ON THE CREATİON OF A SPACE SYSTEM FOR SCİENTİFİC PURPOSES KAZSCİSAT – 1

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The article is devoted to the creation of a space system for scientific and technological purposes including two independent space systems: KazSciSat for scientific purposes and KazSTSat for technological purposes. The space system for scientific purposes included the nanosatellite KazSciSat and its ground segment consisting of a ground control complex and a ground target complex of the nanosatellite. The nanosatellite was developed on the basis of CubeSat 3U technology and is intended for operation in a sun-synchronous orbit with an altitude of ~600 km. The nanosatellite included a payload, an onboard control system, an attitude determination and control system, a communication system, a power supply system, a structure and mechanisms. The results of the development of the nanosatellite attitude determination and control system are presented in detail.

Key Words: Nanosatellite, Orientation, Control, Design, Assembly, Testing, Launch

1. History of creation

In the period 2007-2014 the National Space Agency of the Republic of Kazakhstan (Kazkosmos) within a strategic partnership with the European company Airbus D&S has come a long way to create a modern space infrastructure. The National space research center was organized which includes the Institute of space technique and technology created to develop instruments, devices and subsystems of satellites and their ground complexes. The special design and technology bureau of space technology was created with pilot production for the design of satellites and the manufacture of their components. The construction of an assembly and test complex for spacecraft has begun. Two space communication systems including satellites KazSat-1 and KazSat-2 and their ground complexes, two space remote sensing systems, including satellites KazEOSat-1 and KazEOSat-2 and their ground complexes, as well as the system of high-precision satellite navigation of the Republic of Kazakhstan were created and put into operation.

In the process of creation of space communication and remote sensing systems at European enterprises the young engineers completed a three-year practical training working alongside their European colleagues who created these space systems. This joint work allowed Kazakhstani specialists to gain vast practical experience, knowledge, skills and abilities in the development, design, manufacture of components, assembly and testing of space systems in such a short period of time. The efficiency of the internship of Kazakh scientists and engineers is evidenced by the results of creation of a space system for scientific and technological purposes including two independent space systems - KazSciSat for scientific purposes and KazSTSat for technological purposes during this internship.

Scientists and specialists from two laboratories of the Institute of space technique and technology (Space systems development laboratory and the scientific space systems laboratory) developed the KazSciSat scientific nanosatellite and its ground a segment consisting of a ground control complex and a ground target complex of a nanosatellite within the framework of the development work on the creation of the KazSciSat scientific space system commissioned by Kazkosmos.

The KazSciSat nanosatellite was developed by Kazakh scientists and engineers on the basis of CubeSat 3U technology and is intended for operation in a sun-synchronous orbit with an altitude of ~600 km. Monitoring the Earth's magnetic field in order to study physical processes in near space and their relationship with terrestrial processes was the main mission of the nanosatellite. The tasks for the scientific nanosatellite were set by the scientific organizations of Kazakhstan with the participation of foreign partners from Russia, Ukraine, France (CNRS).

The KazSTSat microsatellite was developed with the participation of specialists from the British company SSTL which is a subsidiary of Airbus D&S. In the process of the development of the KazSTSat microsatellite five new technologies were developed: a new platform, an electron-optical telescope with a halved size and weight at a given spatial resolution of images, an onboard control complex based on nano-level electronic components, a ground-based complex based on SDR technologies and a system design technology for microsatellites based on based on the new platform.

2. Nanosatellite architecture

The KazSciSat nanosatellite included the following subsystems:

- payload representing a 3-component fluxgate magnetometer for measuring the components of the Earth's magnetic field vector and a module for collecting and processing scientific information;
- on-board control complex designed to collect and process data from service systems, distribute control commands between them and maintain on-board time;
- attitude determination and control system designed to determine the angular position of the nanosatellite, control its orientation, as well as process data from inertial and sun sensors;
- communication system designed for radio communication with the Earth - receiving command information and resetting service telemetry and target scientific information;
- power supply system designed to provide power to service systems and payloads;
- structure and mechanisms. The structure is intended for mechanical connection of the onboard equipment into a single whole. The movable mechanisms included in its composition ensure the deployment of the deployed elements.

