Using the Technology of Inflatable Structures for the Removal of Spacecraft's from Low Orbits

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***Abstract*—Every year the concentration of objects of space debris is steadily growing, which significantly complicates the conduct of both modern and future space missions using automatic, and especially manned space vehicles. To date, over 15,000 artificial objects and fragments larger than 5 cm have been recorded in near-Earth space. Therefore, the issues of cleansing outer space from objects of space debris of various sizes are quite relevant. In this paper, are considered questions use inflatable structures for deorbiting spacecraft, in order to avoid the formation of new space debris. At the end of the work, conclusions are drawn about the effectiveness using of such inflatable structures.**

***Index Terms*—space debris, deorbiting, disposal orbit, dynamic of motion, inflatable structures, braking device, orbital movement**

I. Introduction

Due to the intensive development of the direction for the creation of small space satellites and in particular on the basis of CubeSat, the issue de-orbiting of spacecraft after the end of their active existence in order to reduce the number of orbital debris in orbit is becoming very topical.

From 2000 to 2017 years, were launched into the low earth orbit (using standard launch vehicles) more than 800 spacecrafts of various types, and more than 200 spacecrafts only in 2017 year.

The majority of spacecraft are concentrated in orbits from 400 km to 700 km. At the same time at an altitude of about 400 km is the International Space Station, which since 2012 year is the platform for the mass launch of CubeSat.

Currently, the international community of scientists and engineers is in the active phase of working out space missions to clean up of space from objects of space debris. At the same time, various technologies for the reduction orbital lifetime and disposal of space debris are being developed.

As the main technologies for the deorbiting of space debris, most popular ones can be distinguished:

- Installation of additional devices (Thruster de-orbiting kit, TDK) in the nozzle space debris (see in Fig. 2 [1]). Functionality of such devices will allow to transfer the space debris to the disposal orbit.
- Capture of space debris with the help of an active spacecraft. It is assumed that the active spacecraft will capture the space debris, transfer it to a given orbit, undock from the space debris, and continue to carry out scheduled flight operations. Within the framework of this concept, a lot of methods for capturing space debris are considered, which are subdivided into active and passive [2].
- Deorbiting of a spacecraft by using a solar sail [3]. But for different shapes [4, 5] and different materials there are problem questions [6, 7].
- Deorbiting of a spacecraft by increasing the aerodynamic resistance of the atmosphere after the deployment of braking devices. In the last two years only two projects have been proposed in Russia that are based on the principle of deploying braking devices [8, 9].

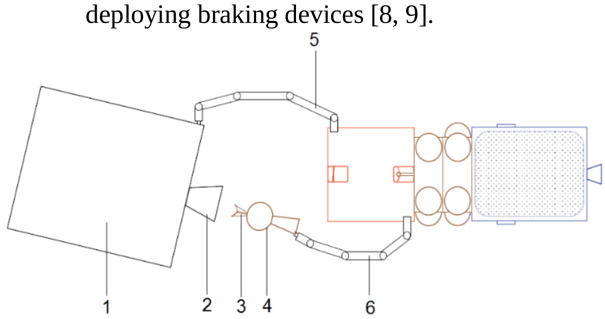

Figure 1. Installation of the TDK device in the nozzle space debris: 1-space debris, 2-nozzle space debris, 3-element fastening, 4-TDK, 5-docking manipulator, 6-manipulator.

The principle of operation of this technology is to increase the ballistic coefficient by creating a larger cross-sectional area of the space vehicle (compared to the original one) due to the deployment of braking devices. The final form of the disclosed braking device may be different.

In this case, the spacecraft can initially be equipped with brake devices during design and assembly on Earth.

Another option is when the braking device is install on the object after it has been classification like the space debris. In this case, will first need to capture the space debris and install the device. But space debris should have standardized interface for docking.

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II. De-orbiting Device Configurations

De-orbiting devices can be designed in shapes of sphere, thorus, cone, pyramid, either dome, plane etc. The development of inflatable structures is covered in other articles [10, 11, 12].

According to the newthonian model for low-density high-velocity flow gas particles impact surface of de-orbiting device.

Body get the momentum component normal to it's surface.

The result force applied to area S is equal

$$\vec{R}_a = -\vec{n}V_\infty^2\rho \cdot S\sin^2\alpha = -\vec{n}\left(\vec{V}_\infty \cdot \vec{n}\right)^2\rho \cdot S, \quad (1)$$

- $\vec{n}$ – unit vector normal to surface S.
- V_∞ – gas partickles velocity, equal to spacecraft velocity relative to moving atmosphere V_{atm}, with minus sign,
- ρ – atmosphere density,
- α – angle between flow velocity vector and surface.

