IAC-16-D2.3.8

Choice of Separation Parameters From a Platform Commits Undirected Movement for Group of Nanosatellites

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Abstract

Orbital stages of launch vehicles can used as a platform for the piggy back orbiting of cluster of nanosatellites. The program of the nanosatellites separation from an orbital stage must realized safe nanosatellites movement after their group deployment. Due to the fact that after separation of the main payload, the orbital stage obtains the angular velocity, the value and direction of which are random, the direction of an each nanosatellite after separation will be random, too. As orbital stages are launched as usual on low altitude the atmosphere influences are very strong for relative motion. In this regard, the task of choosing the separation parameters for each nanosatellite (the velocity and time of separation) from conditions to prevent a collision with the orbital stage, the main payload, and also with each other (safe motion terms) is very important.

If nanosatellites separation is implemented for future formation flight it is required to the keep a certain distance between nanosatellites, the parameters of separations should be chosen on conditions of reducing the removal of nanosatellites one from each other (maximum distance between nanosatellites have to be no more than specified distance during two orbits). Such parameters of separation will allow to save the energy expended on keeping the integrity of nanosatellites group. Thus, the safe motion and maximum distance terms impose limitations on the choice of nanosatellites separation parameters.

It was made a statistical research which have allowed to develop a method for selecting parameters of nanosatellites separation (the velocity and time of separation). Those parameters exclude the possibility of nanosatellites collision and to reduce the removal of one from each other no more than predetermined distance. The developed method is applicable for determining the parameters of nanosatellites separation from the orbital stage or from any space platform moving with random precession. The research was made on an example of nanosatellites separation from the carrier rocket "Soyuz" orbital stage taking into account the random nature of its orientation after separation of main payload. The research was supported by the Ministry of Education and Science of the Russian Federation (project No. 9.1421.2014/K).

Keywords: nanosatellite group, orbital stage, nanosatellite separation, formation flight

Nomenclature

r_i – the distance between each NS and OS;
r_{ij} – the distance between two NS;
r_i^* – the radius of safe area;
r_{ij}^{**} – the maximum distance between two NS;
ΔV_i, Δt_i – separation velocity and time delay of i-th NS; $i=1,\dots n-1$, $j=1,\dots n$, $i>j$, n – NS number;
t – current time;
$P^* = 0{,}997$ – the required value of the probability,
x, y, z – coordinates of NS relative to OS;
μ = 398602 km^3/s^2 – the Earth gravitational parameter;
$\dot{\theta} = \frac{\sqrt{\mu p}}{R^2}$, $\ddot{\theta} = -2e\sqrt{\frac{\mu}{p^3}} \cdot \dot{\theta} \sin\theta$ – derivatives of the angle of true anomaly;
θ – angle of true anomaly;
$R_0 = [x^2+(R+y)^2+z^2]^{1/2}$ – NS radius-vector;
$R = p/(1+e\cdot\cos\theta)$ – OS radius-vector;
p – focal parameter;
e – eccentricity;
$P_x=\rho V^2\cdot\Delta Q$ – the projection of the aerodynamic acceleration on the transversal direction;
ΔQ – the difference between ballistic coefficients of OS and NS;
ρ – the atmospheric density;
V – the free-stream velocity,
r_{ns} – the distance between two NS;
r^* – the radius of safe area around a NS.

Acronyms/Abbreviations

Nanosatellites (NS);
Orbital stages (OS);
Main payload (PL).

1. Introduction

Nowadays many innovative companies and universities work on designing of nanosatellites (NS). Such satellites are so popular because their creation doesn't require a lot of finances for investing. It is possible to test different sensors and elements of onboard systems in space conditions with NS. Besides, participation of young scientists in designing of NS opens opportunity for more effective teaching space technology of students. However, orbiting and flight tests are a big problem which often solves with piggy back launch. This kind of launch is less expensive and it requires only a special separation device.

In work [1] was considered the problem of NS separation from oriented space platform. Separation velocity deviation was a random factor. Altitude of orbit about 600 km was considered. It was not taken into account atmospheric drag.

As usual, every carrier-rocket orbital stage has additional space to place NS. In paper [2] it was suggested to use the transfer compartment of the carrier-rocket "Soyuz" upper (orbital) stage for these purposes (figure 1).

