PASSIVE GRAVITATIONAL AERODYNAMIC STABILIZATION OF NANOSATELLITE

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Uncontrolled attitude motion of a gravitationally-aerodynamically stabilized LEO nanosatellite is considered. The analytical cumulative distribution functions of the maximum angle of attack for Rayleigh and uniform distributions of the nanosatellite's initial transverse angular velocity value were obtained. The formulas for choosing the design parameters of the gravitationally-aerodynamically stabilized CubeSat standard nanosatellite which has the deviation value of the longitudinal axis from the local vertical less than acceptable value with a given probability for fixing altitude and known initial angular velocity errors were acquired. The nomograms, which allow simply and clearly to choose the main design parameters of the gravitationally-aerodynamically stabilized CubeSat standard nanosatellite were constructed.

Keywords: nanosatellite, gravitational aerodynamic stabilization.

I. INTRODUCTION

The conducting of majority space research missions requires a well-defined orientation of the attitude position of the nanosatellite. Passive or combined (passive in combination with active) stabilization systems are often used to ensure the specified orientation of nanosatellite. They do not require or require small expenditure of the working body and/or the energy stored on board.

Obviously, the design conditions of attitude motion of a nanosatellite with passive stabilization system can be ensured only at the design stage by choosing its design and ballistic parameters, as well as specifying limitation on the angular velocity generated by the separation system, and for combined stabilization system at the end of operation of the preliminary damping system.

The most nanosatellites are launched into low circular orbits. That’s why gravitational and aerodynamic moments dominate at such orbits and it is advisable to use both of the moments for stabilization of the attitude position. It should be noted that the value of the angular acceleration of the nanosatellite caused by aerodynamic moment more on one or two orders of magnitude higher than of the satellites with large size and mass (for the same value of the relative statical stability factor). This conclusion give opportunity to extend the range of altitudes at which the aerodynamic moment on the nanosatellite is significant and can be used along with the gravitational moment for attitude stabilization.

This work is a continuation of the authors’ research to develop methods of passive stabilization of nanosatellites. The problem of ensuring the passive stabilization of the nanosatellite is being solved in a probabilistic statement with respect to the angular motion of the nanosatellite after separation from the carrier, or at the end of the operation of preliminary damping system (unlike to the well-known works in which this problem is solved in deterministic statement, for example [1]).

In paper [2] uncontrolled attitude motion of carrier rocket "Soyuz" after payload separation was investigated. In paper [3] the stochastic models of the initial conditions of angular motion of the nanosatellite launched as piggyback payload from the orbital stage of carrier rocket "Soyuz" were obtained. In paper [4] the uncontrolled angular motion of a nanosatellite around its center of mass after separation from stabilized platform was considered. The analytical probability density function and the cumulative distribution function of the maximum nanosatellite angle of attack for Rayleigh and uniform distributions laws of the initial transverse angular velocity value are obtained. In papers [5], [6] the task of ensuring the aerodynamic stabilization of a nanosatellite is considered. The formulas for choosing the design parameters of aerodynamically stabilized nanosatellite (statical stability factor, length of nanosatellite, longitudinal moment of inertia) were obtained on the basis of these analytical distribution laws of the maximum angle of attack. The calculated design parameters provide the deviation value of the longitudinal axis of a nanosatellite from velocity vector less than acceptable with a given probability at a given altitude of its separation and at the known errors of initial angular separation velocity. The Eurasian patent of single-axis aerodynamic stabilization method for CubeSat standard nanosatellite [7] was obtained according to the results of research. This method of single-axis aerodynamic stabilization was used in 2 projects of Samara National Research University. The first of them is creation of the nanosatellite SamSat-218D with passive aerodynamic stabilization system [8]. The second of them is creation of the aerodynamically stabilized nanosatellite of the SamSat-QB50 transformer [9] included in the international QB50 project.

In this paper the problem of passive three-axis stabilization of a nanosatellite is solved in a probabilistic statement with respect to the angular motion of the nanosatellite after separation from the carrier, or at the end of the operation of preliminary damping system.

It is known that the gravitational moment aspires to orient nanosatellite, so that the principal axis of the least moment of inertia (longitudinal axis) coincides with the local vertical, the principal axis of the greatest moment of inertia coincides with perpendicular to the orbit plane and the principal axis of the intermediate moment of inertia coincides with the direction of motion.