Drag force $\vec{X}_a$ respectively is equal

$$\vec{X}_a = -\frac{\vec{V}_\infty}{V_\infty^2}\left(\vec{n}\cdot\vec{V}_\infty\right)^3\rho \cdot S, \quad (2)$$

or

$$X_a = \frac{1}{V_\infty}\left(\vec{V}_\infty\vec{n}\right)^3\rho \cdot S, \quad (3)$$

Spacecraft velocity relative to atmosphere, rotating with Earth (airspeed)

$$\vec{V}_{\text{atm}} = -\vec{V}_\infty = \vec{V} + [\vec{r} \times \vec{\omega}_3], \quad (4)$$

- $\vec{V}$ – spacecraft velocity in ECSF reference frame,
- $\vec{r}$ – spacecraft position vector in ECSF reference frame,
- $\vec{\omega}_3$ – Earth rotation angular velocity vector.

Drag force is usually expressed through dynamic pressure q_∞ and drag coefficient c_{xa}, or through ballistic coefficient σ, respectively

$$X_a = c_{xa} \cdot q_\infty \cdot S, \quad (5)$$

where $q_\infty = \frac{\rho V_\infty^2}{2}$, or

$$X_a = m \cdot \sigma \cdot V_\infty^2 \cdot \rho. \quad (6)$$

From (5) and (6)

$$\sigma = \frac{c_{xa}S}{2m}, \quad (7)$$

m – spacecraft mass.

From (3) and (5) c_{xa} for plane surface

$$c_{xa} = \frac{2}{V_\infty^3}\left(\vec{V}_\infty\vec{n}\right)^3 = 2\cos^3\left(\widehat{\vec{V}\vec{n}}\right), \quad (8)$$

and ballistic coefficient

$$\sigma = \frac{1}{m}\cos^3\left(\widehat{\vec{V}\vec{n}}\right) \cdot S. \quad (9)$$

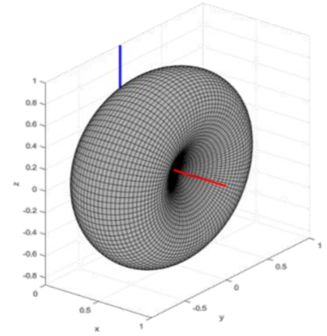

Figure 2. Polar diagram of the dependence of the drag coefficient of the cone on the direction of the speed of the oncoming flow

Calculational software was developed in appliance with newthonian flow theory, which used for estimation of drag and ballistic coefficients for different configurations of deorbiting device and their orientation in the flow. The data are listed below.

For example, *the cone design* is compact in the folded form and provides a large area in the expanded form. The conical shape facilitates the angular stabilization of the spacecraft near the zero angle of attack.

An example of the polar diagram of the dependence of c_{xa} on the direction of blowing for a cone with an half angle of 30 °is shown in Fig. 2.

The maximum drag coefficient in the front hemisphere c_{xa} = 1.05 is achieved with the direction of motion perpendicular to the cone generator, the minimum c_{xa}= 0.505, when moving with the toe in the direction of the velocity vector.

The tetrahedral shape of the braking device can be supported by deployable reinforcing elements, for example, wire or strip ribs unwound from the coil. This design does not need a pressure generator and can not be subject to leakage if the film sheath is damaged, but has less stability and requires the presence of drives for mechanical deployment. The tetrahedral shape contributes to the angular stabilization of the spacecraft near the zero angle of attack.

An example of the polar diagram of the dependence of c_{xa} on the direction of blowing for a cone with an half angle of 30 °is shown in Fig. 3.

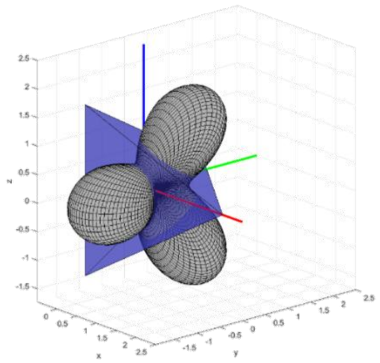

Figure 3. Polar diagram of the dependence of the coefficient of drag of a tetrahedron on the direction of the speed of the oncoming flow

The maximum drag coefficient in the front hemisphere c_{xa} = 2 is achieved with the direction of the incident stream vector perpendicular to the lateral face of the tetrahedron, the minimum c_{xa} = 0.213 - when moving with the toe in the direction of the velocity vector.

