Research of Using Inflatable Braking Devices in the Orbital Service System Application

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Abstract. In this scientific work are considered questions regarding the use of inflatable braking devices to deorbit spacecrafts, thus avoiding the formation of new space debris. The principle 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 its design and assembly on Earth. Another option is when the braking device is installed on the spacecraft after it has been classified as space debris. In this case, we need to capture the space debris and install the device. But then, it requires space debris to have a standardized interface for docking. In this scientific work, several variants of the form, arrangement of types and types of inflatable braking devices are considered. Next, a comparison of these devices according to various criteria is made and a conclusion is made about the advantages and disadvantages of using each of them.

1. Introduction
Currently, the international community of scientists and engineers is in the active phase of working out space missions to clean up space from space debris. Meanwhile, various technologies for the reduction of orbital lifetime and the disposal of space debris are being developed. Among the technologies for deorbiting space debris, these are the most popular:

- Capture of space debris with the help of an active spacecraft. Within the framework of this concept, a lot of methods for capturing space debris, which are subdivided into active and passive [1], are considered.
- Deorbiting spacecrafts by using a solar sail [2]. But the different shapes [3] and materials raise some questions.
- Deorbiting spacecrafts by increasing their aerodynamic resistance 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 [4, 5].

2. De-orbiting device configurations
Deorbiting devices can be designed in shapes of sphere, torus, cone, pyramid, dome, plane etc. The development of inflatable structures is covered in other articles [6, 7, 8].

According to Newton’s theory, it is assumed that in the case of a rarefied high-speed flow, the gas particles experience an inelastic collision with the surface of the braking device. The body is transferred to the velocity component of the particles, normal to its surface. According to this theory, the resultant force acting on a flat surface with an area $S$ is equal to:

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

(1)

$\vec{n}$ – unit vector normal to surface $S$.
$V_{\infty}$ – gas particles’ velocity, equal to spacecraft’s velocity relative to that of the moving atmosphere $V_{atm}$, with minus sign,
$\rho$ – atmosphere’s density,
$\alpha$ – angle between flow velocity vector and surface.

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

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

or

$$X_a = \frac{1}{V_{\infty}^2}(V_{\infty} \cdot \vec{n})^2 \rho \cdot S,$$

(3)

Spacecraft’s velocity relative to that of the atmosphere, rotating with Earth (airspeed)

$$V_{atm} = -\vec{V}_{\infty} = \vec{V} + [\vec{r} \times \vec{\omega}_3],$$

(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

$$X_a = c_{xa} \cdot q_{\infty} \cdot S,$$

(5)

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

$$X_a = m \cdot \sigma \cdot V_{\infty}^2 \cdot \rho.$$

(6)

From (5) and (6)

$$\sigma = \frac{c_{xa}S}{2m},$$

(7)

$m$ – spacecraft’s mass.

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

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

(8)

and ballistic coefficient

$$\sigma = \frac{1}{m} \cos^3 \left(\frac{\vec{V}_{\infty} \cdot \vec{n}}{2}\right) \cdot S,$$

(9)

3. Overview of materials used for the removal system

Shell

The mass industry offers a huge number of film materials having 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 spacecraft staying in the Earth’s orbit (-150 ... 250 °) during the entire period of the spacecraft’s existence and its subsequent descent from orbit.

2. Flexibility and strength sufficient to maintain the integrity and tightness of the shell after installation, pressing into the compartment, storage, subsequent disclosure and pressurization.

3. Low porosity.

4. Manufacturability of cutting and fasteners. For example, weldability for soldering tight joints, or ease of cutting.
5. Mass production and reasonable cost. The main thin-film materials were discussed below. Here is the comparison of material physical parameters (Table 1.)

**Table 1. Comparison of material physical parameters**

| Parameters          | Operating temperature | Tensile Strength | Density (kg/m³) | Elongation at break | Thickness |
|---------------------|-----------------------|------------------|-----------------|---------------------|-----------|
| Polyethylene terephthalate | -60°C~+170°C          | 172 MPa          | 1400            | 2-4%                | ×         |
| Polyimide (Kapton)  | -260°C~+220°C         | 116 MPa          | 1340            | 9%                  | ×         |
| Teflon (floroplast) | -195°C~+200°C         | 11.6MPa~37.4 MPa | 2,150~2,180 kg/m³ | ×                  | 20mkm~1000mkm |

