DEVELOPMENT OF ATTITUDE DETERMINATION AND CONTROL SYSTEM AND ITS COMPONENTS FOR SCIENTIFIC AND TECHNOLOGICAL NANOSATELLITE

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Introduction

Generally first microsatellites were amateur satellites, for example satellites “Iskra” developed in the 1970th. At the end of the 1970th it was set up the SSTL Company (Great Britain), which began development of small satellites «UoSat-1», «UoSat-2» for development of some technologies in space [1]. Over time the technology of microsatellite development became popular worldwide. Many of the last projects on microsatellite development can be listed: European projects (LAPAN-TUBSAT, Berlin technical university) [2], projects in Asia (X-Sat, Nanyang Technological University) [3], projects in Japan(Micro-LabSat 1, JAXA) [4] and USA (ERS microsatellite «SkySat-1» with equipment of resolution of 1m) [5]. All these satellites are united by the fact that they are used for carrying out scientific and technological experiments in space and possess price appeal, which is supplemented with rather short terms for their development. Thus, microsatellites represent quite convenient service for development of new technologies and carrying out researches under the condition of small budget that allows developing countries to move to a level of intensive development of space engineering.

Experimental model of attitude determination and control system (ADCS) of microsatellite which is being developed in the Institute of space technique and technologies (Almaty, Kazakhstan) is considered in this paper. For testing the developed ADCS in space it is considered the version of its integration in the service platform CubeSat 3U that was tested in space before and have a good reputation in the field of space technique.

1 Structure and main requirements to ADCS of microsatellite

ADCS of the microsatellite, as well as any satellite, is one of the main subsystems influencing the functionality of the microsatellite and providing the implementation of its mission. Actually each satellite is unique according to its mission and structure, parameters of subsystems and its characteristics, etc. But despite of this, it is possible to note that ADCS of satellite generally consists of following functionally different groups of devices: sensors, which allow to define attitude of satellite, actuators, which allow to control the attitude of the satellite and control unit, providing a control program of the satellite. This composition of ADCS components must provide the implementation of various attitude control modes of satellite due to its mission.

The developed ADCS is planned to use on the microsatellites with the mission of technology demonstration, assuming the development of main control modes of the ADCS. In this connection, the following main modes for the experimental model of the ADCS were defined: detumbling of the microsatellite and orientation relative to the force lines of terrestrial magnetic field, Sun tracking, nadir pointing, orientation along the required direction.

As is known detumbling and orientation of the satellite along the lines of terrestrial magnetic field can be provided by means of B-dot algorithm on the basis of magnetic sensors and magnetorquers. To provide the Sun tracking it is necessary to determine the attitude of microsatellite relative to the Sun by means of sun sensors and implement the orientation by means of the reaction wheels. To provide nadir pointing it is necessary to determine the current attitude of the microsatellite by means of magnetic and sun sensors and implement maneuver of orientation by means of the reaction wheels. Magnetorquers can be used for desaturation of reaction wheels in all corresponding modes.

Thus, on the basis of requirements to ADCS of microsatellite its structure was defined: magnetic sensors defining the components of a magnetic inductance vector of the Earth, sun sensors intended for determination the satellite attitude relative to the Sun, gyro sensors determining the angular velocity of the microsatellite, navigation equipment for determination the position and velocity of the microsatellite, reaction wheels and magnetorquers for implementation maneuvers of the orientation.

At present design and development of experimental model of some satellite's ADCS components is carried out: magnetic sensor, sun sensor, reaction wheel.

2 Magnetic sensor experimental model

Magnetic sensors give as output parameters the components of the magnetic inductance vector of the Earth. The experimental model of magnetic sensor was developed on the basis of commercially available magneto-inductive sensor MICROMAG 3-AXIS, representing relaxation generator on the basis of three inductance coils. In this case components of the magnetic inductance vector can be defined on the basis of frequencies of the relaxation generator:

$$\mathrm{B_i} = \frac{P_i dt}{k_i S_i w_i}, \; i = 1,2,3 , \qquad (1)$$

where $\mathrm{B_i}$ are the components of the magnetic inductance vector , P_i is the quantity of cycles of the generator during the measurement of a magnetic field, k_i is the coefficient of the relaxation generator, S_i is the sectional area of inductance coils, w_i is the number of turns of the inductance coils.

To test the experimental model of magnetic sensor given in fig.1 software was developed by means of which processing and visualization of data, received from magnetic sensor through microcontroller and wireless transceiver, is carried out.