The brake device is *a flat frame* of various shapes, on which the film is stretched. Has the greatest drag coefficient c_{xa} = 2 (see Fig. 4).

The maximum drag coefficient in the front hemisphere c_{xa} = 2 is achieved with the direction of the vector of the incident flow perpendicular to the plane of the brake.

The cupola device is a parachute. The film canvas is stretched by means of unfold able wire "slings" to maintain the maximum area and radius of curvature. Unlike a flat device, does not have a reinforcing frame around the perimeter, so under the influence of the oncoming flow the shape can differ substantially from the flat one and have a radius of curvature. However, in comparison with a flat device, the structure and the deployment scheme are simplified, and the pressure of the oncoming flow naturally contributes to maintaining the shape of the cupola and stabilizing the objects.

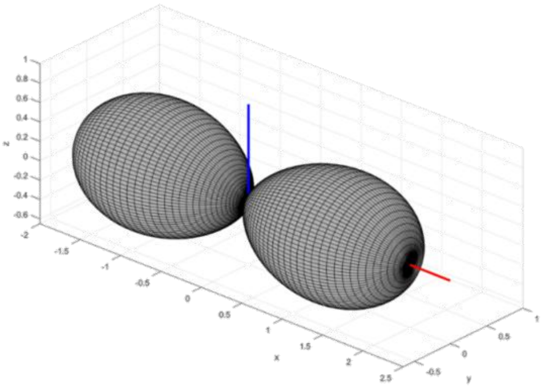

Figure 4. Polar diagram of the dependence of the coefficient of the drag of the plane on the direction of the speed of the oncoming flow

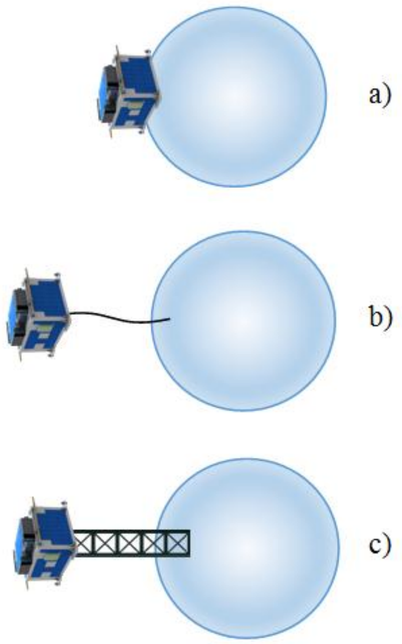

Figure 5. Schemes of mutual placing of satellite and braking device: a) adjacent; b) remote on the cable; c) remote on a hard construction

Spherical braking device is structurally the simplest and does not require reinforcing elements. It can be a thin-film ball, supercharged by a gas generator. Has the same drag coefficient c_{xa} = 1 for any orientation of the objects.

There are three main variants of the mutual placing of the braking device and the satellite is shown in Fig. 5. If there are no projecting parts from the side of the braking device, capable of damaging it, the most effective placement is assumed to be closely. This arrangement prevents the satellite from spinning with respect to the braking device and possible impacts on it.

If there are projecting parts on the body of the spacecraft from the opening side, the braking device can be carried out on a remote on a hard construction. However, with such a scheme, the braking device is less protected from damage when hits the housing, the overall rigidity of the structure is reduced.

In this case, it is preferable and technologically feasible to create a braking device shape using inflatable beams (see Fig. 6 and Fig. 7).

That will allow reducing the volumes of working gas for inflation and maintenance of the required form.

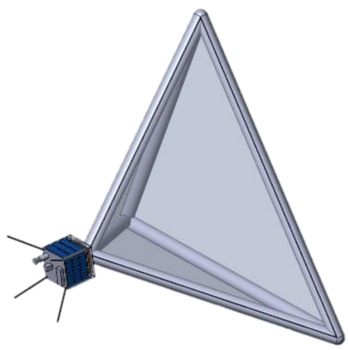

Figure 6. Braking device in the form of a pyramid with ribs in the form of inflatable beams

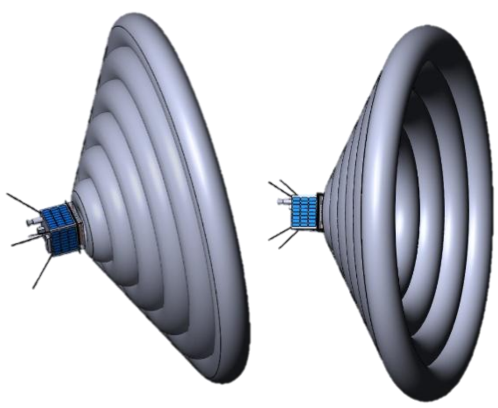

Figure 7. Braking device in the form of a cone with inflatable beams

In addition, one of the tasks is to calculate the volume that will be occupied by the braking device in the folded state. In Table I shown an estimate of the volume of film the braking device for various design parameters.

