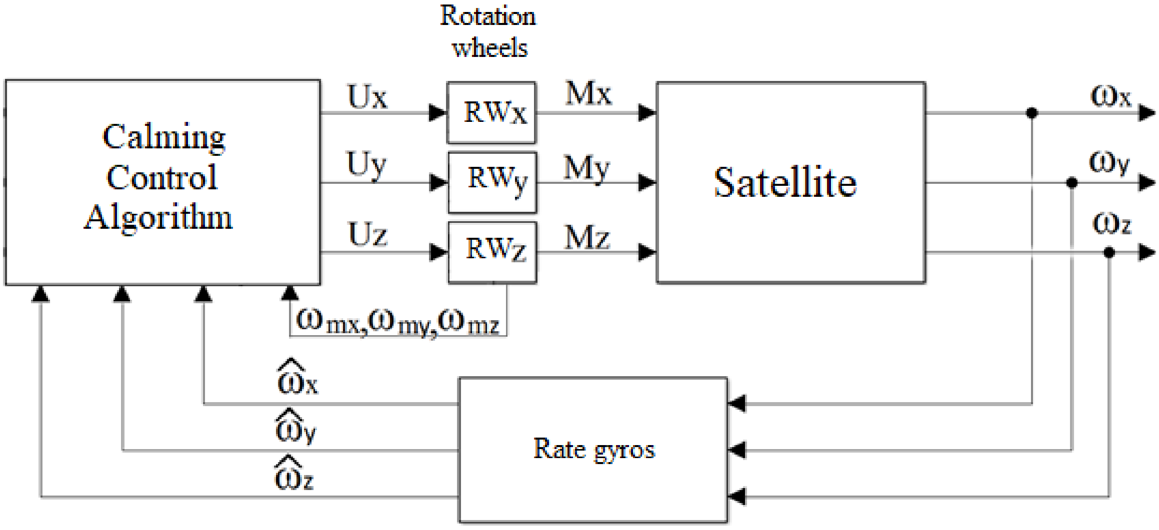

Fig. 1. Functional scheme of the system for controlling the rotational movement of the satellite by the rotation wheels at the stage of calming down

The magnetic control system creates a control torque [9] (Fig. 2)

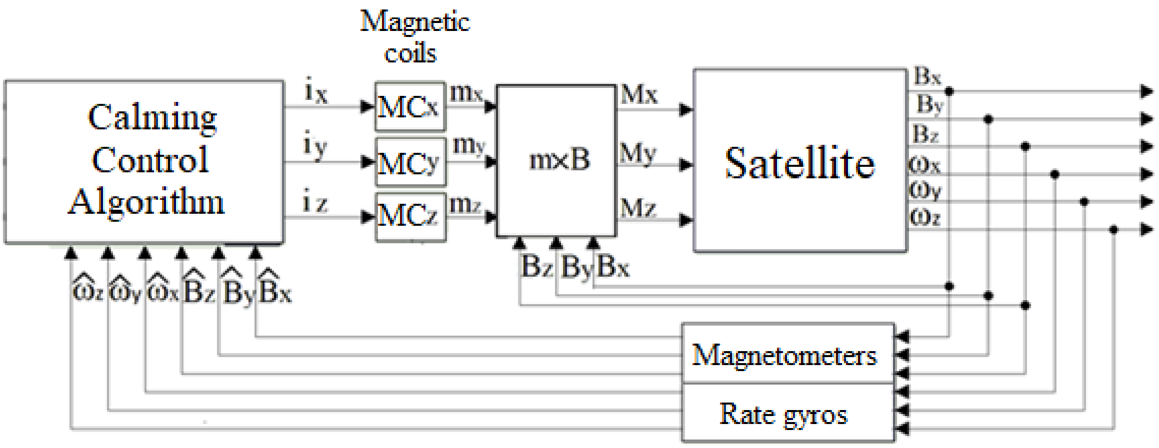

Fig. 2. Functional scheme of the magnetic system for controlling the rotational movement of the satellite during the settling stage