Fig. 1 - Magnetic sensor experimental model

3 Sun sensor experimental model

Sun sensor gives as output parameters the angular coordinates of the Sun. Developed experimental model of sun sensor represents a slit sun sensor. General scheme of this sun sensor is given in the fig.2.

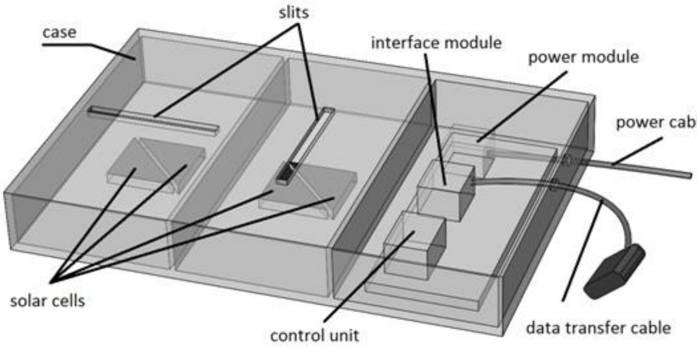

Fig. 2 - Scheme of sun sensor experimental model

Module of sensors on the basis of photovoltaic cells (solar cells) is placed inside the case of the sun sensor. The light falling at a certain angle on the sensor elements stimulates the change of their basic parameters, which are processed in the control unit and determination of the angular position of the sun is carried out on the base of this analysis.

The principle of work of sun sensor experimental model is based on the dependence of solar cell power on the level of its illumination, which can be written as the ratio:

$$P_{sc} = P_{sun} S_{sc} \eta_{sc} \cos(\alpha_{sun}), \tag{2}$$

where P_{sun} is the power of light, S_{sc} is the area of solar cell, η_{sc} is the efficiency of solar cell, α_{sun} is the incidence angle on the solar cell.

Each pair of combined solar cells (fig. 2) placed in the case of the sun sensor is used to determine the angular position of the sun according to one of the axes of the sensor. When the Sun position changes according to the considered axis the band of light passing through the corresponding slit, slides along a pair of solar cells in one direction or another. As a result of its displacement the area of illuminations of solar cells varies due to their triangular shape. Illumination of solar cells induces the production of electric power that can be measured and converted into the desired form suitable for determining the angular position of the sun relative to the considered axis.

Thus, the pair of solar cells generates two signals S_1 and S_2 ,wherein:

$$\begin{cases} S_1 = S_2,\ npu\ \mathrm{L_{sun}} = 0°; \\ \mathrm{S_1} = \mathrm{S_{max}}, S_2 = S_{\min},\ npu\ \mathrm{L_{sun}} = L_{\max}; \\ \mathrm{S_2} = \mathrm{S_{min}}, S_2 = S_{\max},\ npu\ \mathrm{L_{sun}} = L_{\min}, \end{cases} \tag{3}$$

where S_1 is the signal from 1-st solar cell, S_2 is the signal from 2-nd solar cell, $\mathrm{S}_{\max}$ is the maximum signal of solar cell, $\mathrm{L_{sun}}$ is the angular position of the Sun relative to the sensing axis in the reference frame of sun sensor, $L_{\min}$ is the minimum value of the angular position of the Sun relative to the sensing axis in the reference frame of sun sensor, $L_{\max}$ is the maximum value of the angular position of the Sun relative to the sensing axis in the reference frame of sun sensor.

Determination of angular position of the Sun relative to the other axis of the sun sensor is also carried out on the basis of formula (3) using the signals received from the second pair of solar cells.

4 Reaction wheel experimental model

Reaction wheels are one of the main actuators of ADCS, as they allow orientating the spacecraft in space with rather high precision.

Developed experimental model of reaction wheel of the microsatellite consists of reaction wheel and electric motor. To control the electric motor the feedback control law is used, which has the form:

$$\mathrm{U} = \mathrm{K}_0 \Delta\varphi + K_1 \Delta\dot{\varphi} + K_2 \Delta\ddot{\varphi}\,, \tag{4}$$

where K_0, K_1, K_2 are the feedback gains, $\Delta\varphi = \varphi - \varphi_1$ is the misalignment of angular position of the microsatellite from the required angular position φ_1.

To test the work of the reaction wheel laboratory bench was manufactured, which is shown in fig.3. Laboratory bench consists of the following main parts: moving platform, reaction wheel as the actuator, gyro sensor and control unit (personal computer). In addition wireless transceiver is mounted on a platform for information transfer in the control unit. This laboratory bench allows to control the platform angular position by means of the applied software of the control unit.

