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Study of the Possibility of Using the Mechanics of Inflatable Braking Devices to Remove the Spacecraft

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Abstract. The problem of accumulation of space debris in near-Earth space is very relevant now. More than 15,000 debris have been recorded, and this represents a danger for current and future missions to space. A solution to this issue is to remove these spacecrafts from orbit. One of the ways to do it is to use inflatable device. These inflatable braking device can be installed on the landing vehicles on Earth, before their launch, or after they have been labelled as space debris. Studies have already been conducted about inflatable device. Using inflatable device instead of rigid device has advantages, such as a small mass and a great compacity, which is convenient to respect the required launching volume. This paper is dedicated to use of various inflatable brake devices and they are compared with each other.

1. Introduction

The braking device is designed to reduce the lifetime of a spacecraft in a near-earth orbit after its active operation has ceased for its intended purpose. The removal of the spacecraft (SC) from orbit is expected to be carried out by natural aerodynamic deceleration in the upper rarefied atmosphere of the Earth [1, 2, 3]. During the operation of the spacecraft in orbit, the device is in a folded compact state.

After the decision is made to terminate the target use of the spacecraft or by command of the long-term timer, the device is activated. At the same time, the compactly laid thin-film shell of the device under the action of pressurization takes a volumetric shape, which leads to an increase in the area of the projection of the spacecraft and its ballistic coefficient by tens to hundreds of times.

In contrast to mechanical opening, when using gas pressurization, it is necessary to solve the problem of gas leakage and pressure loss due to the porosity of the film, damage to the shell by particles of space debris. Maintaining the shape of the shell in these conditions is assumed by equipping the device with a gas reserve for multiple pressurization.

In addition, the device must ensure reliable issuance and execution of the activation command after several years of the spacecraft operation, and even after its possible partial or complete failure. To meet these requirements, the device must contain its own built-in separate control unit and a power source that are independent of the onboard network of the spacecraft and whose reliability is higher than the reliability of the spacecraft's control system and power supply.

Finally, in the device during the entire period of the active life of the spacecraft, a supply of compressed gas of boost or reagent stock for the production of cold gas due to chemical transformations should be stored.



2. Mass calculation

The mass of the inflatable braking device (IBD) m_{IBD} includes the masses

- 1) Mass of film m_{film} ,
- 2) The mass of pressurized gas with a balloon and an opening system (when stored in cylinders in a compressed state) or a reactant with a reactor (using a cold gas chemical generator) m_{pg} ,
- 3) Body mass m_{body} – mass of control system, elements of a separate power system for an inflatable braking device and other parts not dependent on the area of disclosure.

In this way,

$$m_{IBD} = m_{film} + m_{pg} + m_{body}. \quad (1)$$

Mass of film

$$m_{film} = S_{film} \cdot \delta_{film} \cdot \rho_{film}, \quad (2)$$

where:

S_{film} , m^2 – film area,

δ_{film} , mcm – film thickness,

ρ_{film} , $\frac{kg}{m^3}$ – density of the film material.

The mass of the substance and pressurization devices m_{pg} is selected on the basis of a range of standard sizes of gas generators or cylinders.

Estimation of the mass of the body, components and assemblies in the first approximation is taken depending on the area of the film in proportion to

$$m_{body} = k_{body} \cdot S_{film}, \quad (3)$$

where:

k_{body} – coefficient of proportionality between the area of the film and the mass of the body. This coefficient is calculated separately for each spacecraft. For example, for the spacecraft Mayak [4].

3. Estimate of time from de-orbit

The reduction of spacecraft from low near-earth orbital orbits is considered. The moment of the termination of the ballistic existence will conditionally be considered the moment when the height of the orbit decreases to 100 km.

For an approximate estimate of the lifetime, the differential equation for the focal parameter is solved [5]:

$$\frac{dp}{dt} = 2r \sqrt{\frac{p}{\mu}} N, \quad (4)$$

or for the major axis of the orbit [6]

$$\frac{da}{dt} = \frac{2a^2}{\sqrt{\mu p}} N. \quad (5)$$

where r , m is the orbit radius, p , m is the orbit parameter, μ , $\frac{kg^3}{s^2}$ is the gravitational parameter, N , $\frac{m}{s^2}$ is the transversal projection of the disturbing acceleration.

The initial conditions are values $h_k = 400 \text{ km}$, 600 km и 800 km .