$$M = m \times B,$$

where $m = (m_x,\ m_y,\ m_z)^T$ is a dipole moment of the coils; $B = (B_x,\ B_y,\ B_z)^T$ is the induction vector of the Earth's magnetic field in projections on the axis of the bound coordinate system. We will stabilize the satellite with magnetic coils according to the control law [4]

$$m = k\omega \times B, \qquad (12)$$

where k is a positive coefficient determined by the ability of the coils to create a dipole moment; ω is an angular velocity of the satellite.

For the simplest satellites, the settling algorithm "B – dot" is widespread [1, 4]:

$$m = -k\dot{B}. \qquad (13)$$

We will apply this control law in the absence or failure of the angular velocity sensors, as well as for excessively large initial angular velocities of the satellite.

Results of simulation modelling of the operation of the control system at the calming stage

The simulations were carried out according to the satellite motion simulation model, which uses the full equations of rotational motion for an orbit with an altitude of 600 km and an inclination angle of $i = 97{,}8^{\circ}$. The simulation results (Fig. 3, 4) confirm the correctness of the synthesis of control laws for all possible combinations of component ratios and signs of the initial angular velocity vector. The modulus of the initial angular velocity did not exceed = 0,4 rad/c. The time to stabilize the satellite using frotation wheels does not exceed 13 minutes (Fig. 3), and with the use of magnetic coils with the maximum dipole moment, it reaches 20 minutes (Fig. 4).

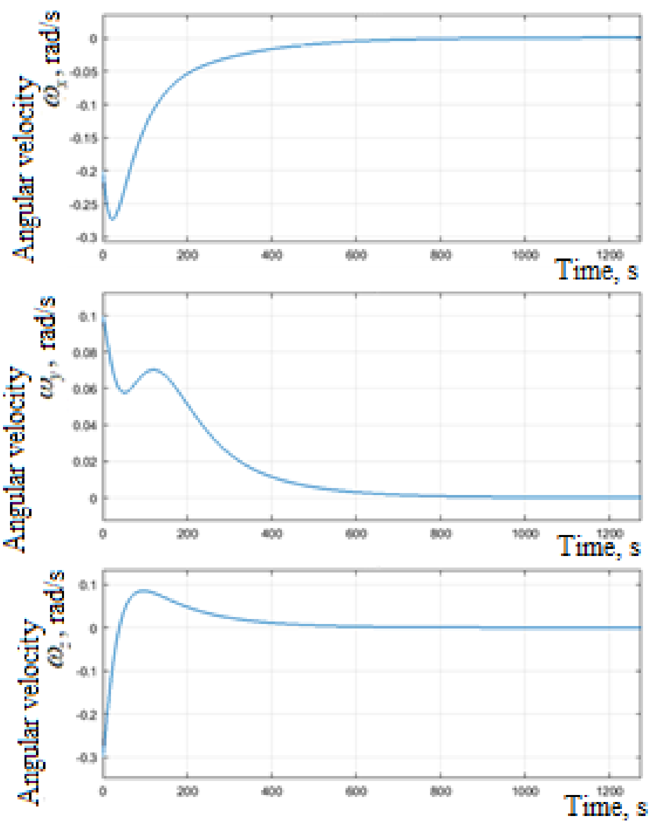

Fig. 3. Calming the satellite with rotation wheels under initial conditions ω_{x0}=-0,2 rad/s, ω_{y0}=0,1 rad/s, ω_{z0} =-0,3 rad/s

Development of satellite orientation control algorithms at the stages of reversal and stabilization of the angular position. The orientation of satellites can be controlled by both magnetic coils and rotation wheels, or their joint use [4]. Consider orientation control using rotation wheels (Fig. 5). The control influences are calculated on the basis of information about pitch, roll and yaw angles and about the projections of the angular velocity of the satellite on the axis of the linked coordinate system. Then in expressions (4), (5) there will be state and control vectors