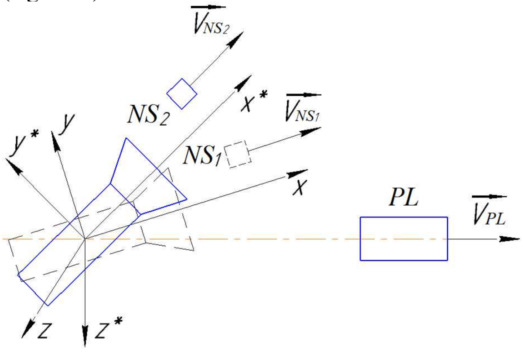


Fig. 1. Separation process of the main PL and NS

Orbital stages (OS) of carrier-rockets usually has a nearcircular low orbit. The lifetime of the NS after separation on such kind of orbits is short (a few days) but to conduct short-term experiments it often can be enough. On low orbits the atmosphere has a strong effect on the movement. Each NS, the main payload (PL) and the OS have different values of ballistic coefficients. In that way there is a risk of collision [3].

The timing diagram of the separation process of the main payload (PL) and each NS is presented in figure 2. Time delay of a NS separation (Δt_i) is an important parameter of the considered problem due to the fact that after separation of the main PL orbital stage has uncontrolled movement around its center of mass (description of the OS precessional motion placed in [4]). The orientation of OS longitudinal axis is undefined (therefore, the direction of each NS separating is also not known in advance).

In this regard, the parameters of the several NS (velocity and time of separation) must satisfy the conditions of avoiding their collision with the OS, the main PL and with each other (conditions of safety).

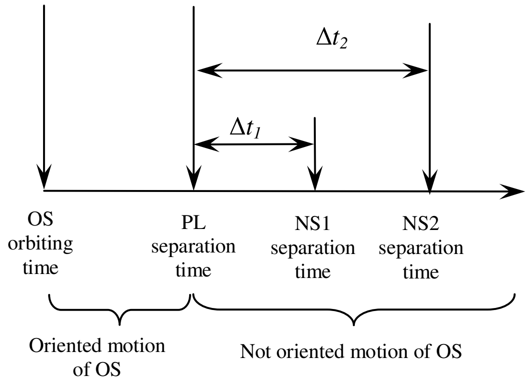


Fig. 2. The timing diagram of the separation process

Because nanosatellites have limitations on mass and dimensions, there is no possibility to have a high supply of energy on board. Thus, when it is required to maintain the defined distance for the NS cluster, you should choose such parameters of separation, which make the removal of NS from each other during initial stages (two turns) small (initial conditions of formation). Such parameters will allow to save the energy expended on achieving needed configuration of a NS group after separation.

The conditions of safety and formation impose limitations on the choice of parameters of the NS separation:

$$P(r_i(\Delta V_i,\ \Delta t_i,\ t) \geq r_i^* \wedge$$
$$\wedge\ r_i^* \leq r_{ij}(\Delta V_i,\ \Delta t_i,\ \Delta V_j,\ \Delta t_j,\ t) \leq r_{ij}^{**}) \geq P^*, \quad (1)$$

Thus, it is required to find the separation parameters of each NS (ΔV_i, Δt_i, $i=1,\ldots n$) to make conditions (1) true.

Currently, the OS motion around its mass center after separation of the main PL is unknown exactly since it was not supposed to use them further. For example, for OS the rocket Soyuz in [5] was conducted numerical simulation, which allowed us to determine the range of possible projections of the angular velocity on the axis of the associated coordinate system, which it obtains after separation of the main PL:

$$\omega_x = -(2{,}5 \pm 0{,}3)\ °/s;$$
$$\omega_y = (0{,}0 \pm 2{,}5)\ °/s;$$
$$\omega_z = (0{,}0 \pm 2{,}5)\ °/s$$

The random nature of the OS precessional motion and a large range of angular velocity projections values actualize the problem of choosing NS safe separation parameters since the laws of relative motion and the atmospheric effects may lead to the collision with OS, and/or nanosatellites with each other.