To estimate the time of spacecraft descent, the initial near-circular orbits are $ce \approx 0$, for which $a \approx p \approx r$. These ratios are also valid in the course of further descent in the upper atmosphere along a spiral path.

Perturbing transversal acceleration N in this case is equal to the acceleration of the resistance force of the atmosphere

$$N = \sigma \rho(h) v^2, \quad (6)$$

where:

$\sigma = \frac{c_{xa} S}{2m}, \frac{m^2}{kg}$ – ballistic coefficient,

$\rho(h), \frac{kg}{m^3}$ – dependence of the density of the Earth's upper atmosphere on height,

$v, \frac{m}{s}$ – the flow velocity of the gas.

Presumably the spacecraft and the inflatable braking device are coaxial to the velocity vector of the spacecraft dilution relative to the moving atmosphere; the period of stabilization to this position is not considered in this work.

A more accurate estimate can be obtained by the joint solution of the complete system from the differential equations of motion of the center of mass of the spacecraft, as well as the angular motion of the spacecraft around the center of mass, including other typical perturbing factors of low orbits.

4. The estimated volume of the film in the folded state

Experiments conducted, in particular, in the development of the student satellite "Mayak" revealed that the volume of the folded film V_{film} , l is approximately

$$V_{film} = k_{film} \cdot S_{film} \cdot \delta_{film}, \quad (7)$$

where:

$k_{V_{film}}$ – coefficient of proportionality between the volume of the film material and the volume of the film in the folded pressed state, according to the results of work on the Mayak spacecraft $k_{V_{film}} \approx 0,0128$ [4],

S_{film}, m^2 – shell area,

δ_{film}, mcm – film thickness.

Industry offers a huge amount of film materials with different composition, thickness, purpose. Film materials were selected according to the following criteria:

- 1) Preservation of mechanical, chemical and electromagnetic properties in the temperature range of the stay of a spacecraft on the Earth's orbit (-150 ... 250°) during the entire lifetime of the spacecraft and its subsequent de-orbit.
- 2) Flexibility and strength sufficient to preserve the integrity and tightness of the shell after installation, pressing into the compartment, storage, subsequent disclosure and pressurization.
- 3) Low porosity.
- 4) Manufacturability cutting and fasteners. For example, weldability for the possibility of soldering hermetic joints, or ease of cutting.
- 5) Mass production and reasonable cost.

Currently, the development of promising materials with improved properties. Currently, they are either too expensive or have technological limitations, but in some perspective they can enter the mass market, and they deserve mention in this review, such as, for example, graphene film.

5. Pressurization system

In the framework of this work, braking devices of inflatable type are considered. Charging involves the use of gas to open and maintain the shape of an aerodynamic device. In view of the similarity of the task, will consider the overpressure of the boosting device as equal to the excess internal pressure for stratostats in the Earth's atmosphere. This will simplify the assessment of the possibility of using these or other materials for an inflatable braking device: if in the conditions of a ground-based experiment, the shells maintain their shape and integrity at this pressure, then they will be able to maintain the shape and withstand similar breaking stress in space conditions. According to the publications, the overpressure of atmospheric balloons is about 150 Pa according to the publications of the Laboratory of Autonomous Systems at Stanford University [7] or 180 Pa [8]. It is also assumed that in space conditions even less excessive pressure will be required, since in orbit the gravity will not counteract the opening of inflatable structures.

The mass of gas required for a single deployment of the cylinder, according to the equation of state of an ideal gas

$$pV = \frac{m_{pg}}{M} RT, \quad (8)$$

makes up

$$m_{pg} = \frac{pVM}{RT}, \quad (9)$$

where:

m_{pg} , kg – boost gas mass,

p , Pa – boost pressure (in this case approximately equal to 150 Pa),

V , m³ – the volume of the expanded shell,

$R = 8,315 \frac{J}{mol \cdot K}$ – universal gas constant,

T , K – temperature of gas filling device.

Pressurized structures are vulnerable to pressure leaks, both due to the leakage of the original components of the structure (film porosity) or breakdowns obtained, and due to changes in pressurized gas of a chemical or physical nature (for example, temperature heating or compression). In this paper, only the problem of leaks is considered. To assess the time interval between repeated aspirations, a review of the operation of aerostatic systems, in particular, super-pressure stratostats, was conducted. Currently, Google and NASA are developing sealed (super pressure) stratostats with a flight duration of 100 days [8]. Considering the similarity of sealed balloons and the space inflatable braking device, will consider 100 days as a typical interval with which it is necessary to produce boost (during this time the gas in the aerodynamic device is completely replaced by repeated activation of the charge device).