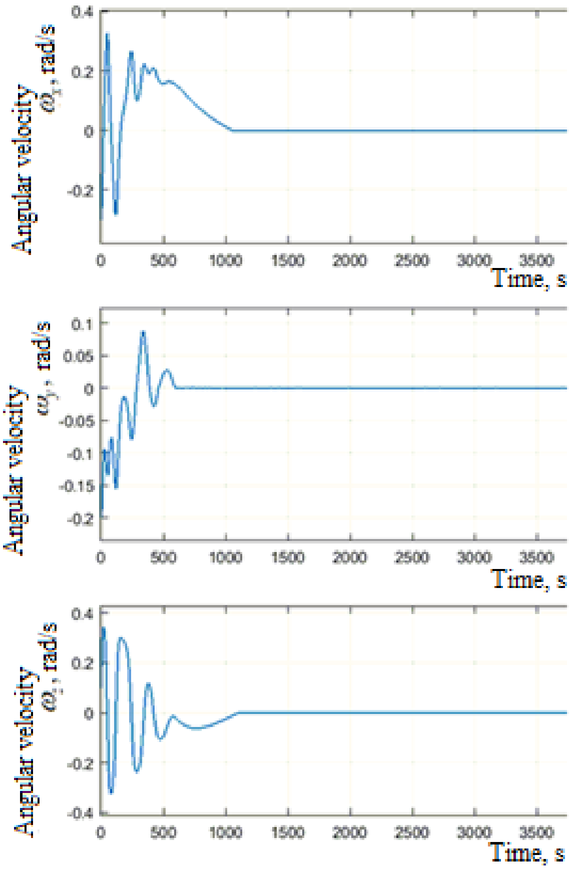

Fig. 4. Calming the satellite with magnetic coils under initial conditions ω_{x0}=-0,3 rad/s, ω_{y0}=-0,2 rad/s, ω_{z0} =0,1 rad/s

$$X=\left(\Delta\gamma,\Delta\psi,\Delta\vartheta,\Delta\omega_x,\Delta\omega_y,\Delta\omega_z\right)^T;\quad U=\left(\Delta M_x,\Delta M_y,\Delta M_z\right)^T.$$

The solution of the Riccati equation from (6) determines the optimal matrix of the controller coefficients

$$K=\begin{pmatrix} 0{,}018 & -0{,}0001 & -0{,}027 & 0{,}11 & -0{,}07 & -0{,}068 \\ -0{,}016 & 5{,}8\cdot 10^{-5} & 0{,}018 & -0{,}067 & 0{,}068 & 0{,}019 \\ 0{,}0002 & 0{,}00016 & 0{,}017 & -0{,}068 & 0{,}02 & 0{,}12 \end{pmatrix} \qquad (14)$$

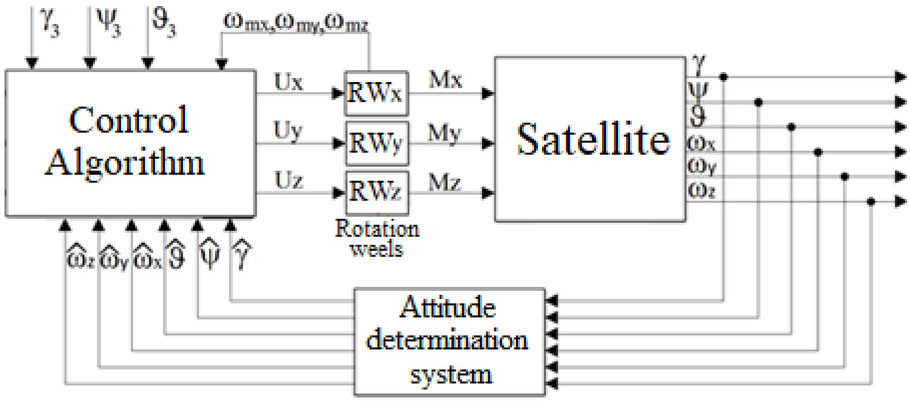

Fig. 5. Functional diagram of the satellite angular position control system

We will obtain the algorithm for controlling the rotational movement of the satellite at the stage of stabilization of the angular position, taking into account (14) and Fig. 5.