Fig. 3 - Laboratory bench for testing of reaction wheel

Unknown feedback gains in the equation (4) are determined by means of the platform stability and its dynamics analysis.

Let’s consider dynamics of a platform. Under the condition that external moments are small in comparison with control moment of the reaction wheel angular momentum conservation law has the form [6]:

$$J_s \omega_\mathrm{s} + J_\mathrm{a} \omega_a = C = c\mathrm{onst}\,, \tag{5}$$

where $\mathrm{J_s}$ is the moment of inertia of the platform, ω_s is the angular velocity of the platform, $\mathrm{J_a}$ is the moment of inertia of the reaction wheel, ω_a is the angular velocity of the reaction wheel.

Assuming that by the moment of time t_0 reaction wheel is already rotated, but platform does not rotate and holds particular angular position, for C we have:

$$C = \mathrm{J_a} \omega_a^0\,, \tag{6}$$

where ω_a^0 is the angular velocity of the reaction wheel at moment t_0.

Then dependence of platform angular velocity on the reaction wheel angular velocity has the form:

$$\omega_s = -\frac{\mathrm{J_a}}{\mathrm{J_s}}(\omega_a - \omega_\mathrm{a}^0)\,. \tag{7}$$

Let’s use the equations of motion of electric motor and reaction wheel in the form [7]:

$$\begin{cases} \mathrm{L}\dfrac{\mathrm{dI}}{\mathrm{dt}} = -IR - \dfrac{c\Phi}{K_{\mathrm{p}}}\omega_a + U, \\ J_a^1\dfrac{d\omega_a}{\mathrm{dt}} = \dfrac{c\Phi}{K_{\mathrm{p}}}I, \end{cases} \tag{8}$$

where I,L,R,U are current, inductance, resistance and voltage of motor armature respectively, c is the electromagnetic constant, Φ is the magnetic flux, passing through armature winding, k_p is the ratio of reduction, J_a^1 is the inertia moment of reaction wheel reduced to the motor shaft.

And then using (7) we obtain one differential equation relative the platform describing the dynamics of system:

$$\ddot{\omega}_{\mathrm{s}} + \frac{R}{L}\dot{\omega}_{\mathrm{s}} + \frac{c\Phi}{J_a^1 L}\omega_{\mathrm{s}} = -\frac{c\Phi}{\mathrm{J}_{\mathrm{s}} k_p}\Delta U \ . \tag{9}$$

where U is the control law in the form (4).

5 Versions of testing the ADCS experimental model

For testing, working out and obtaining a flight history of ADCS it is necessary to carry out its integration into the service platform of the satellite containing all other subsystems, already having flight history, and further launch of this satellite for testing the operation of developed components in the conditions of space. In this regard it is considered the version of development the microsatellite on the basis of the CubeSat 3U platform for the purpose of ADCS working-out. This platform have flight history and good reputation in the field of space technique.

Microsatellites on the basis of the CubeSat 3U platform are developed according to the standard created under the direction of professor Bob Twiggs (aeronautics and astronautics faculty, Stanford) [8]. They have the weight no more than four kilograms and the sizes of 10x10x30 cm. The main advantage is that their design allows using all range of ADCS devices for satellites, both self-developed and COTS-components. As examples we can consider:

- microsatellite CanX-2, developed at Toronto University (Canada) [9] and having sun sensors and magnetometers as a part of ADCS and reaction wheel and engines on cold gas as a part of payload for technology demonstration;
- microsatellite Delfi-C3, developed at Delft Technological University(Denmark) and having on board sun sensors, permanent magnets and magnetic hysteresis rod as a part of ADCS and sun sensor as a part of payload for technology demonstration [9].

It is necessary to note also that fact that design, development, assembly and tests of microsatellites on the basis of the CubeSat 3U platform allows to work out not only mathematical support and software of ADCS of microsatellite, developed by domestic experts, but also to get development and operation skills.

Conclusion

Experimental model of the microsatellite ADCS is considered in this paper. At present experimental models of some ADCS components – three-axis magnetic sensor, two-axis slit sun sensor and reaction wheel are developed. For testing the developed ADCS and its software in space it is considered the version of its integration in the microsatellite that is developed on the basis of CubeSat 3U platform. Results of carried out tests will be used as the basis for development of ADCS prototype, which is planned to use on-board the Kazakhstan’s microsatellites.

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