SELECTION OF DESIGN PARAMETERS OF AERODYNAMICALLY STABILIZED NANOSATELLITE STANDARD CUBESAT

I.V Belokonov, I.A. Timbai

Samara State Aerospace University, Samara, Russia

ibelokonov@mail.ru, timbai@mail.ru

To ensure required orientation of small satellites are often used passive or combined (passive in combination with active) orientation system. As you know, ensure design conditions such uncontrolled motion of satellites can only at the design stage by choosing its design and ballistic parameters, as well as specifying limits on the angular velocity generated by the separation system

In [1] be considered the task of ensuring the aerodynamic stabilization of nanosatellite standard CubeSat by deploying solar panels at an angle to the longitudinal axis after separation from the adapter, wherein this problem was considered in a deterministic statement.

In this paper we consider the problem of selecting the design parameters (statical stability factor, length, longitudinal moment of inertia) aerodynamically stabilized nanosatellite standard CubeSat, that at motion in low circular orbits provide deviation the longitudinal axis of the nanosatellite from velocity vector of the center of mass is less than acceptable with a given probability on a given height at the known errors of angular velocity for separation system. In the derivation of formulas for the Scientifical and technological experiments on university “AIST” type smallsatellites constellation parameters are used analytical distribution functions of the maximum angle of attack of nanosatellite which obtained in [2].

It was decided that the nanosatellite wrapping is free-molecule and the gas molecules collision is perfectly inelastic, the resultant aerodynamic forces is applied to the nanosatellite geometric center. In this case, the aerodynamic drag force is determined by the nanosatellite area projected on a plane, normalized with respect to the flow velocity vector [3] and the restoring aerodynamic moment coefficient measured about the center of mass of the nanosatellite is determined by the formula:

$$m_\alpha(\alpha,\varphi) = -c_0\bar{S}(\alpha,\varphi)\Delta\bar{x}\sin(\alpha),$$

where c_o = 2.2 is drag force coefficient; $\Delta\bar{x} = \Delta x / l$ is relative static stability margin, Δx - is static stability margin (the distance measured from the center of mass to the geometric center of the nanosatellite); $\tilde{S}(\alpha,\varphi) = |\cos(\alpha)| + k|\sin(\alpha)|\cdot(|\sin(\varphi)| + |\cos(\varphi)|)$ is nanosatellite area projected on a plane, normalized with respect to flow velocity vector divided by the characteristic nanosatellite square, α is spatial angle of attack (the angle between the longitudinal axis and nanosatellite mass center velocity vector), φ is proper rotation angle (the angle between the angle of attack plane and the lateral axis, perpendicular with respect to the side).

For the approximately analysis of angular motion nanosatellite the restoring aerodynamic moment coefficient can be averaged over the angle of proper rotation and describe by sinusoidal dependence:

$$m_\alpha(\alpha) \approx a_0\sin(\alpha), \tag{1}$$

where $a_0 = m_\alpha(\alpha = \pi/2) = -c_0\Delta\bar{x}\dfrac{4k}{\pi}$.

Then, change the angle of attack of a dynamically symmetric nanosatellite under the influence of gravitational and restoring aerodynamic moment moving in a circular orbit described by an equation of the form [3]:

$$\ddot{\alpha} - a(H)\sin\alpha - c(H)\sin 2\alpha = 0, \tag{2}$$

where $a(H) = a_0 Slq(H)/J_n$ is coefficient associated with aerodynamic restoring moment; J_n is the transverse moment of inertia; $q(H) = V^2\rho(H)/2$ is velocity head; V is flight speed; H is orbit altitude, $\rho(H)$ is atmospheric density; $c(H) = 3(J_n - J_x)(\omega(H))^2/(2J_n)$ is coefficient associated with the gravitational moment; J_x - is the longitudinal moment of inertia; $\omega(H) = \sqrt{\mu/(R_3 + H)^3}$ is the angular orbital velocity of the nanosatellite; R_E is radius of the spherical Earth; μ is Earth's gravitational parameter.

The value of the maximum angle of attack after separation of nanosatellite from adapter is random and 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. Assuming, that among these values the angular velocity has the largest range of values and neglecting the scatter of other variables, for the motion model (1) in [2] are obtained the cumulative distribution function of the maximum angle of attack $\alpha_{\max}$ at the time of separation from the adapter. If the module values distributed according to the Rayleigh law, the cumulative distribution function of the maximum angle of attack is determined by the formula:

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

where $\sigma > 0$ is scale parameter of the distribution.
If the module values distributed according to a uniform law in the range [0, $\dot{\alpha}_{0\max}$], the cumulative distribution function of the maximum angle of attack is determined by the formula:

$$F(\alpha_{\max}) = \frac{\sqrt{2a(\cos\alpha_{\max} - \cos\alpha_0) + 2c(\cos^2\alpha_{\max} - \cos^2\alpha_0)}}{\dot{\alpha}_{0\max}}. \tag{4}$$