$$
\begin{aligned}
U_x &= \frac{1}{k_x}(0{,}018(\gamma-\gamma_3)-0{,}0001(\psi-\psi_3)\ -0{,}027(\vartheta-\vartheta_3)+\\
&\quad +0{,}11\omega_x-0{,}07\omega_y-0{,}068\omega_z-I_m\omega_{my}\omega_z+I_m\omega_{mz}\omega_y);\\
U_y &= \frac{1}{k_y}(\text{-}0{,}016(\gamma-\gamma_3)+5{,}8\cdot10^{-5}(\psi-\psi_3)\ +0{,}018(\vartheta-\vartheta_3)\ -\\
&\quad -0{,}067\omega_x+0{,}068\omega_y+0{,}019\omega_z-I_m\omega_{mz}\omega_x+I_m\omega_{mx}\omega_z);\\
U_z &= \frac{1}{k_y}(0{,}0002(\gamma-\gamma_3)+16\cdot10^{-5}(\psi-\psi_3)+0{,}017(\vartheta-\vartheta_3)\ -\\
&\quad -0{,}068\omega_x+0{,}02\omega_y+0{,}12\omega_z-I_m\omega_{mx}\omega_y+I_m\omega_{my}\omega_x),
\end{aligned}
\tag{15}
$$

In order to turn the satellite from an arbitrary position to a given one, in some cases the orientation angles must be limited. The results of simulation modelling of the operation of the orientation control system for various variants of the initial conditions are shown in Fig. 6, Fig. 7.

The results of simulation of microsatellite reversal with parameters (7) show the possibility of quickly reaching a given angular position from an arbitrary initial without the need to limit the control signals of the rotation wheels. The turnaround time in all cases did not exceed 110 s (Fig. 6).

Control system settings. In order to make the controller widely available, an algorithm for its adjustment is proposed, according to which the user: chooses the type of control body that will be used; indicates the presence of a block of angular velocity sensors; introduces the maximum torques of the control bodies and moments of inertia of the rotation wheels; introduces the satellite inertia tensor. All calculations and settings are performed automatically by the controller software.