The novelty of the work is that the passive three-axis gravitational aerodynamic stabilization is carried out by certain shifting the center of mass from the center of pressure on the principal axis of the intermediate moment of inertia of nanosatellite. Herewith the design parameters (statical stability factor, moments of inertia) of gravitationally-aerodynamically stabilized nanosatellite are chose in such a way that provide deviation value of longitudinal axis of nanosatellite from the local vertical less than acceptable with a given probability at a given attitude and known initial transverse angular velocity errors from separation system, or in case of combined system of stabilization, at the end of operation of the active preliminary damping system.

II. RESEARCH OF THE ANGULAR MOTION

The following assumptions were accepted for construction of a mathematical model of angular motion. The flow about nanosatellite of the CubeSat standard is free-molecular and the gas molecules collision is perfectly inelastic. The center of mass of the nanosatellite is shifted from its geometric center on the principal axis of intermediate moment of inertia by the quantity Δz and on the longitudinal axis by the quantity Δx. The axis with maximum value of nanosatellite's moment of inertia is pointed perpendicular to the plane of the orbit. Then the angular motion in the plane of the circular orbit with respect to the trajectory reference frame by aerodynamic and gravitational moments is described by equation:

$$\begin{gathered}\ddot{\alpha}-\left(a_z(h)\cos\alpha+a_x(h)\sin\alpha\right)\cdot\\ \cdot\left(\left|\cos\alpha\right|+k\left|\sin\alpha\right|\right)-c(h)\sin 2\alpha=0\end{gathered}, \qquad (1)$$

where α is the angle of attack (the angle between the longitudinal axis and nanosatellite mass center velocity vector $\bar{V}$); $a_z(h)=\Delta\bar{z}c_0Slq(h)/J_y$ is the coefficient associated with component of the aerodynamic moment caused by the center of mass shifting on the principal axis of the intermediate moment of inertia; $\Delta\bar{z}=\Delta z/l$ is the relative statical stability factor by the axis Oz; l is the characteristic length; $a_x(h)=-\Delta\bar{x}c_0Slq(h)/J_y$ is the coefficient associated with component of the aerodynamic moment caused by the center of mass shifting on the longitudinal axis; $\Delta\bar{x}=\Delta x/l$ is the relative statical stability factor by the axis Ox; $c_0=2.2$; S is the characteristic nanosatellite square; $q(h)=V^2\rho(h)/2$ is the velocity head; h is the flight altitude; $\rho(h)$ is the atmospheric density; J_y is the value of the nanosatellite's greatest principal moment of inertia; $c(h)=3(J_z-J_x)(\omega(h))^2/(2J_y)$ is the coefficient associated with the gravitational moment; J_z is the value of the nanosatellite's intermediate principal moment of inertia; J_x is the value of the nanosatellite's least principal moment of inertia; $\omega(h)=\sqrt{\mu/(R_E+h)^3}$ is the angular orbital velocity of the nanosatellite; R_E is the radius of the spherical Earth; μ is the Earth's gravitational parameter.

Changing the altitude of the circular orbit because of atmospheric drag is very slow and when considering the angular motion of the nanosatellite on one or more turns it can be taken $h=const$. In this case, the system (1) has an integral of energy:

$$\dot{\alpha}^2/2+a_xu(\alpha)-a_zv(\alpha)+c\cos^2\alpha=E_0, \qquad (2)$$

where

$$\begin{gathered}u(\alpha)=\frac{1}{2}sign(\cos(\alpha))\cos^2\alpha+\frac{k}{2}sign(\sin(\alpha))\cdot\\ \cdot\left(\frac{\sin 2\alpha}{2}-\alpha+2\pi\cdot\left\lfloor\frac{\alpha+\pi}{2\pi}\right\rfloor\right)\end{gathered},$$

$$\begin{gathered}v(\alpha)=\frac{1}{2}sign(\cos(\alpha))\left(\frac{\sin 2\alpha}{2}+\alpha-\frac{\pi}{2}-2\pi\cdot\left\lfloor\frac{\alpha+\pi/2}{2\pi}\right\rfloor\right)+\\ +\frac{k}{2}sign(\sin(\alpha))\sin^2\alpha\end{gathered},$$

$\lfloor x\rfloor$ is equal to $floor(x)$,

$E_0=a_xu(\alpha_0)-a_zv(\alpha_0)+c\cos^2\alpha_0+\frac{\dot{\alpha}_0^2}{2}$ is determined by the initial conditions.

It was executed qualitative analysis of the angular motion about the nanosatellite mass center by using the expression for the integral of energy (2). Phase portraits of system were analyzed.

