On the way to the optimal design of an inflatable aerodynamic decelerator of space debris removal system for CubeSat nanosatellites

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Abstract. In order to avoid pollution of the near-Earth space out-of-service small spacecrafts could be transferred to the disposal orbits in dense atmosphere with the help of inflatable decelerator. The issues of aerodynamics and heat transfer are of key importance for such systems design. The movement conditions in a low Earth orbit of a spherical inflatable aerodynamic decelerator designed for small spacecrafts removal are considered. The preliminary results of thermal analysis of the decelerator made of polymer film with the surface metallization are presented.

1. Introduction.
Human activity in space, including the near-Earth space, causes the problem of space debris formation [1-5]. Under space debris out-of-service or broken-down spacecrafts are meant. According to the forecast of many specialists till the mid the 21st century the level of space debris density in the most popular near-Earth orbits (sun-synchronous and geostationary orbits) could reach critical values [6]. The tendency to use small spacecrafts leads to a multiple increase of potential space debris objects.

A number of projects of space debris removal are known including projects of large transformable traps made of composite materials [7-9]. Space debris traps have design similar to transformable space antenna reflectors [10-12]. It is obvious that space debris elements gathered by traps as well as traps themselves need to be deorbited. For example, one of the possible removing ways is transferring of space debris objects to the dense atmosphere [6]. Current study is dedicated to the research of CubeSat type nanosatellites removal from an orbit with the help of an inflatable aerodynamic decelerator (IAD).

2. Modelling of movement conditions and aerodynamic flow
Values of mass and dimensional parameters are of vital importance for the development of the IAD for small spacecrafts deorbiting. If the form of IAD is spherical then its mass depends on the diameter and thickness of the shell. From the other hand, the diameter of the shell determines drag force and consequently atmospheric descent duration.

The following system of equations [13] was used for the modelling of IAD movement together with a small spacecraft in the central gravitation field:
\[
\frac{dV}{dt} = -\sigma_x g_0 \frac{pV^2}{2} - g \sin \theta;
\]
\[ \frac{d\theta}{dt} = \sigma_x K g_0 \frac{\rho V}{2} + \left( \frac{V}{R} - g \right) \cos \theta; \]

\[ \frac{dH}{dt} = V \sin \theta; \]

\[ \frac{dL}{dt} = V \frac{R_{pl}}{R} \cos \theta, \]

where \( V \) is the velocity of the center of mass; \( \theta \) is a slope angle of the velocity vector to the local horizon; \( H \) is a flight altitude; \( L \) is a flight distance measured along the planet surface; \( \sigma_x = C_x S / Mg \) is a ballistic parameter; \( g_0 = \gamma M_p l / R_{pl}^2 \), \( g = g_0 R_{pl}^2 / R^2 \) are gravity acceleration on the surface and at a height \( H \) correspondingly; \( S_m \) is a body reference area; \( R_{pl}, R = R_{pl} + H \) is a planet radius and a distance from its center of mass to the centre of mass of the apparatus correspondingly; \( C_x = C_x(t), C_y \) are drag and lift coefficients correspondingly; \( K = C_y / C_x \) is aerodynamic quality; \( \gamma \) is the gravitational constant; \( M_p \) is a planet mass.

This system of equation does not take into account spacecraft movement around the center of mass. The spacecraft movement was assumed to occur under the influence of the gravity force and aerodynamic forces [13]. It was assumed that \( C_y = 0 \), as the axisymmetric flow was considered.

For the modelling purpose, the atmosphere was conditionally divided in two sections depending on the Knudsen number: \( \text{Kn} = l / l_{sc} \), where \( l \) is the mean free path; \( l_{sc} \) is the characteristic linear size of IAD. The first section with the free-molecular flow regime corresponds to the Knudsen number \( \text{Kn} > 0.01 \), while the second section – to \( \text{Kn} < 0.01 \), where the continuous medium mode is realized. Based on the estimations for spherical shells with diameters from 1 to 6 m the border between the free-molecular and continuum flow regimes lies at 106 km. The standard atmosphere model was used for calculations [14]. The following formula [15] was used for determination of the drag coefficient of a sphere at free-molecular flow regime:

\[ C_x = 2 + \frac{4}{35} \left( \frac{\pi T_r}{T_{\infty}} \right)^{1/2} + \frac{1}{5^2}, \]

where \( T_{\infty}, T_r \) are the gas temperatures in the incident and reflected flows (here we are talking about reflected molecular flows, not thermal radiation); \( S \) is the relation of an incident flow velocity to a possible thermal velocity of molecules in a flow.