3. Stages of work on creating a nanosatellite

In the course of work on the KazSciSat nanosatellite the following main stages of work were performed:

- designing a space system for scientific purposes;
- development of software for the onboard control complex of the nanosatellite;
- development of software for the ground control complex, including systems for transmitting and receiving control commands and transmitting and receiving telemetry;
- development of software for the ground target complex, including systems for planning and scientific processing of useful data, as well as a web portal for providing processed scientific information to end users;
- autonomous testing of subsystems and assembly of the KazSciSat nanosatellite and its ground segment;
- functional ground tests of the KazSciSat nanosatellite for the impact of outer space factors in accordance with the developed plans and test methods;
- integration of the KazSciSat spacecraft for launch on the Falcon-9 launch vehicle.

4. Nanosatellite launch and operation

The launch of the KazSciSat nanosatellite was successfully launched on December 4, 2018 at 00:32 (GMT+6) on the Falcon-9 launch vehicle. Then at 03:54 (GMT+6) the nanosatellite successfully separated from the launch vehicle UFF platform. 30 minutes after separation, the nanosatellite's VHF antenna system was deployed, and then, 10 minutes later, the payload boom was deployed. Since January 1, 2019, the regular operation of KazSciSat in orbit has been carried out. More than 1,000 communication sessions with a nanosatellite were made and more than 4,000 measurement points were obtained for the parameters of the state of service systems and the constant magnetic field of the Earth in the visibility zone of the ground control complex over the region. With a warranty period of 3 months, the nanosatellite worked successfully for 30 months.

5. Development of a nanosatellite attitude control system

5.1 Representation of Dynamic Equations in Linear Form

The dynamics of the satellite attitude determination and control system (ADCS) is described by nonlinear differential equations. In this regard their linearized equations of dynamics are used in engineering practice[1),2)]. An obvious disadvantage of using linearized equations of motion is that they describe the ADCS dynamics approximately. In the work of the authors[3)] the possibility of representing the initial nonlinear equations of the dynamics of the ADCS in the form of a linear system of differential equations with time-varying parameters is shown. The use of a linear model of the ADCS dynamics makes it possible to abandon the use of its approximate linearized model.

The initial nonlinear equations of motion of the nanosatellite have the form:

$$J\dot{\vec{\omega}} + \vec{\omega}\times(J\vec{\omega} + J_{M}\overrightarrow{\omega_{M}}) = \vec{\mathrm{M}}\,, \quad (1)$$

where $J = \{J_1, J_2, J_3\}$ is the diagonal (3x3) matrix of the nanosatellite inertia tensor ; $\vec{\omega} = (\omega_1, \omega_2, \omega_3)^T$ is the vector of the absolute angular velocity of the satellite in projections on the axes of the associated coordinate system; $J_M = \{J_{M1}, J_{M2}, J_{M3}\}$ is the diagonal (3x3) reaction wheel inertia tensor matrix; $\overrightarrow{\omega_M} = (\omega_{M1}, \omega_{M2}, \omega_{M3})^T$ is the vector of angular velocities of reaction wheels; $\vec{\mathrm{M}} = (M_1, \mathrm{M}_2, M_3)^T$ is the control moments of reaction wheels.

We accept the feedback control law as a linear function:

$$M_i = -h_i\omega_i - \alpha_i\varphi_i, (i = \overline{1,3})\,, \quad (2)$$

where; $\dot{\varphi}_i = \omega_i$, h_i, α_i are unknown arbitrary parameters of the reaction wheel moment control law.

The representation of equations (1) - (2) in a linear form has the form:

$$\dot{X} = \left[A + C^0 + B(t)\right]X \quad (3)$$

where $X = (x_1, ..., x_6)^T \equiv (\varphi_1, \omega_1, \varphi_2, \omega_2, \varphi_3, \omega_3)^T$,

$A = A_{6x6}$ - quasi -diagonal matrix with constant elements,

$A + C^0 + B(t)$ is a matrix with constant and variable elements;

$$C_i = J_i\omega_i(0) + J_{Mi}\omega_{Mi}(0), \quad (i = \overline{1,3}) \quad (4)$$

are the components of the angular momentum vector of the nanosatellite in the body coordinate system at the initial moment of time t=0.

