The technology of using inflatable structures made of special materials to adapt the de-orbiting system for removing spacecraft

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Abstract. We are today facing a huge issue on the concentration of space debris in near-Earth space. 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 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. The results of these studies show that using an inflatable device on an orbital spacecraft significantly reduces its lifetime (it then does not exceed 25 years in most cases). 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.

1. Introduction

Currently, the number of devices launched into space is constantly increasing. Spacecraft may fail for one reason or another, or they may run out of life. They remain to fly in orbit, becoming space debris. Various measures, both administrative and technical, are being taken to combat space debris. One of the options that can be offered is to use inflatable braking devices for converting spent spacecraft, which must be laid into the design of spacecraft. At the last stage, when the spacecraft becomes space debris, an inflatable braking device unfolds, which, by changing the geometry of the body, gives impetus to the spacecraft and the spacecraft begins its movement from orbit along a ballistic trajectory. Here you can consider two options for the development of further events. The first option is movement in a ballistic orbit, when the spacecraft burns in the atmosphere, the second case is movement along a ballistic trajectory, in which the spacecraft performs a successful landing on the surface using inflatable braking devices.

The authors of the paper consider the most to consideration both options. The paper is devoted to the creation of such a structure, the use of materials for such a design of inflatable braking devices, which would allow to open up in space and fulfill the assigned mission. The main types of forms that can be applied for such a purpose are considered.

Previously, landing issues were considered by the authors in [1, 2, 3].

The prototype for such a proposal in the use of inflatable braking devices is the MetNet project [4] and one of its continuations - the RITD project [5].
2. Review of materials for such a shell

**Shell.** Mass 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 °C to 250 °C) 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.

**Polyethylene terephthalate.** The material is also known as polyethylene glycol terephthalate, PET, PETG, polyester glycol, mylar. Non-toxic. Well cooked. Mass produced and finds extensive use in the national economy from films, sheets, hoses, to bottles, cases and other products. Relatively hard to break (destroyed at 2-4% deformation).

PET is often the basis for a multi-layer metallized film used to limit radiant heat transfer on spacecraft. Film porosity varies depending on thickness, supplier and other factors.

The general purpose film produces a large number of domestic and foreign manufacturers.

**Polyimide (Kapton).** Among the advantages of this polymer, in addition to chemical and temperature resistance, high radiation resistance is distinguished, however, it is unstable to alkalis. In particular, NASA viewed it as the preferred material for solar sails [6]. Depending on the variety, the working temperature range can reach -260 °C to +220 °C. The review revealed an industrial release of film with a thickness ranging from 30 microns. Kapton is used in special industries (electronics, energy, aerospace), as well as in construction.

**Teflon (PTFE).** Organofluorine compound. Heat-resistant, welded, not flammable. Chemically neutral, films have low porosity. Finds a huge number of applications in industry. In the Russian Federation, fluoro-plast properties are standardized according to GOST 24222-80. More plastic to break than PET (breaks at 50 - 200% strain, depending on the grade). Accordingly, films with a thickness ranging from 0.1 mm were found on sale.

**Graphene film.** Graphene is a modification of solid carbon in which atoms are lined up in layers, with each layer representing a repeating structure in the form of carbon atoms lined up in the form of regular hexagons. Currently an experimental material. It is not produced in large quantities and is used mainly in the chemical and electronic industry. However, potentially producing films in large formats for mechanical applications. This has the record withstand tensile stresses.

GrapheneX Group (https://www.facebook.com/GrapheneXDT/) from the University of Delft (Delft University of Technology), the Netherlands, since 2015 has been developing and testing elements of spacecraft, the design of light sails based on the use of graphene.

3. De-orbiting device configurations

De-orbiting devices can be designed in shapes of sphere, torus, cone, pyramid, either dome, plane etc. The development of inflatable structures is covered in other articles [7, 8, 9].

According to the newtonian 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

$$\vec{R}_a = -\vec{n}V_{\infty}^2 \rho \cdot S \sin^2 \alpha = -\vec{n}(V_{\infty} \cdot \vec{n})^2 \rho \cdot S,$$

(1)

Where:

- $\vec{n}$ – unit vector normal to surface $S$. 

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\( V_\infty \) – gas particle velocity, equal to spacecraft velocity relative to moving atmosphere \( V_{atm} \), with minus sign,
\( \rho \) – atmosphere density,
\( \alpha \) – angle between flow velocity vector and surface.