2. Relative motion model

For the study problem it was used a mathematical model of relative motion in orbital coordinates [6]. It describes the motion of one NS relatively to OS, moving in an elliptical orbit, in the orbital coordinates (Oxyz), the center of which is located in the mass center of the OS. The Ox axis is directed along the vector of orbital velocity, the axis Oy is directed along the radius-vector of the OS, the Oz axis complements the right coordinates. This model describes the movement of NS in the Central gravitational field with the influence of aerodynamic drag.

$$\begin{cases} \ddot{x} + 2\dot{\theta}\dot{y} + \ddot{\theta}y - \dot{\theta}^2 x + \dfrac{\mu}{R_0^3}x = P_x \\ \ddot{y} - 2\dot{\theta}\dot{x} - \ddot{\theta}x - \dot{\theta}^2 y - \dfrac{\mu}{R^2} + \dfrac{\mu}{R_0^3}(y+R) = 0, \\ \ddot{z} + \dfrac{\mu}{R_0^3}z = 0 \end{cases} \qquad (2)$$

3. Safety of NS motion relatively to the OS

It was made a statistical research of the occurrence probability of such NS separation conditions, which can lead to a dangerous approach to the OS. As mentioned earlier, the occurrence of such conditions is possible due to the fact that the OS oscillates around its center of mass with a random value of the angular velocity after separation of the main payload. Depending on the time interval Δt, the longitudinal axis of the OS will occupy a random position in space. In this regard, the direction of the NS separation is also not known in advance. The position of the OS was determined in the probabilistic formulation with the model of regular precession and it is presented in work [7].

The probability of NS reaching a dangerous area around the OS was estimated. The dangerous area is a sphere of a defined radius r* with the center in the OS mass center (when NS reaches this area it is considered as dangerous approach). Probabilistic safety condition of the NS movement around the OS:

$$P(r(\Delta V, \Delta t, t) \geq r^*) \geq P^*.$$

For the statistical research was used the following algorithm:

1) generating of 10000 random values for each projection of the OS angular velocity in the assumption of the normal distribution (to make errors in the calculation of the probability characteristics less than 1%);

2) the calculation of the initial conditions of NS separation in orbital coordinates (ΔV_{x0}, ΔV_{y0}, ΔV_{z0});

3) relative motion simulation with using of the mathematical model (2);

4) the determination of the NS closest approach distance;

5) checking of problem if NS reached the danger area around the OS;

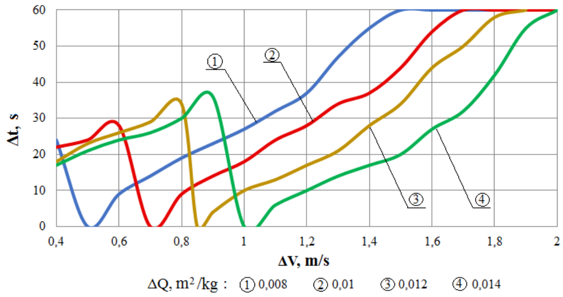
6) the calculation of statistical estimates of NS reaching the danger area probability.

In previous work [8] was obtained a probability density distribution for initial conditions of NS separation (projections of separation velocity).

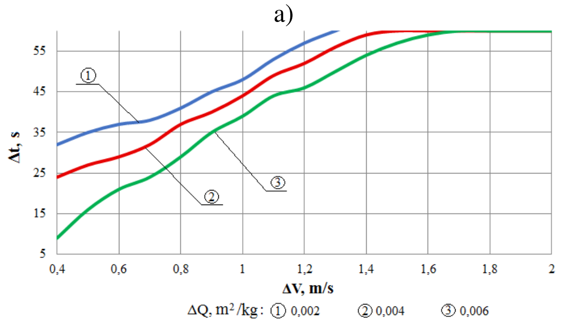
As an example, was chosen the case of NS separation from the orbital stage of the Soyuz, because the ranges of the angular velocity projections which it acquires after separation of the main PL are defined (geometry of the orbit: 190×240 km). The results of statistical simulation allowed us to establish initial conditions of NS separation to make its motion safe relatively to the OS.

The areas under the lines in figure 3 (a and b) show the parameters of the NS separation from the Soyuz (separation velocity ΔV and time delay Δt), in which NS after separation will not reach an area with a radius of 100 m around the OS with probability $P^* = 0{,}997$.

Each line corresponds to the values of the difference in ballistic coefficients between NS and OS (ΔQ).



a)



b)

Fig. 3. Area of safe NS separation parameters relatively to orbital stage

As you can see in figure 3, the area of NS separation parameters which provide a safe movement in relation to the OS is increased when the difference between ballistic coefficients reduces. Thus, to select a guaranteed safe NS separation parameters from the OS is required to determine the maximum difference in their ballistic coefficients and choose the NS separation velocity and time delay.

