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Space traffic hazards from orbital debris mitigation strategies

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ABSTRACT

The paper gives coverage of recent advances in mathematical modeling of long term orbital debris evolution within the frames of continua approach. Under the approach the evolution equations contain a number of source terms responsible for the variations of quantities of different fractions of orbital debris population due to fragmentations and collisions. Mechanisms of hypervelocity collisions of debris fragments with pressurized vessels are investigated. The spacecraft shield honeycomb concept is suggested based on principles of impact energy conversion and redistribution and consumption by destroyable structures. The paper is devoted to the 100th anniversary of the founder of space debris research in Moscow State University Prof. G.A. Tyulin.

1. Introduction

The rapid growth of the orbital debris population in Low Earth Orbits results in an increase in collision probability of space vehicles with debris particles, especially with those sizing less than 1 cm [1–3]. The continua approach to space debris evolution modeling was first developed at the end of 1980s in Moscow M.V. Lomonosov State University in the Laboratory under the direction of Georgy Tyulin (1914–1990), whose 100th anniversary is celebrated this year (Fig. 1). After completing graduation from the University in 1940, Georgy Tyulin was in the Second World War from 1941 to 1945 as a commander of ram artillery troops units. After the War he was working in the team of pioneers of Russian cosmonautics (Figs. 2 and 3) serving as a state commission chairman for many space programs. After his retirement from military service in the grade of two stars general he returned to his Alma Mater Moscow M.V. Lomonosov State University in 1977 and became the head of Wave Processes Laboratory in 1978. The main topic of research was numerical investigation of irreversible wave processes relevant to space applications.

The suggested continua method for orbital debris evolution modeling [2,4] has the following peculiarities:

- making use of a statistical approach describing the current debris environment in the form of distribution functions for the main elements of debris orbits;
- applying the averaged description for the sources of space debris production;
- taking into account collisions of debris fragments of different sizes (including non-cataloged ones) that could lead not only to debris self-production but also to self-cleaning of the Low Earth Orbits;
- developing numerical methods for integration of the governing system of evolution equations in partial derivatives.

Examples of long-term forecasts of the space debris environment were studied and the role of collisions of

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Fig. 1. Space debris research in Moscow M.V. Lomonosov State University was launched in 1980s by Prof. G.A. Tyulin.

Fig. 2. S.P. Korolev and G.A. Tyulin. Final instructions to the cosmonaut P. Belyaev at a launch site Baikonur, March 18, 1965.

Fig. 3. G.A. Tyulin and first cosmonauts team members. From left to right: Yu Gagarin, G. Tyulin, G. Titov, A. Nikolaev, A. Kuklin.

debris fragments of different sizes in the overall processes of space contamination and self-cleaning of the low orbits was evaluated [4–7].

The growth of collision probability with debris fragments brought spacecraft designers to the necessity of shielding the space vehicles. For the scenario business as usual without explosions and disposal following our prediction model the number of fragments larger than 20 cm in size will increase 1.5 times during 200 years. The number of objects with size from 10 to 20 cm will increase 3.2 times, whereas predicted increase in smaller-sized fragments is 13–20 times [6,7]. The number of small-size, non-cataloged objects will grow exponentially in mutual collisions.

The shield should meet the following requirements: providing an effective protection for the spacecraft in collisions with small size debris at relative velocities up to 12 km/s, and having a relatively low mass.

The double bumper and multi-shock shield concepts [8–10] suggested at the end of 20th century proved their effectiveness. A new concept suggested in the beginning of the 21st century [2,11,12] states that protecting the spacecraft by a honeycomb of small gas-filled containments could form a much more efficient shield with lower mass. As multi-sheet shielding concept uses thin shield elements to repeatedly shock the impacting projectile to cause its melting and vaporization, the new gas-filled containment shield concept uses continuous effect of pressurized gas to cause fragments slowing down, heating, melting, atomization and evaporation. Besides, using gas-filled bumpers makes it possible to increase the area of the zone of impact energy redistribution including the side and front walls due to the property of gas to transmit pressure in all directions. This is a considerable advantage of the present concept.

The gas-filled bumper shields could be reusable, as the rate of gas phase leakage on depressurization is rather low and the loss of mass is negligible during the characteristic time of impact. The influence of molar mass of the gas phase and other parameters on the rate of impact energy consumption and transformation is important. This principle could be used for effective shielding of space vehicles.

2. Shielding concepts in hypervelocity collisions

Developing a concept for spacecraft elements shielding needs answering the main question: which characteristic determines effective shield or shielding failure? This characteristic is, usually, penetration of a projectile behind the shield, or perforation. The impacting projectile carries definite momentum and energy. In spite of different breakup criteria used in engineering practice the most detailed examination of accumulation of damages and fragmentation shows that energetic criteria reflect the true physics. Methods avoiding perforation are similar for all shields, which means that redistribution of momentum and energy on a larger area is needed to provide lower local loading. However, the momentum conservation law is that of a vector type, which means that, despite all efforts, momentum carried by the projectile would be transmitted to the target plus projectile agglomeration in case of inelastic collision. From this point of view impact momentum of 1000 kilo body at velocity 1 m/s is equivalent to impact momentum of 1 kilo bullet at velocity 1 km/s. However the probability of shield perforation in the second case is much higher because damages in the target are determined using delivered energy. And the delivered energy in the second example surpasses three orders of magnitude impact energy in the first example. Thus in developing the shield concept it seems more profitable to