Specifying p^* - the probability of the maximum allowable angle of attack $\alpha^*_{\max}$, solving (3), (4) with respect to the design parameters, combined in a structural parameter, we obtain the requirement to its value. To the maximum angle of attack was less than allowable value with a probability no less than p^* is necessary to satisfy the following conditions for nanosatellite structural parameter:
in the case of the distribution of the initial angular velocity according to the Rayleigh law

$$d = \frac{\Delta x}{J_n} lb \geq d_r = \frac{\pi\left(\sigma^2 \ln(1-p^*) + c(\cos^2\alpha^*_{\max} - \cos\alpha_0)\right)}{4c_0\left(\cos\alpha^*_{\max} - \cos\alpha_0\right)q(H)}; \tag{5}$$

in the case of the distribution of the initial angular velocity according to a uniform law

$$d = \frac{\Delta x}{J_n} lb \geq d_r = \frac{\pi\left(\left(\dot{\alpha}_{0\max} p^*\right)^2 - 2c\left(\cos^2\alpha^*_{\max} - \cos^2\alpha_0\right)\right)}{8c_0\left(\cos\alpha_0 - \cos\alpha^*_{\max}\right)q(H)}, \tag{6}$$

where b is side of the base of rectangular parallelepiped.

In expressions (5), (6) included the coefficient of C associated with the gravitational moment, which varies slightly over the height compared to the coefficient of A, associated with aerodynamic restoring moment. Therefore, calculating the value of the coefficient c at altitude H = 150 km, taking into account that under the condition $J_n > J_x$ the ratio of the difference of transverse and longitudinal to transverse moments of inertia can not exceed unity, we obtain the limit value of the coefficient $c = 2.2 \cdot 10^{-6}$ rad/s^2. This coefficient can be used for the upper bound of the required value of the structural parameter.

Using the obtained expressions (5) - (6), we can construct the nomograms to assess the possibility of implementation of the required values of the structural parameter. For example, in Figures 1, 2 on the right are shown the dependences of the required structural parameter of the nanosatellite on orbit altitude H and on the parameter σ (initial transverse angular velocity is distributed according to the Rayleigh law) for the values of the maximum angle of attack $\alpha^*_{\max} = 20$ deg (Figure 1), $\alpha^*_{\max} = 30$ deg (Figure 2), the probability $p^* = 0.95$ and an initial angle of attack $\alpha_0 = 0$ and on the left are shown values of the structural parameter of nanosatellite CubeSat 3U ($0.1\times0.1\times0.3m^3$) with different values of transverse moment of inertia on static stability margin and structural parameter aerodynamically stabilized nanosatellite with transformable design SamSat QB50, developed as the part of the international project QB50 [5]. Calculations were performed for the standard density of the atmosphere in accordance with standard GOST 4401-81. [4]. Nanosatellite transformable design SamSat QB50 is 2 kg nanosatellite, having an initial CubeSat 2U form with dimensions $0.1 \times 0.1 \times 0.2$ m^3 and the initial distance between the center of pressure and center of mass is $\Delta x = 0.02$ m. After separation from the adapter transforms into nanosatellite CubeSat 3U form with dimensions of $0.1 \times 0.1 \times 0.3$ m^3, thereby significantly increasing the distance between the center of pressure and center of mass (up to $\Delta x = 0.055$ m) [5].