6. Comparison of various configurations of inflatable braking devices

In principle, the inflatable device can be positioned closely adjacent to the spacecraft (see Figure 1), or remotely on a cable/rod. In the absence of protruding parts of the spacecraft from the deployment of a cylinder that can damage it, the most effective is to be placed closely. This placement prevents the spinning of the spacecraft relative to the balloon and possible impacts on it. If there are protruding parts on the body of the spacecraft from the side of the disclosure of the braking device, the cylinder can be placed on a rigid rod. However, with such a scheme, the cylinder is less protected from damage when it strikes the hull, and the overall rigidity of the structure is reduced. In this paper, being considered only the layout closely.

Calculations were made for the masses and volumes of the film and the pressurization system of three spherical shells with diameters of 5 m, 10 m and 15 m, as well as pyramidal shells of equal diameter (4 faces, angle of inclination to the axis 60°) (and conical 60°), pressurized with nitrogen (N_2). The maximum and minimum values of the mass of the gas were taken for temperatures of, respectively, -120° and +120°, taking into account possible daily temperature differences [9], the level of illumination, the greenhouse effect inside the film. The maximum and minimum masses of the film m_{film} and the volumes in the laid state V_{film} are given for films 50 and 100 microns thick, respectively. The corresponding tables with the results of calculations are given below for each section.

6.1. Spherical braking device

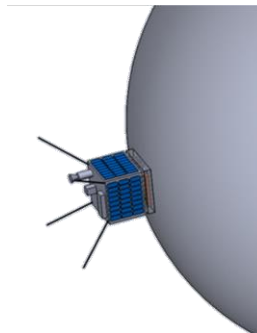


Figure 1. Possible view of a spacecraft with a spherical inflatable braking device.

Spherical braking device [10, 11] has the simplest design, the scheme of pressurization and disclosure. However, this brake device has the largest amount of gas and film area, which must be used to manufacture such a brake device. In addition, this design, in comparison with other forms, has not the highest coefficient of resistance $C_x = 1,0$.

The lifetime of the bundle of spacecraft and activated inflatable braking device with the three ballistic coefficients considered in the table is shown in Figures 2 and 3.

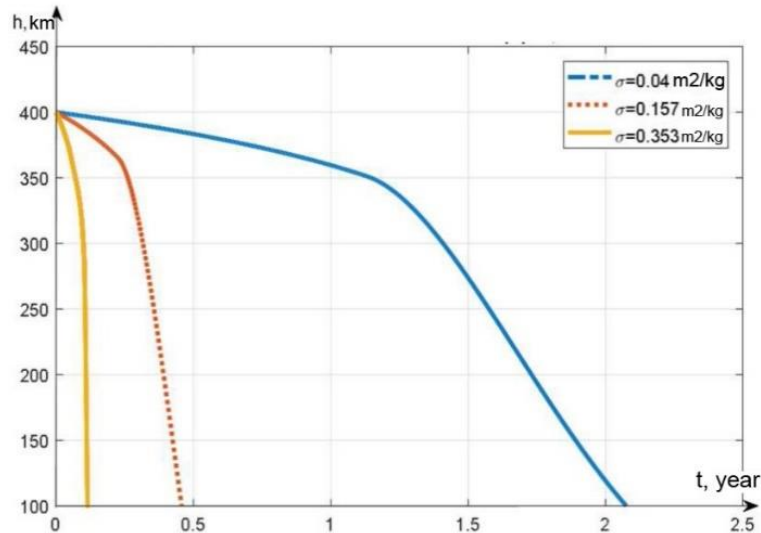


Figure 2. Estimation of the lifetime of a spacecraft with three different ballistic coefficients at an initial altitude of 400 km.