In this regard:

$$C_i(t) = C_i^0 + B_i(t), \quad (i = \overline{1,3}),\ t \in [0, \infty) \quad (5)$$

5.2. Conditions of ADCS stability

The authors of[3] proved that for the asymptotic stability of the nonlinear system (1)-(2) it is necessary and sufficient that the homogeneous linear system of differential equations with constant coefficients be asymptotically stable:

$$\dot{X} = \left[A + C^0\right]X \tag{6}$$

It follows from the form of the system matrix (6) that its elements are determined by the parameters control law (2) and the initial angular momentum of the nanosatellite. This makes it possible to construct the stability regions of the ADCS in the region of the parameters of the control law depending on the initial angular momentum of the nanosatellite. In a particular case, when the initial angular momentum of the nanosatellite is equal to zero, system (6) takes the form:

$$\dot{X} = AX \tag{7}$$

The stability of the ADCS is determined only by the parameters of the control law h_i, α_i. The authors of [3] also proved that if the parameters of the control law are determined from the condition of the maximum degree of stability of system (7), then system (6) is globally asymptotically stable.

The characteristic polynomial of system (7) can be represented as:

$$\det(\mathrm{A} - \lambda\mathrm{E}) = \prod_{i=1}^{3}\left(\lambda^2 + \frac{h_i}{J_i}\lambda + \frac{\alpha_i}{J_i}\right) = \sum_{i=0}^{6} a_i \lambda_i \tag{8}$$

where

$$a_0 = \frac{\alpha_1\alpha_2\alpha_3}{J_1J_2J_3}; \quad a_1 = \frac{\alpha_1\alpha_2 h_3}{J_1J_2J_3} + \frac{h_1\alpha_2\alpha_3}{J_1J_2J_3} + \frac{\alpha_1 h_2\alpha_3}{J_1J_2J_3};$$

$$a_2 = \frac{\alpha_1\alpha_2}{J_1J_2} + \frac{\alpha_1\alpha_3}{J_1J_3} + \frac{\alpha_2\alpha_3}{J_2J_3} + \frac{h_1\alpha_2 h_3}{J_1J_2J_3} + \frac{\alpha_1 h_2 h_3}{J_1J_2J_3} + \frac{h_1 h_2\alpha_3}{J_1J_2J_3};$$

$$a_3 = \frac{h_1}{J_1}\left(\frac{\alpha_2}{J_2} + \frac{\alpha_3}{J_3}\right) + \frac{h_2}{J_2}\left(\frac{\alpha_1}{J_1} + \frac{\alpha_3}{J_3}\right) + \frac{h_3}{J_3}\left(\frac{\alpha_1}{J_1} + \frac{\alpha_2}{J_2}\right) + \frac{h_1h_2h_3}{J_1J_2J_3};$$

$$a_4 = \frac{h_1h_2}{J_1J_2} + \frac{h_1h_3}{J_1J_3} + \frac{h_2h_3}{J_2J_3} + \frac{\alpha_1}{J_1} + \frac{\alpha_2}{J_2} + \frac{\alpha_3}{J_3};$$

$$a_5 = \frac{h_1}{J_1} + \frac{h_2}{J_2} + \frac{h_3}{J_3}; \; a_6 = 1.$$

The characteristic polynomial of system (6) has the form:

$$\det\left[\left(A + C^0\right) - \lambda E\right] = \sum_{i=0}^{6} b_i \lambda^i, \tag{9}$$

where $b_0 = a_0$; $b_1 = a_1$;

$$b_2 = a_2 + \frac{1}{J_1J_2J_3}\left(C_1^2\alpha_1 + C_2^2\alpha_2 + C_3^2\alpha_3\right);$$

$$b_3 = a_3 + \frac{1}{J_1J_2J_3}\left(C_1^2 h_1 + C_2^2 h_2 + C_3^2 h_3\right)$$

$$b_4 = a_4 + \frac{C_1^2}{J_2J_3} + \frac{C_2^2}{J_1J_3} + \frac{C_3^2}{J_1J_3}; \quad b_5 = a_5; \quad b_6 = a_6.$$