Value of the maximum angle of attack of nanosatellite with oscillations can be found from the integral of energy (2) provided that $\dot{\alpha}=0$. The value of the maximum angle of attack determined by the initial value of the angle of attack α_0, the initial value of the angular velocity $\dot{\alpha}_0$, aerodynamic and gravitational moments. Accepted, that among the quantities included in (2), the angular velocity $\dot{\alpha}_0$ has the largest range of values, scatter of the other quantities are neglected. Rayleigh and uniform distributions of value $\dot{\alpha}_0$ are considered. For example, if the module of value $\dot{\alpha}_0$ has Rayleigh distribution ($\sigma>0$ is scale parameter of the distribution), then cumulative distribution function of the maximum angle of attack is determined by equation:

$$F(\alpha_{\max}) = \\ = 1 - \exp\left(\frac{a_z\left(u(\alpha_{\max}) - u(\alpha_0)\right) - a_x\left(v(\alpha_{\max}) - v(\alpha_0)\right) - c(\cos^2\alpha_{\max} - \cos^2\alpha_0)}{\sigma^2} \right) \tag{3}$$

Fig. 1 shows the change in the cumulative distribution function of the maximum angle of attack of nanosatellite CubeSat 3U ($J_x = 0.005\,kg \cdot m^2$, $J_y = 0.025\,kg \cdot m^2$, $J_z = 0.02\ kg \cdot m^2$, $S = 0.01 m^2$, $l = 0.3 m$, $\Delta\bar{x} = 0.0033$, $\Delta\bar{z} = 0.033$) depending on the values of mean square deviations σ of the initial of the angular velocity components (initial altitude h_0 = 300 km, the initial angle of attack is α_0 =100 degree).

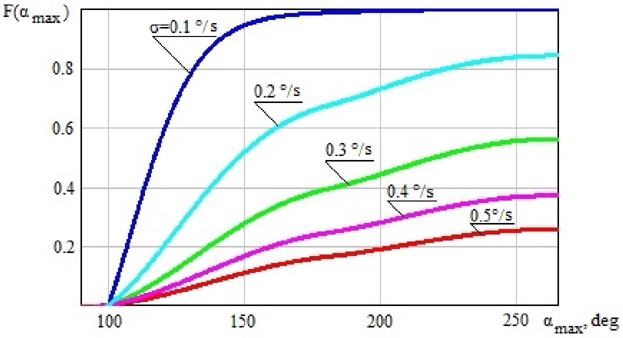

Fig. 1. Cumulative distribution function of the maximum angle of attack of nanosatellite

III. CHOOSING THE DESIGN PARAMETERS

The formulas for choosing the design parameters of the nanosatellite of the CubeSat standard (statical stability factor, moments of inertia) were obtained by giving the probability of realization p^* of allowable value of the maximum angle of attack $\alpha^*_{\max}$ and by solving the cumulative distribution functions of the maximum angle of attack about design parameters. For example, the formula for choosing the design parameter K_1 (the ratio of the statical stability factor by the axis Oz to the value of the greatest principal moment of inertia) with allowance for shifting the mass center by the longitudinal axis, when the module of value $\dot{\alpha}_0$ has Rayleigh distribution (3):

$$K_1 = \frac{\Delta z}{I_y} = \\ = -\frac{\ln(1 - p^*)\sigma^2 + c(\cos^2\alpha^*_{\max} - \cos^2\alpha_0) - a_x\left(v(\alpha^*_{\max}) - v(\alpha_0)\right)}{c_0 S_0 q (u(\alpha^*_{\max}) - u(\alpha_0))}.$$

The nomograms, which allow to choose the main design parameters of the gravitationally-aerodynamically stabilized nanosatellite of the CubeSat standard were constructed on the basis of calculations. For example, Fig. 2 shows the graphics of the dependence of required design parameter $K_1 = \Delta z / J_y$ of the nanosatellite CubeSat 3U to the orbit altitude h and on the parameter σ, for the values of the maximum deviation of the longitudinal axis of nanosatellite from the local vertical $\beta^*_{\max} = 30\ \text{deg}$ ($\alpha^*_{\max} = 120\ \text{deg}$), the probability $p^* = 0.95$ and an initial angle of attack $\alpha_0 = 95\,\text{deg}$, considering the relative statical stability factor by the axis Ox $\Delta\bar{x} = 0.0033$ and values of the principal moments of inertia are equal: $J_x = 0.005\,kg \cdot m^2$, $J_z = 0.02\ kg \cdot m^2$.