TABLE I. MASS VOLUME OF FILM THE BRAKING DEVICE

D, m	S, m^2	Area of the shell, m^2	Volume of the shell, m^3	The volume of the folded braking device, liters			
				5 µm	20 µm	50 µm	100 µm
1,0	0,7	3,1	0,52	0,2	0,8	2,0	4,0
1,5	1,7	7,0	1,77	0,4	1,8	4,5	9,0
2,0	3,1	12,5	4,19	0,8	3,2	8,0	16,0
2,5	4,9	19,6	8,18	1,2	5,0	12,5	25,1
3,0	7,0	28,2	14,14	1,8	7,2	18,1	36,1
3,5	9,6	38,4	22,45	2,4	9,8	24,6	49,2
4,0	12,5	50,2	33,51	3,2	12,8	32,1	64,3
4,5	15,9	63,6	47,71	4,0	16,2	40,7	81,4
5,0	19,6	78,5	65,45	5,0	20,1	50,2	100,5
5,5	23,7	95,0	87,11	6,0	24,3	60,8	121,6
6,0	28,2	113,1	113,10	7,2	28,9	72,3	144,7
6,5	33,1	132,7	143,79	8,4	33,9	84,9	169,9
7,0	38,4	153,9	179,59	9,8	39,4	98,5	197,0
7,5	44,1	176,7	220,89	11,3	45,2	113,1	226,1
8,0	50,2	201,0	268,08	12,8	51,4	128,6	257,3
8,5	56,7	226,9	321,56	14,5	58,1	145,2	290,5
9,0	63,6	254,4	381,70	16,2	65,1	162,8	325,7
9,5	70,8	283,5	448,92	18,1	72,5	181,4	362,9
10,0	78,5	314,1	523,60	20,1	80,4	201,0	402,1

III. ESTIMATING THE LIFETIME OF A SPACECRAFT ON ORBIT

To estimate the spacecraft's orbital lifetime, a software complex for predicting the motion of the center of mass of the spacecraft was developed, which makes it possible to evaluate the possibilities of using braking devices of various configurations.

For an altitude of 200 km, the disturbing effect of atmospheric inhibition is 10^{-4} m/s^2. For an altitude of 400 km, the order of the perturbing acceleration decreases and is 10^{-6} m/s^2.

For altitudes from 800 km to 1500 km, the order of acceleration varies from 10^{-9} m/s^2 to 10^{-12} m/s^2.

However, even a slight perturbing acceleration from the atmosphere on will make a significant contribution to deceleration, since the drag force acts constantly and the direction of action is always opposite to the direction of motion of the space vehicle.

This fact makes it possible to use inflatable, unfolding and other braking devices quite efficiently for the purpose of reducing spacecraft from orbit.

IV. CALCULATION RESULTS

As part of the research:

- calculation of the rate of fall of the orbit altitude of the spacecraft was carried out for nominal estimates of the forecast of the values of the indices *F10.7* and *ap*;
- the mass of satellite varied from 5 kg to 600 kg;
- the initial cross-sectional area of the satellite (S0) varied from 0.05 m ²to 1 m ²;
- considered two values of the cross-sectional area of the braking device after opening: $S_1 = 4$ m^2 and $S_2 = 10$ m^2;
- the shape of the disclosed braking device was selected as a tetrahedron.

Mass and geometric parameters of satellites with shown in Table II.

TABLE II. MASS AND GEOMETRIC PARAMETERS OF SATELLITES

Number	**Mass, kg**	**S0, m ²**
1	5	0.05
2	10	0.10
3	20	0.20
4	30	0.30
5	40	0.40
6	50	0.50
7	100	0.65
8	150	0.75
9	200	0.80
10	300	0.85
11	400	0.95
12	500	0.95
13	600	1.00

The results of calculating the lifetime of satellite on a circular orbit from 300 km to 600 km shown in Fig. 8-12.