**Boost system**

In the framework of this work, inflatable type brake devices are considered. Supercharging involves the use of gas to open and maintain the shape of an aerodynamic device. In view of the similarity of the task, we will consider the excess boost pressure of the device to be equal to the excess internal pressure for stratostats in the Earth’s atmosphere. This will simplify the assessment of the possibility of using certain materials for Inflatable Braking Device: if, under the conditions of a ground-based experiment, the shells maintain their shape and integrity at this pressure, then they will be able to maintain their shape and withstand similar breaking stress in space conditions. According to publications, the overpressure of atmospheric balloons is about 150 Pa according to publications of the Laboratory of Autonomous Systems at Stanford University [9] or 180 Pa [10]. It is also assumed that in space conditions an even lower excess pressure will be required, since in the orbit the opening of the inflatable structures is not counteracted by Earth’s gravity.

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

\[ pV = \frac{m_{\text{gas}}}{M}RT, \]  \hspace{1cm} (10)

makes up

\[ m_{\text{gas}} = \frac{pVM}{RT}, \]  \hspace{1cm} (11)

where

- \( m_{\text{gas}} \), kg - mass of boost gas,
- \( p, \) Pa - boost pressure (in this case, approximately equal to 150 Pa),
- \( V, \) m³ - the volume of the expanded shell,
- \( R = 8.315 \) J/(mol·K) - universal gas constant,
- \( T, \) K is the temperature of the gas filling the device.

**Cold gas generator**

Cold gas generators are used in the chemical industry, fire extinguishing systems, and in automotive inflatable rescue systems.

**Benefits:**

- Non-explosive, lack of constant internal stress and pressure.
- Longer preservation of working capacity (7 years, in the long term> 10 years http://www.esa-tec.eu/space-technologies/from-space/cool-gas-generators/).

**Disadvantages:**

- Requires a slightly higher energy input for operation, compared with the cylinder (heaters).
Well-known manufacturers of aerospace gas generators are TNO Defense, CGG Safety and Systems BV, EXXFIRE BV (Netherlands), General Dynamics (USA), the international enterprise MOOG Inc. and others.

One example of the use of a gas generator in a laboratory bench for testing a space aerodynamic braking device [9]. As a sample of the onboard nitrogen generator used in the calculations in this work, the model of this enterprise is adopted [10]. The generator has a height of 166 mm, a diameter of 47 mm, a mass of 0.55 kg and a mass of released gas of 43 g. That is, 2 gas generators provide 95% of the mass of gas stored in a liter cylinder, and at the same time they will occupy about half the volume and weight.

4. Comparison of different configurations of inflatable brake devices

Spherical brake device
Fundamentally, an inflatable device can be located adjacent to the spacecraft, or remotely on a cable/rod. If the spacecraft has no protruding parts from the side of the balloon deployment that can damage it, the most effective is assumed to be close. Such placement prevents the spin of the spacecraft relative to the balloon and possible impacts on it. In the presence of protruding parts on the spacecraft hull from the side of the opening of the brake device, the cylinder can be taken out on a rigid rod. However, with this scheme, the cylinder is less protected from damage when it hits the body, and the overall rigidity of the structure decreases. In this paper, we consider only scheme a). (Figure 1.)

![Figure 1. Schemes of the mutual arrangement of the spacecraft and the braking device: a) adjacent; b) remote on the cable; c) remote on a rigid beam](image)

Pyramidal brake device
The pyramidal device is a regular pyramid, the edges of which are formed by inflated aerobalks, a film is 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 a film (Figure 2a).

![Figure 2. A possible view of an apparatus equipped with a reduction device with pyramidal inflatable brake devices a) without aerial beams at the base; b) with aerial beams at the base for clarity.](image)
Both options in comparison with a spherical shell have a number of important advantages:

- to maintain the volume requires a smaller supply of boost gas or reagent,
- increased survivability

5. Conclusions

1. The use of inflatable brake devices to provide spacecraft information is possible and promising.

2. Direct calculations of the used form of an inflatable brake device showed the following:

   Comparing the approximate masses of inflatable brake devices, which must be mounted on a spacecraft weighing 250 kg for orbiting 400 km and 600 km, it becomes even more obvious that pyramidal devices are the only ones considered that provide a rational ratio of the mass of the inflatable brake device to the mass reducible spacecraft (up to 20% for any type of inflatable device and duration of information). For more than 20 years, a cone-type inflatable brake device will weigh about 100 kg (40% of the spacecraft’s mass) and their use with promising spacecraft is a rational solution. Spherical inflatable devices, due to vulnerability, small Cx and large volumes required, are only feasible for altitudes of approximately 400 km.

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