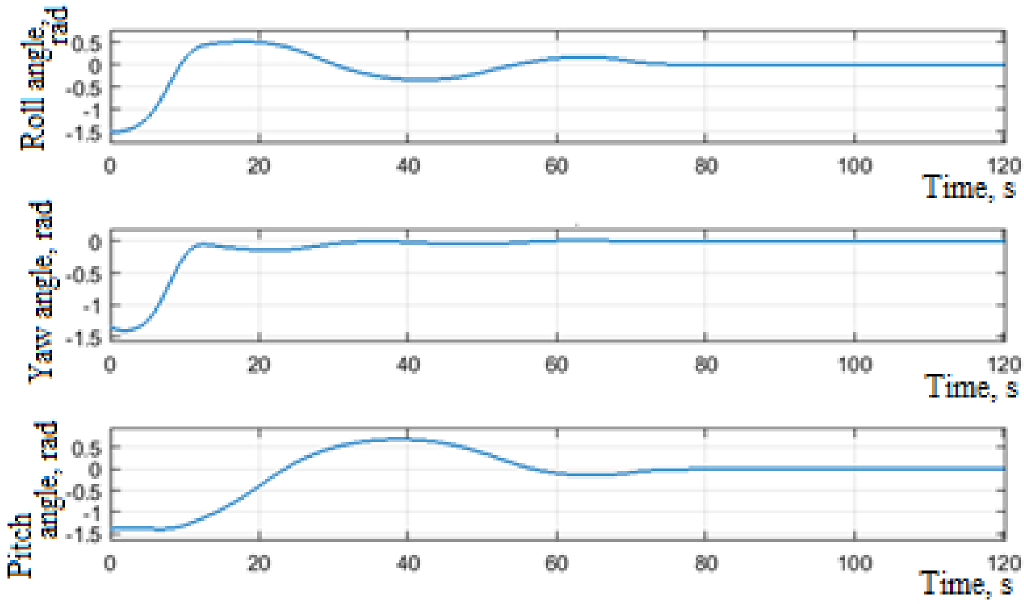

Fig. 6. Turning the microsatellite from an arbitrary angular position to a given one

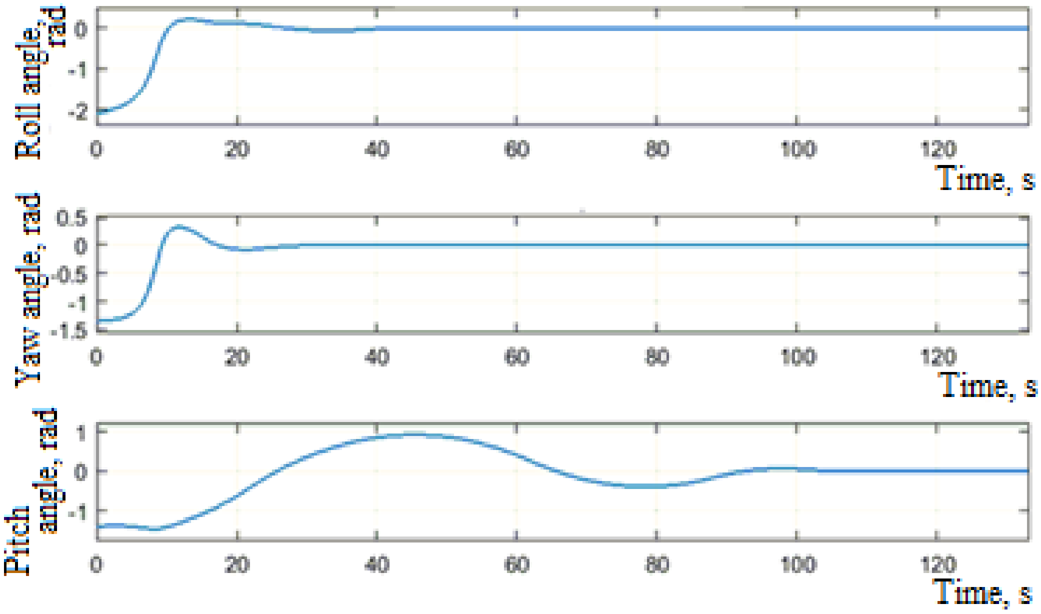

Fig. 7. Turning the microsatellite to large angles

The low sensitivity of the adjusted control laws to changes in the satellite characteristics ensures stable control without significant quality degradation when the satellite moments of inertia are set inaccurately within 50 % of the nominal values.

Conclusions

The developed mathematical model, algorithms of the control system and settings depending on the parameters of the satellite ensure its stable movement during stabilization, turns and stabilization of the angular position. Algorithms can be used in a universal flight controller for a wide class of micro- and nanosatellites. They provide stabilization of the satellite with an initial angular velocity of no more than 0,3 deg/s in any direction, and the stabilization time using flywheel engines for the satellites in question does not exceed 14 minutes. When using magnetic coils in such cases, the calming time was up to 31 minutes. The time for satellites to move from an arbitrary initial angular position to a given one does not exceed 5,5 minutes.

The efficiency and universality of the algorithms are confirmed by simulation modelling of nonlinear models of three satellites, whose diagonal moments of inertia differ from each other by 11-60 times. The structure of the algorithms ensures their simple configuration for a specific satellite.

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