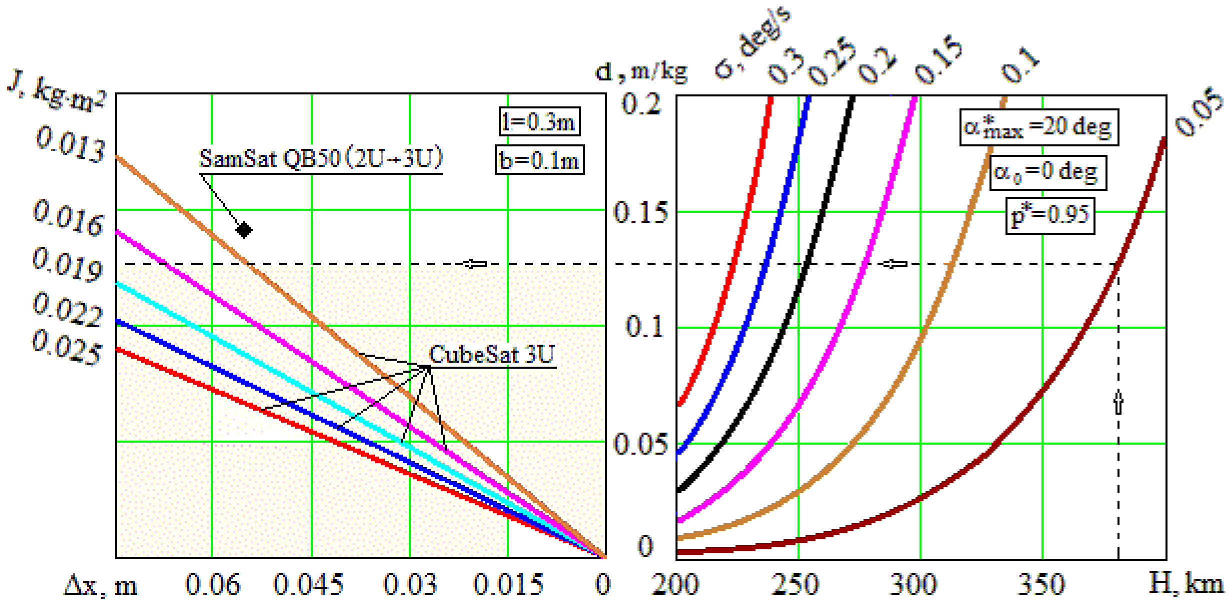

Fig. 1. Nomogram to select structural parameter of nanosatellite depending on the altitude H and the parameter values σ at $\alpha^*_{\max} = 20$ deg, $p^* = 0.95$, $\alpha_0 = 0$.

Nomograms can be used to select of design parameters of nanosatellite, and for specify requirements to errors of separation system of existing nanosatellites. For example, Figure 1 shows an example to select of structural parameter of nanosatellite for orbit altitude H = 380 km (planned altitude of grouping nanosatellites in the international project QB50) for given values $\alpha^*_{\max} = 20$ deg, $p^* = 0.95$, $\alpha_0 = 0$, $\sigma = 0.05$ deg/s. As can be seen, the value of structural parameter of nanosatellite for a given motion should be $d \geq 0.13 m/kg$. Figure 2 shows an example of setting of the requirements for the initial transverse angular velocity of nanosatellite SamSat QB50 for the given values H = 380 km, $\alpha^*_{\max} = 30$ deg, $p^* = 0.95$, $\alpha_0 = 0$. As can be seen, in order to nanosatellite SamSat QB50 commited the given motion is necessary satisfy the requirement: $\sigma \leq 0.05$ deg/s.

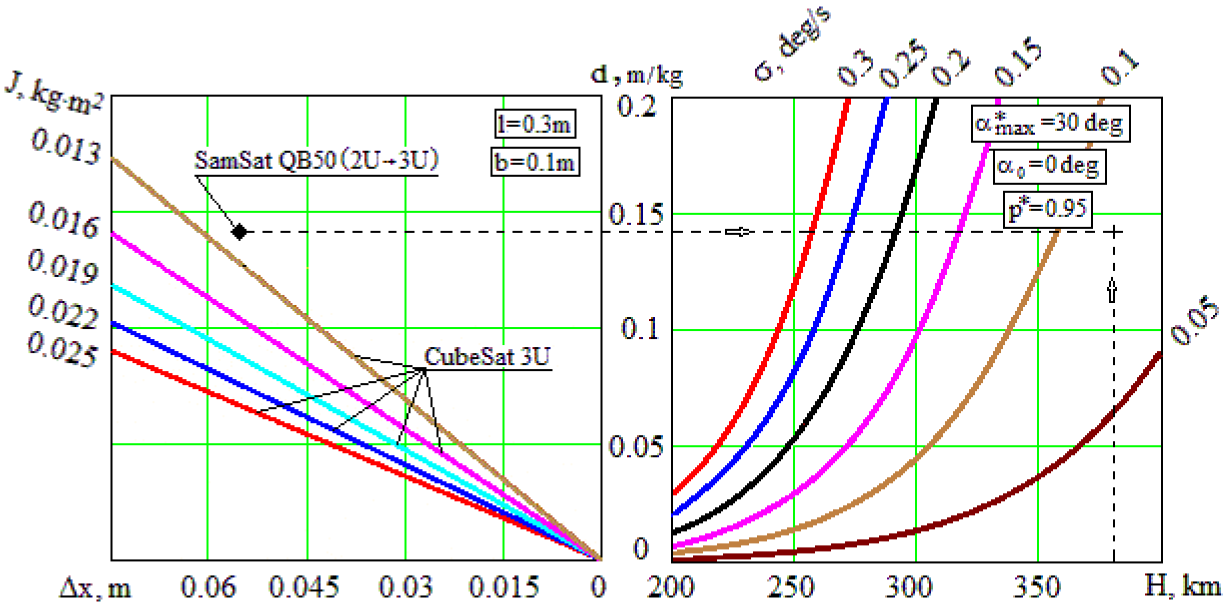

Fig. 2. Nomogram to select structural parameter of nanosatellite depending on the altitude H and the parameter values σ at $\alpha^{*}_{\max} = 30\ \text{deg}$, $p^{*} = 0.95$, $\alpha_0 = 0$.

The study was partially supported by RFBR, research project No. 13-08-97015- r_Volga region_a.

This work was supported by the Ministry of Education and Science of the Russian Federation, in frame of project part of state task in scientific activity area (№ 9.1421.2014/K).

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