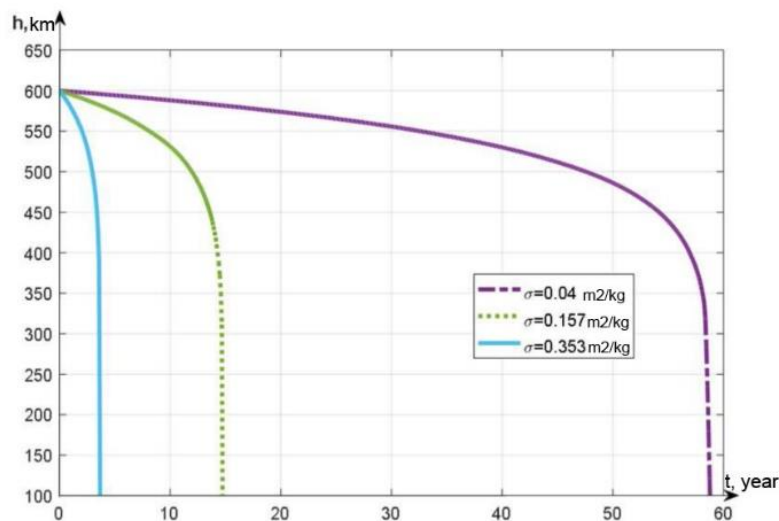


Figure 3. Estimation of the lifetime of a spacecraft with three different ballistic coefficients at an initial altitude of 600 km.

In the case of a spherical device, the area of the shell film is calculated as the surface area of the sphere using the formula

$$S_{film} = 4\pi R_{sph}^2. \quad (10)$$

R_{sph} , m – radius of the spherical shell.

The volume of gas filling the device is defined as

$$V = \frac{4}{3}\pi R_{sph}^3, \quad (11)$$

the area of the middle of the spherical shell

$$S_m = \pi R^2. \quad (12)$$

S_m, m^2 – middel area.

6.2. Pyramidal braking device

The pyramidal device [12, 13] is a regular pyramid, the edges of which are formed by inflated aerobals, with a film stretched between them. The base of the pyramid, which after stabilization of the tandem “spacecraft + inflatable braking device” will be leeward (not blown), is not supposed to be covered with film (see Figure 4a).



Figure 4. A possible view of an apparatus equipped with a braking device with a pyramidal inflatable braking device a) without air rails at the base; b) with aerobals at the base for rigidity

To give the brake device greater rigidity and stability, the base of the pyramid can be additionally reinforced with inflatable beams around the perimeter (see Figure 5b).

Both options compared to the shell of a spherical shape have several important advantages:

- to maintain the volume, a smaller supply of pressurized gas or reagent is required,
- increased survivability;
- less probability of penetration of the aerobals due to the fact that from any direction of impact they occupy only a small part of the projection area of the apparatus, and not every film penetration will fall on aerobals ;
- aerobals can be pneumatically separated by bypass valves, which even in case of penetration and descent, if one beam is damaged, prevent leakage from the other beams ;
- when the number of sides is more than 4, the functionality of the device is preserved when one or several air racks are lowered, due to the fact that the adjacent girders support the volume of the structure.

A rough estimate of the mass of gas and film is made on the basis of the total length of the air racks, without taking into account the gas in the adapters, corners and folds. The shape of the beam in the first approximation is cylindrical:

$$V = n \cdot L \cdot \frac{1}{4} \pi d_a^2, \quad (13)$$

n – the number of faces of the aerodynamic device,,

d_a, m – diameter of airbals,

L, m – the length of the edge of the pyramid (aerobals).

The middel area pyramidal shell

$$S_m = \frac{\left(\frac{V}{n \cdot \frac{1}{4} \pi d_a^2}\right)^2 - h_p^2}{2} \sin \frac{360^\circ}{n}. \quad (14)$$

h_p, m – the height of the pyramid.

Thus, the area of the mid-section grows in proportion to the square of the volume, $S_m \sim V^2$, so this form of fairing is the most economical of the proposed.

The coefficient of resistance of the pyramid when blowing along the axis (at zero angles of attack and slip) is calculated by the expression

$$C_x = 2 \cos^3 \alpha_{bf}. \quad (15)$$

α_{bf} – the angle between the face and the base of the pyramid.

Estimated film area required for assembly

$$S_{film} = n \left(\underbrace{L\pi d_a}_{sleeve} + \underbrace{\frac{1}{2} \sqrt{L^2 - h_p^2} \sin \frac{360}{2n} \sqrt{L^2 - (L^2 - h_p^2) \left(\sin \frac{360}{2n} \right)^2}}_{side} \right) \quad (16)$$

7. Results

The following Table 1 shows the final qualitative comparison of the two types of shells, from which it can be concluded that pyramidal-type devices have a significant advantage.

Table 1. Comparison of the shells of various shapes.