Dependency of \( S \) of an orbital flight altitude at various levels of solar activity was taken from [15]. The minimum solar activity \( F_{10.7} = 65 \, \text{W/(m}^2 \cdot \text{Hz}) \) at local time \( t_l = 4 \, \text{am} \) was considered for calculations. The temperature relation was taken similar to [17] \( T_r / T_{\infty} = 0.4 \). The spacecraft mass was calculated by the formula:

\[ M_\Sigma = n \cdot M_{sp} + M_{sd} + M_g, \]

where \( n \) is a number of CubeSats in a cluster; \( M_{sp} \) is a spherical shell mass; \( M_{sd} \) is an IAD mass with the exception of a spherical shell mass and compressant mass; \( M_g \) is the mass of compressant necessary for a decelerator inflation.

3. The results of the numerical simulation of motion IAD

Simulation was carried out for the IAD spherical shell that removes one or three CubeSats from the low orbit with the altitude of 300 km. As a result of the calculations, the interrelation between the diameter of the IAD spherical shell \( d \) and the time of the spacecraft descent into the dense layers of the atmosphere \( t_d \) was established (Tables 1 and 2 and Figures 1-4). It can be seen that the descent time decreases with the increasing sphere diameter, and this dependence is non-linear. As the spherical shell diameter impedes to the maximum value in the selected range, the descend time of the IAD with the spacecraft changes only slightly.
Table 1. Dependence of the descent time of the IAD with one spacecraft of CubeSat type on the sphere diameter

| Sphere diameter, m | \( M_\Sigma \), kg | \( t_d \), hour |
|-------------------|-------------------|---------------|
| 1.0   | 2,247             | 29.54         |
| 1.5   | 2,306             | 15.86         |
| 2.0   | 2,388             | 11.07         |
| 2.5   | 2,494             | 8.88          |
| 3.0   | 2,623             | 7.64          |
| 3.5   | 2,775             | 6.83          |
| 4.0   | 2,952             | 6.25          |
| 4.5   | 3,151             | 5.82          |
| 5.0   | 3,374             | 5.51          |
| 5.5   | 3,621             | 5.24          |
| 6.0   | 3,891             | 5.05          |

Table 2. Dependence of the descent time of the IAD with three spacecrafts of CubeSat type on the sphere diameter

| Sphere diameter, m | \( M_\Sigma \), kg | \( t_d \), hour |
|-------------------|-------------------|---------------|
| 1.0   | 4,647             | 56.63         |
| 1.5   | 4,706             | 27.74         |
| 2.0   | 4,788             | 17.86         |
| 2.5   | 4,894             | 13.11         |
| 3.0   | 5,023             | 10.64         |
| 3.5   | 5,175             | 9.14          |
| 4.0   | 5,352             | 8.14          |
| 4.5   | 5,551             | 7.42          |
| 5.0   | 5,774             | 6.88          |
| 5.5   | 6,021             | 6.45          |
| 6.0   | 6,2891            | 6.11          |

Based on the obtained results and by taking into account technological complexity of manufacturing and inconvenience of using large diameter spherical shells, it was concluded that an efficient choice of the IAD spherical shell diameter for the most popular CubeSat nanosatellite cluster configurations is the diameter not more than 6 m.

Figure 1. The descent duration of the different diameters IAD with one spacecraft of CubeSat type: 1 – \( d=1.0 \text{ m} \); 2 – \( d=1.5 \text{ m} \); 3 – \( d=2.0 \text{ m} \); 4 – \( d=2.5 \text{ m} \); 5 – \( d=3.0 \text{ m} \)
Figure 2. The descent duration of the different diameters IAD with one spacecraft of CubeSat type: 
1 – $d=3.5$ m; 2 – $d=4.0$ m; 3 – $d=4.5$ m; 4 – $d=5.0$ m; 5 – $d=5.5$ m; 6 – $d=6.0$ m

Figure 3. The descent duration of the different diameters IAD with three spacecrafts of CubeSat type: 
1 – $d=1.0$ m; 2 – $d=1.5$ m; 3 – $d=2.0$ m; 4 – $d=2.5$ m; 5 – $d=3.0$ m
Figure 4. The descent duration of the different diameters IAD with three spacecrafts of CubeSat type:
1 – $d=3.5\,\text{m}$; 2 – $d=4.0\,\text{m}$; 3 – $d=4.5\,\text{m}$; 4 – $d=5.0\,\text{m}$; 5 – $d=5.5\,\text{m}$; 6 – $d=6.0\,\text{m}$

Conclusion
1. The methodology was developed and the descent time modelling results of one or three CubeSat type spacecrafts deorbiting from the 300 km with the usage of the spherical IAD are presented.
2. It was demonstrated that the duration of the descent in the discharged atmosphere decreases with the increasing diameter of the IAD shell and moreover depends nonlinearly on it.

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