This method is also applicable for undirected movement of NS and OS around their mass centers because in this movement their ballistic coefficients changed in time, what affects their relative motion. In this case averaging values of ballistic coefficients are used.

4. Safety of several NS motion relatively to each other

The study of occurrence probability of such nanosatellites separation conditions, which can lead to their dangerous approach to each other. Probabilistic condition of safe motion of the two NS with respect to each other can be represented as:

$$P(r_{ns}(\Delta V_1, \Delta t_1, \Delta V_2, \Delta t_2, t) \geq r^*) \geq P^*.$$

For the study was used the same algorithm described previously. It was considered the case of two NS separations.

The study showed that if separation velocity of the first NS is more than separation velocity of the second NS more than 0.1 m/s, the probability of their approach at 20 m is less than 0.003. If separation velocity of the second NS is more than separation velocity of the first NS than 0.1 m/s, the maximum probability of their approach is less than 0.01 and increasing the difference we decrease the probability of collision.

The lines in figure 4 are limiting NS separation parameters, in which two NS with a probability of less 0.997 will not approach closer than 20 m. To provide safe motion it is necessary to select the separation parameters outside of the areas under the lines.

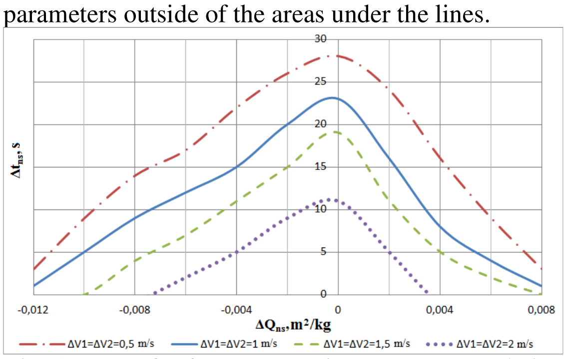


Fig. 4. Area of safe NS separation parameters relative to each other

On the horizontal axis of the figure 4 the ballistic coefficients difference between the second and the first NSs (ΔQ_{ns}) is shown; on the vertical axis the time separation delay difference between the second and the first NSs ($\Delta t_{NS} = \Delta t_2 - \Delta t_1$) is shown. Each line corresponds to its absolute separation velocity ΔV which is the same for each NS.

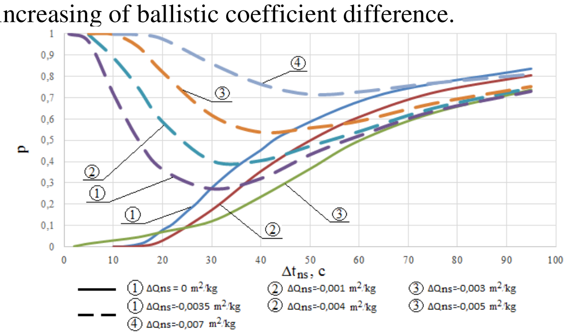
Thus, to determine the cluster NS separation parameters, which will provide their safe motion relatively to each other (with probability 0.997), you need to consider their combinations; choose the separation velocity of each NS such that they difference from each other has to be more than 0.1 m/s. If nanosatellites have the same separation velocity you need to select the separation parameters of each pair of NS in accordance with figure 4.

5. Study of distance limitations between nanosatellites

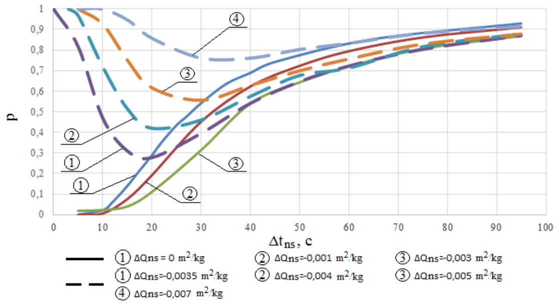
It was made a study of the nanosatellites flying apart probability from each other on a specified distance during a certain time interval for various separation parameters.