Criterion	Type	
	Sphere	Pyramid
Dependence of projection area on volume	$S_m \sim V^{2/3}$	$S_m \sim V^2$
The probability of penetration of the beam during the passage of the fragment through the projection of an inflatable braking device	100%	$\ll 100\%$ (for 4-sided pyramid with base 10 m – 2%)
Potential survivability when breaking through	Low	High
Mechanical stability	High	Determined by beam diameter

Comparing the approximate masses of an inflatable braking device, which should be mounted on a 250-kg spacecraft for removal from orbits of 400 km and 600 km, it becomes even more obvious that pyramidal devices are the only types of devices considered that provide a rational ratio of the mass of an inflatable braking device to the mass of the reconstructed spacecraft (up to 20% for any variant of the initial conditions and duration of the data). Spherical inflatable devices, in view of vulnerability, small C_x and large required volumes are realizable only for heights of about 400 km.

8. Conclusion

1. Taking into account the results obtained, it can be said that the use of passive brake devices in the form of inflatable structures can significantly help in the fight against comic debris in orbit.
2. 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.
3. 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. The results section shows the results of comparing two forms of inflatable braking devices.

References

- [1] V.V. Koryanov. Method of calculating the descent of the spacecraft in the atmosphere using technology adaptation landing in different environmental conditions, IAC-14-C2.3.4, 65th Astronautical Congress, Toronto, Canada, 2014, 29 September – 03 October.
- [2] Michele Iacovazzo, Valerio Carandente, Raffaele Savino, Gennaro Zuppari. Longitudinal stability analysis of a suborbital re-entry demonstrator for a deployable capsule. *Acta Astronautica. Volume 106*, January–February 2015, pp. 101–110.
- [3] V.V. Koryanov, V.P. Kazakovtsev. Dynamics of angular motion of landing vehicle in martian atmosphere with allowance for small asymmetries. *International Journal of Mechanical Engineering and Robotics Research*, Volume 7, Issue 4, 1 July 2018, Pages 385-391.
- [4] Scientific significance. [Electronic resource]: Project "Mayak". - Access mode: <http://cosmomayak.ru/about/science>.

- [5] M.D. Koptev. Dynamics and control of a swarm of nanosatellites in the task of studying the earth's magnetosphere [Electronic resource]. - Access mode: http://www.keldysh.ru/microsatellites/Bachelor_Thesis_Koptev.pdf. (15.05.2018)
- [6] M. Macdonald. Handbook of Space Technology / Malcolm Macdonald, Viorel Badescu. // [Electronic resource]. - Access mode: URL: https://books.google.ru/books?id=w_65BQAAQBAJ. (15.05.2018)
- [7] Low Cost, High Endurance, Altitude-Controlled Latex Balloon for Near-Space Research (ValBal) [Electronic resource]. - Access mode: URL: <https://asl.stanford.edu/wp-content/papercite-data/pdf/Suskho.Tedjarati.ea.AERO2017.pdf>. (15.05.2018)
- [8] The Super Pressure Balloon (SPB) [Electronic resource]. - Access mode: URL: https://sites.wff.nasa.gov/code820/docs/outreach/The_Super_Pressure_Balloon.pdf. (15.05.2018)
- [9] M. Finckenor. A Researcher's Guide to International Space Station. Space Environmental Effects [Electronic resource]. - Access mode: URL: https://www.nasa.gov/sites/default/files/files/NP-2015-03-015-JSC_Space_Environment-ISS-Mini-Book-2015-508.pdf. (15.05.2018)
- [10] V.S. Zarubin, V.N. Zimin, G.N. Kuvyrkin. Temperature Distribution in the Spherical Shell of a Gauge-Alignment Spacecraft. *Journal of Applied Mechanics and Technical Physics* (2017) 58. pp. 1083-1090. <https://doi.org/10.1134/S0021894417060141>.
- [11] V.V. Leonov. The design features of inflatable large-scale mirror concentrators for space high-temperature solar power plant. Proceedings of the international astronautical congress, IAC 67, Making Space Accessible and Affordable to All Countries. 2016.
- [12] V.I. Mayorova, N.A. Nerovnyy, D.A. Rachkin, S.M. Tenenbaum, O.S. Kotsur, A.S. Popov. Current status of BMSTU-Sail space experiment. 66 International Astronautical Congress 2015, Volume 14. pp. 10679-10683.
- [13] N.A. Nerovny, I.E. Lapina, A.S. Grigorjev. Light radiation pressure upon an optically orthotropic surface. *Journal of Quantitative Spectroscopy and Radiative Transfer*. Volume 202, November 2017, pp. 64-73. <https://doi.org/10.1016/j.jqsrt.2017.07.016>.

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