5.3. Synthesis of control law parameters

The decomposability of the characteristic polynomial (8) of the truncated system (7) into three similar factors means that the rotations of the satellite around the three coordinate axes are not only independent of each other, but are also described by identical systems of two first-order differential equations. To ensure maximum speed, we will set the roots of the characteristic equation of system (7) real and multiple, i.e. for satellite rotation around each of the three coordinate axes, we have:

$$\lambda^2 + 2\Omega_0\lambda + \Omega_0^2 = 0 \tag{10}$$

where Ω_0 is the scale of the transition from the normalized time of the transient process to the real time of the transient process.

The normalized time of the transient process will be determined by its graphical plotting at $\lambda_i = -1 \; (i = 1..6)$.

Unknown parameters of the control law h_i, α_i are determined from the solution of algebraic equations with respect to the coefficients of the characteristic polynomial (8).

5.4. Numerical results of calculating the parameters of the control law

Moments of inertia of the nanosatellite *J_1=0.0472 kgm²*, *J_2=0.0490 kgm²*, *J_3=0.0133 kgm²* moments of inertia of flywheels: *J_{M1}=J_{M2}=J_{M3}=0.0000045 kgm²*, maximum angular velocity of reaction wheels *753 rad/sec*, maximum moment of reaction wheels is *2 mNm*. Two versions of the initial conditions for the angular velocities of the nanosatellite are considered *0 rad/sec and 0.125 rad/sec*, the initial angular velocities of the reaction wheels are taken equal to zero, and the initial angular positions of the satellite are taken equal to 45 degrees. The results of calculating the transient processes are shown in Figures 1 and 2.

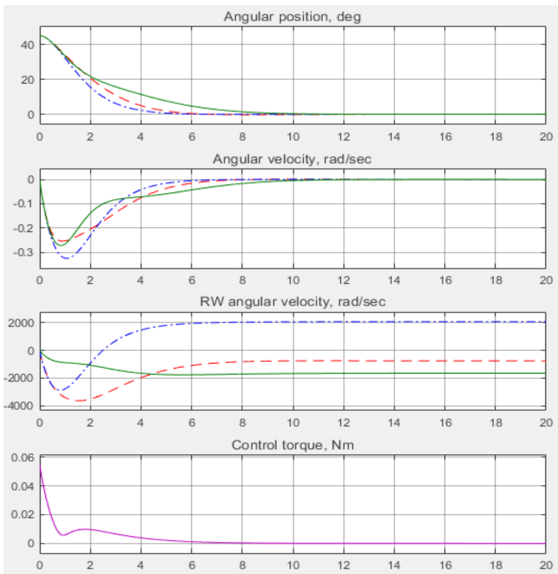

Fig. 1. The results of the calculation when Ω_0=1 and angular velocities of the nanosatellite are *0 rad/sec.*

It follows from Figure 1 that the normalized time of the transient process is *10 s*. The highest velocity of the reaction wheels is *3750 rad/sec* which is 5 times higher than the maximum allowable velocity of the reaction wheels. The maximum control torque is *50 Nm* which is 25 times higher than the nominal control torque of the reaction wheels. Consequently reaction wheels with specified characteristics cannot provide a transient process *10 s*, it is necessary to increase the specified transient process time by *5* times.

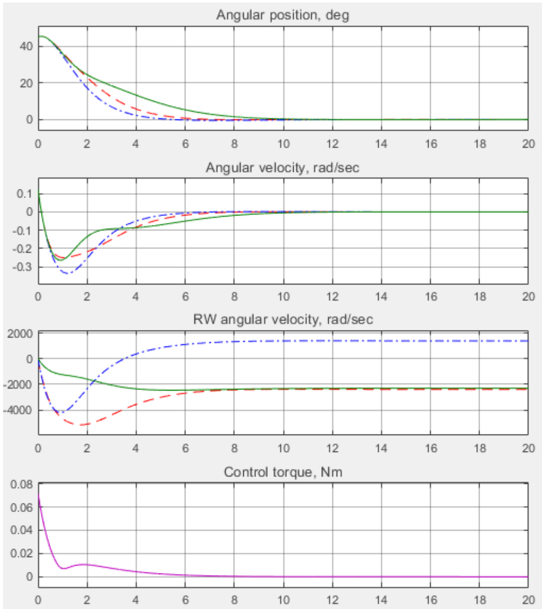

Fig. 2. The results of the calculation when Ω_0=1 and angular velocities of the nanosatellite are *0.125 rad/sec.*

The results of calculation of transient processes at Ω=0.2 which corresponds to a 5x time of the transient process increase are shown in Figure 3, 4.