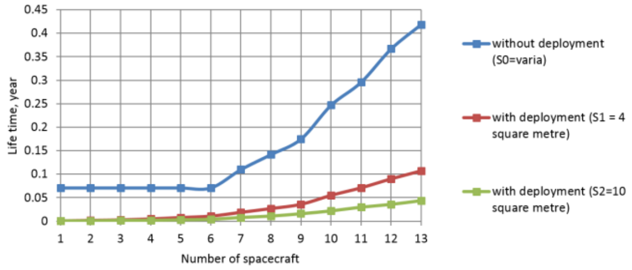

Figure 8. Changes in the height of spacecraft of various configurations for the initial altitude H0 = 300 km

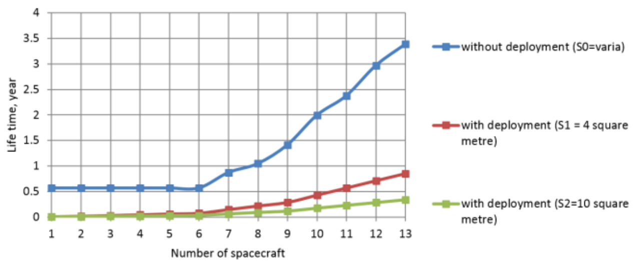

Figure 9. Changes in the height of spacecraft of various configurations for the initial altitude H0 = 400 km

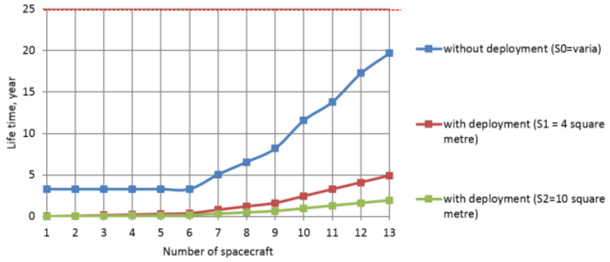

Figure 10. Changes in the height of spacecraft of various configurations for the initial altitude H0 = 500 km

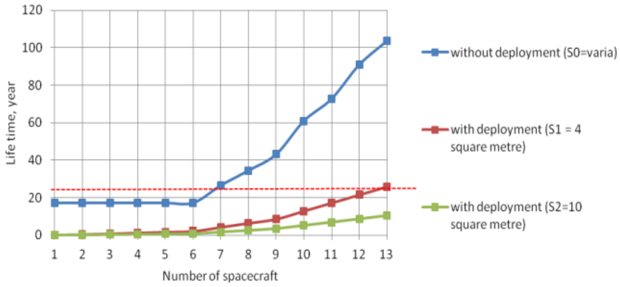

Figure 11. Changes in the height of spacecraft of various configurations for the initial altitude H0 = 600 km

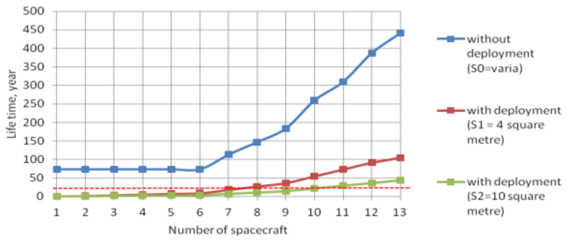

Figure 12. Changes in the height of spacecraft of various configurations for the initial altitude H0 = 700 km

As can be seen from the obtained results Fig. 8-12, the disclosure of the inflatable braking device allows to significantly reduce the duration of passive ballistic spacecraft existence in orbit. And in most cases, the existence time does not exceed 25 years, which meets one of the requirements of the provisions of the Inter-Agency Committee on Space Debris [13].

So, according to preliminary calculations, an inflatable braking device in the form of a tetrahedron with a cross-sectional area of 4 m^2 will weigh about 1.5 kg.

V. Conclusions

Taking into account the obtained results, we can say that the use of passive braking devices in the form of inflatable structures can significantly reduce the time of existence of spacecraft in orbit, so the demand for such systems in the future will be very high.

The main advantage of inflatable structures before rigid ones is a small mass and the possibility of compact stacking in the required volume when putting into orbit. However, to date, inflatable braking devices are not sufficiently tested in outer space conditions, although ground handling has been conducted for a long time.

At the same time, there is a probability of breakdown of the inflatable structure by the fragments of the space debris and the occurrence of leaks of the supercharged gas, which can significantly reduce the efficiency of such a system. It is assumed that such leaks can be compensated by the multiple actuation of the gas generator.

Acknowledgment

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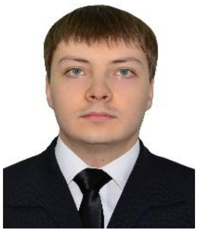

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