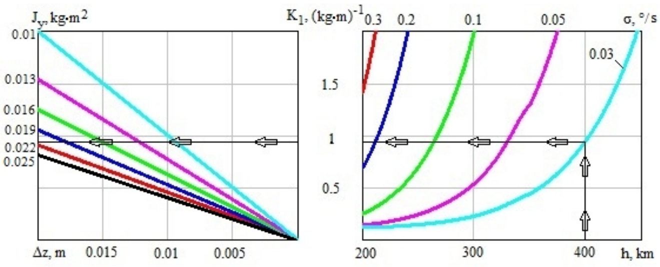

Fig. 2. The nomogram for choosing design parameter K_1

The nomograms can be used for choosing design parameters of the nanosatellite and for choosing the requirements to errors of the separation system of the existing nanosatellite. For example, on the Fig. 2 marked an example of choosing the design parameter of the nanosatellite CubeSat 3U for orbit altitude $H = 400\ km$ for given values of maximum deviation of the longitudinal axis from the local vertical $\beta^*_{\max} = 30\ \text{deg}$ ($\alpha^*_{\max} = 120\ \text{deg}$), $p^* = 0.95$, $\alpha_0 = 95\,\text{deg}$, $\sigma = 0.03$ deg/s. The value of the design parameter of the nanosatellite CubeSat 3U for the given motion should be $K_1 \geq 0.95\left(kg \cdot m\right)^{-1}$.

IV. CONCLUSIONS

The analytical cumulative distribution functions of the CubeSat standard nanosatellite's maximum angle of attack for Rayleigh and uniform distributions of the initial transverse angular velocity value were obtained. The formulas for choosing the design parameters of the gravitationally-aerodynamically stabilized nanosatellite were acquired. The calculated design parameters provide the deviation value of the longitudinal axis of a nanosatellite from local vertical less than acceptable with a given probability at a given altitude of its separation and at the known errors of the initial angular separation velocity. The nomograms, which allow to choose the main design parameters of gravitationally-aerodynamically stabilized nanosatellite of the CubeSat standard, were constructed.

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REFERENCES

[1] Samir A. Rawashdeh and James E. Lumpp, Jr., Aerodynamic Stability for CubeSats at ISS Orbit, JoSS, 2015 vol. 2, no. 1, pp. 85-104.

[2] Belokonov, I.V., Storozh, A.D., Timbay, I.A., Modes of motion of Soyuz orbital stage after payload separation at carrying out of the short-

term research experiments, Advances in the Astronautical Sciences, 2012, vol. 145, pp. 99-107.

[3] Belokonov, I., Kramlikh, A., Timbai, I., Lagno, O., Problems of satellite navigation and communications for nanosatellites launched as piggyback payload from the orbital stage of carrier rockets, 21st Saint Petersburg International Conference on Integrated Navigation Systems, St. Petersburg, Concern CSRI Elektropribor, 2014, Proc., 2014, pp. 407-415.

[4] Belokonov, I.V., Kramlikh, A.V., Timbai, I.A., Low-orbital transformable nanosatellite: Research of the dynamics and possibilities of navigational and communication problems solving for passive aerodynamic stabilization, Advances in the Astronautical Sciences, 2015, vol. 153, 383-397.

[5] Belokonov, I., Timbai, I., The selection of the design parameters of the aerodynamically stabilized nanosatellite of the CubeSat standard, Procedia Engineering, 2015, vol. 104, pp. 88-96.

[6] Belokonov I. V., Timbai I. A., Choice of the design parameters of aerodynamically stabilized nanosatellite , Izv. vuzov. Priborostroenie. 2016. vol. 59, no 6. P. 450—458 (in Russian).

[7] Belokonov, I.V., Timbai, I.A., Ustyugov, E.V., Method of aerodynamic stabilization of CubeSat class nanosatellite and a device for its implementation (options), Eurasian patent for the invention (21) 201 400 132 (13) A1, 2015.

[8] Kirillin, A., Belokonov, I., Timbai, I., Kramlikh, A., Melnik, M., Ustiugov, E., Egorov, A., Shafran, S., SSAU nanosatellite project for the navigation and control technologies demonstration, Procedia Engineering, 2015, vol. 104, pp. 97-106.

[9] Shakhmatov, E., Belokonov, I., Timbai, I., Ustiugov, E., Nikitin, A., Shafran, S., SSAU Project of the nanosatellite SamSat-QB50 for monitoring the earth's thermosphere parameters, Procedia Engineering, 2015, vol. 104, pp. 139-146.