Drag force \( X_\alpha \) respectively is equal
\[
X_\alpha = -\frac{V_\infty}{V_\infty^2} (\vec{n} \cdot \vec{V}_\infty) \rho \cdot S, \tag{2}
\]
or
\[
X_\alpha = \frac{1}{V_\infty} (\vec{V}_\infty \vec{n}) \rho \cdot S, \tag{3}
\]

Spacecraft velocity relative to atmosphere, rotating with Earth (airspeed)
\[
\vec{V}_{atm} = -\vec{V}_\infty = \vec{V} + [\vec{r} \times \vec{\omega}_3], \tag{4}
\]

\( \vec{V} \) – 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 \( q_\infty \) and drag coefficient \( c_{xa} \), or through ballistic coefficient \( \sigma \), respectively
\[
X_\alpha = c_{xa} \cdot q_\infty \cdot S, \tag{5}
\]
where \( q_\infty = \frac{\rho V_\infty^2}{2} \), or
\[
X_\alpha = m \cdot \sigma \cdot V_\infty^2 \cdot \rho. \tag{6}
\]

From (5) and (6)
\[
\sigma = \frac{c_{xa} S}{2m}, \tag{7}
\]

\( m \) – spacecraft mass.

From (3) and (5) \( c_{xa} \) for plane surface
\[
c_{xa} = \frac{2}{V_\infty^2} (\vec{V}_\infty \vec{n})^3 = 2 \cos^3 (\vec{V} \vec{n}), \tag{8}
\]
and ballistic coefficient
\[
\sigma = \frac{1}{m} \cos^3 (\vec{V} \vec{n}) \cdot S. \tag{9}
\]

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. 1.
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 cannot 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. 2.

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. 3).
Figure 3. Polar diagram of the dependence of the coefficient of the drag of the plane 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 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.

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. 4. 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.

Figure 4. Schemes of mutual placing of satellite and braking device: a) adjacent; b) remote on the cable; c) remote on a hard construction

In this case, it is preferable and technologically feasible to create a braking device shape using inflatable beams (see Fig. 5 and Fig. 6).

That will allow reducing the volumes of working gas for inflation and maintenance of the required form.
4. 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.

5. 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 ($S_0$) varied from 0.05 m$^2$ to 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 1.
Table 1. Mass and geometric parameters of satellites

| Number | Mass, kg | S0, m² |
|--------|----------|--------|
| 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. 7-11.

**Figure 7.** Changes in the height of spacecraft of various configurations for the initial altitude H0 = 300 km

**Figure 8.** Changes in the height of spacecraft of various configurations for the initial altitude H0 = 400 km
As can be seen from the obtained results Fig. 7-11, 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 [10].

So, according to preliminary calculations, an inflatable braking device in the form of a tetrahedron with a cross-sectional area of 4 m² will weigh about 1.5 kg.

6. 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.

7. 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] 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.

[3] Michele Iacovazzo, Valerio Carandente, Raffaele Savino, Gennaro Zuppardi. Longitudinal stability analysis of a suborbital re-entry demonstrator for a deployable capsule. Acta Astronautica. Volume 106, January–February 2015, pp. 101–110.

[4] The Mars MetNet Mission. Concept Drawing. http://fmispace.fmi.fi/old-metnet/index.php?id=100, (accessed: 05.02.2019).

[5] Jyri Heilimo, Ari-Matti Harri, Sergey Aleksashkin, Vsevolod Koryanov, Ignacio Arruego, Walter Schmidt, Harri Haukka, Valery Finchenko, Maxim Martynov, Boris Ostresko, Andrey Ponomarenko, Viktor Kazakovtsev, Susanna Martin, and Tero Siili. RITD - Adapting Mars Entry, Descent and Landing System for Earth. Geophysical Research Abstracts Vol. 16, EGU2014-5506-1, 2014, EGU General Assembly 2014

[6] Solar Sail Propulsion [Electronic]. – Access mode: URL: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120015076.pdf. (15.05.2018)

[7] Koryanov V. Research of the dynamics motion of landing vehicle with inflatable braking device in the planet atmosphere // Proceedings of the International Astronautical Congress, IAC vol. 8, 2013. pp. 5831-5836.

[8] Aleksashkin S.N., Pichkhadze K.M., Finchenco V.S. Printsipi proyektirovaniya spuskayemykh v atmosferakh planet apparatov s naduvnymi tormoznymi ustroystvami // Vestnik FGUP NPO im. S.A. Lavochkina [Design principles in planetary atmospheres reentry vehicles with inflatable braking systems // Herald Federal State Unitary Enterprise Scientific and Production Association named after Lavochkin] 2012. №2. pp. 4-11.

[9] V.V. Leonov. The design features of inflatable large-scale mirror concentrators for space high-temperature solar power plant. Proceedings of the international astronomical congress, IAC 67, Making Space Accessible and Affordable to All Countries. 2016.

[10] Report of the Committee on the Peaceful Uses of Outer Space. General Assembly Official Records Sixty-second session Supplement No. 20 (A/62/20). p.50, 2007.