For the study it was used the same algorithm described previously, but checked the condition of exceeding a predetermined distance. The case of the two NS separation was considered. As an example, the maximum distance between two NS was assumed 10 km and the time interval of motion – two orbits. Figure 5 illustrates the simulation results.

In figure 5 the probabilities that two NS will spread to a distance greater than 10 km for two orbital turns are shown. The results correspond to the cases where the ballistic coefficient of the second NS less than the ballistic coefficient of first NS (ΔQ_{ns}<0), since when ΔQ_{ns}>0 the probability of NS spreading increases with increasing of ballistic coefficient difference.



a) $\Delta V_1 = \Delta V_2 = 1$ m/s



b) $\Delta V_1 = \Delta V_2 = 2$ m/s

Fig. 5. The probability of two NS flying apart more 10 km

From figure 5 we can conclude that if two NS separate at the same time ($\Delta t_{нс}$=0) and the difference between ballistic coefficients of the NSs ΔQ_{ns}<–0,003 m^2/kg, they will fly apart into a distance after two turns more than 10 km only because of various effects of the atmosphere.

6. The method application example.

It is considering an example of using the obtained results for the Soyuz orbital stage for the two cases:

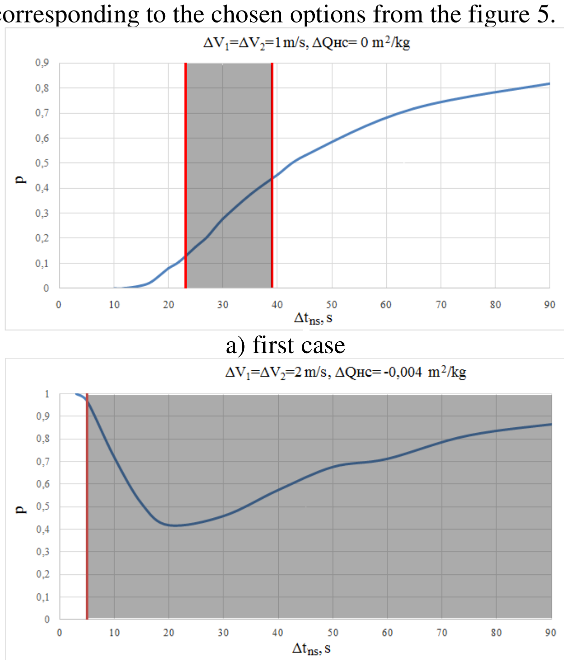
1) chosen separation device provides NS separation velocity ΔV = 1 m/s; averaged ballistic coefficients are equal, and the difference of the averaged ballistic coefficients of each NS and OS is 0.006 m^2/kg;

2) chosen separation device provides NS separation velocity ΔV = 2 m/s; the average ballistic coefficient of the first NS is more than the second one for 0.004 m^2/kg, and the difference of the averaged ballistic

coefficients of the first NS and OS is 0.008 m^2/kg, while for the second NS and OS the difference is 0.004 m^2/kg.

To provide a safety for each NS in the area around OS will use parameters from the figure 3b. For the first case the separation delay of the last NS Δt_2 should be less than 39 s, and there is no limitations for the second one.

To provide a safety of the nanosatelites relatively to each other, we use results from the figure 4. It can be seen that there should be a separation time delay between the first and second NSs Δt_{ns} more than 23 s for the first case and more than 5 s for the second case (shaded region in figure 6). This should satisfy the condition $\Delta t_2 \leq 39$ s for the first case. Next, choose the separation time delay based on the minimum probability of two NS flying apart. For this, we will add a curve corresponding to the chosen options from the figure 5.



a) first case

b) second case

Fig. 6. Example of separation parameters choosing

Thus, for the first case should provide the separation time delay between two NS 23 s and to separate the first NS in 16 s after main PL separation, and for the second case – in 19 s after main PL separation.

7. Conclusions

The developed method is applicable for determination of NS separation from the OS parameters field. These parameters provide the safe motion of an each NS relatively to an OS from which they separated and relatively to each other. Also it was considered the issue of NS flying apart from each other at a predetermined distance. The study was conducted on the example of NS separation from the orbital stage of Soyuz carrier rocket with the random nature of its orientation. The developed method is applicable for separation of the group of nanosatellites from any platform, performing a random motion.

The research was supported by the Ministry of Education and Science of the Russian Federation (project No. 9.1421.2014/K).

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