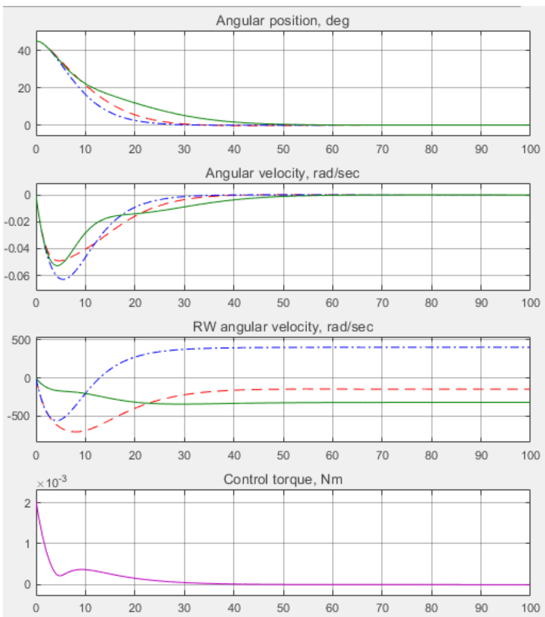

Fig. 3. The results of the calculation when Ω_0=0.2 and angular velocities of the nanosatellite are *0 rad/sec.*

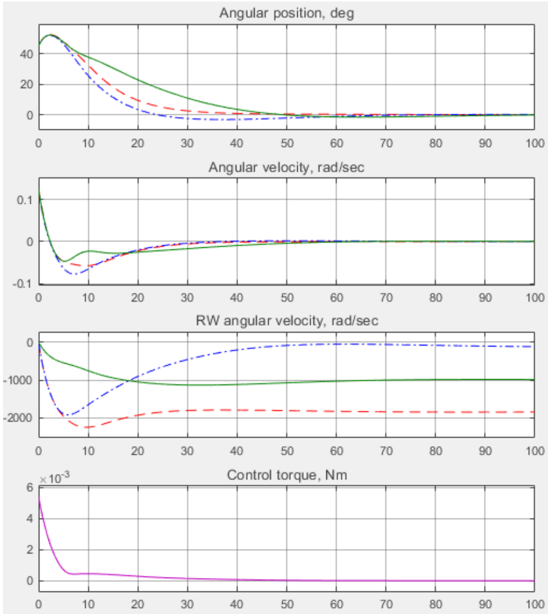

Fig. 4. The results of the calculation when Ω_0=0.2 and angular velocities of the nanosatellite are *0.125 rad/sec.*

From Figure 3 it follows that the velocity and moments of the reaction wheels do not exceed their maximum allowable values.

It follows from Figures 2 and 4 that the presence of a nonzero initial angular velocity of the nanosatellite leads to an increase in the maximum values of the required angular velocities and reaction wheel moments. Electromagnetic actuators are used to dampen the initial angular velocities of the nanosatellite and reaction wheels.

6. Conclusion

1. The successful operation of the scientific nanosatellite KazSciSat in orbit for 30 months with a warranty period of 3 months indicates a high level of scientific and technological base and qualifications of scientists and engineers in the space industry of Kazakhstan.
2. With a certain choice of parameters of the control law, the global asymptotic stability of the satellite ADCS can be ensured, i.e. stability under any initial conditions with respect to the angular velocities of the satellite.
3. A method for synthesizing the parameters of the control law is proposed which provides the required indicators of the quality of transient processes of satellite orientation by choosing a given distribution of the roots of the characteristic equation of a linear system with constant parameters and the scale of transition from normalized time to real time.

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