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Jet-charge as an effective tool in the development of spacecraft shields testing against micrometeoroids and man-made debris

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ABSTRACT

This paper introduces a new method using jet-charges for testing shields developed for spacecraft protection against micrometeoroids and man-made debris. A test pattern for obtaining a gradient-free, explosively formed jet is considered. Values of the high-speed projectile velocity, mass and energy are assessed in relation to the angle of the conical liner and the angle of the high-explosive detonation front. Maximum parameters of the high-velocity projectile have been found, and the range of the practical interest has been determined.

1. Introduction

The process of space development results in intensive pollution of the circumterrestrial space by man-made debris. It is reported that approximately 29,000 debris of more than 10-cm in size, nearly 670,000 debris in the range from 1 cm to 10 cm and more than 170 million debris ranging in size from 1 mm to 1 cm are circling the Earth. Each year, 100–150 tons of debris are deposited in to the terrestrial atmosphere [1].

The development of advanced, highly reliable and competitive space technologies is an important task of the Russian spacecraft industry. These technologies are proposed to significantly increase the active lifetime of telecommunication satellites in retransmission, navigation, optoelectronic and radiolocating observation of Earth in contaminated circumterrestrial space with destabilizing factors. A similar requirement is also important for permanent manned space stations.

In-space fuel and refuel technologies are widely applied throughout the world. This technology requires the development of protected fuel stations equipped with large-size depots and propulsion and power-plant systems.

The most dangerous natural factors for space vehicles are meteorites and space debris, as their kinetic energy is capable of damaging a spacecraft and partially or completely displacing the craft [1–3].

Therefore, the development and industrial production of large-size super low-weight screens protecting an object in one or various directions are urgent, as these screens deflect the impact of various destabilizing factors in circumterrestrial space. For updated development and advanced solutions of the aforementioned problems, the Russian spacecraft industry has worked to develop innovative designs and to make technological decisions for transformative modular protective screens.

The totality adverse factors in outer-space, both natural and manmade, reveal the necessity of developing special materials and tools that are capable of providing reliable protection. An individual protection solution is required for each spacecraft because of the quantitative value of the acceptable risk and cost efficiency resulting from space

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debris and meteoroids. This value depends on the mass, dimensions and configuration of a particular spacecraft and its working orbit and missions.

The general flow of space debris and meteoroids that can collide with a spacecraft depends on the altitude and inclination of the orbit, the dimensions and shape of the craft, the orientation to the flow velocity vector, the operational time of the spacecraft in the orbit, and the current level of solar activity. Numerous contamination models covering the circumterrestrial space and prognostication of the contamination level have been developed. These models can be used for the risk assessment of space debris and meteoroids, and the models are constantly being updated [4–11].

Efficient passive protection of a spacecraft can be provided using multi-layer structures containing interlacing layers of materials with various mechanical characteristics. A multi-layer shield provides better protection against high-speed space debris/meteorites than a monolith shield of the identical mass.

It is necessary to find new ways to protect against man-made debris and micrometeoroids in space to complement the known protective screens used for this purpose. For spacecraft operating in the circumterrestrial orbit, there is an urgent need for the development of the new generation of spacecraft and shell structures providing protection for both the spacecraft and the power supply equipment [12].

The key task of the protective screen development is the hyper-velocity impact testing for various types of targets. Currently, apart from light alloys, the list of target materials includes composites, ceramics, polymer and amorphous materials [13–20].

Totality of the hyper-velocity impact testing data has been obtained in tests with light-gas guns. Masses and velocities of projectiles launching by those guns are constantly increasing and their structures and measurement tools are becoming more complicated [21–24].

2. Using hypervelocity jets for impact tests

Apart from the light-gas guns, using blast energy is another way to reach high velocities [25,26]. Both of those methods are successfully applied in current testing assemblies [21]. As a rule, in both cases, a projectile is a metal ball; its shape preserves the moment of impact with a target. A jet-charge can be used if a certain mass is to be accelerated up to high velocities and the projectile shape is not preserved.

Jet-charges using blast energy have been used for obtaining high-velocity projectiles (up to 12 km/s) for a long time [27,28]. The advantages of jet-charges over other methods of reaching high velocities have been predetermined by vast investigative data on their use in ammunitions [29] and relatively low cost of testing. This fact is very important because the number of high-velocity testing is growing quickly in conjunction with the wider range of materials used.

A jet is generated at the moment when a metal shell collapses. In case of a simple shell shaped as a cone (2*A* angle), the jet parameters are determined by the angle value. When 2*A* angle is in the 300–600 range, the high-velocity jet (on the order of 10 km/s) with a corresponding high velocity gradient is formed. The velocity gradient results in the jet fragmentation. The jet mass is 10–20% of the shell mass, and the jet fragment mass is much less.

When the 2*A* angle value exceeds 900, an explosively formed projectile (a hit core) is formed with a mass close to the primary shell mass. However, the velocity of such a projectile does not exceed 2 km/s.

Hypercumulation scheme for laboratory tests was investigated in [30]. It is shown that in process of realization of hypercumulation conditions for jet formation without complete stagnation point involving formation of the inner zone of constant pressure (dead zone), the flow mass is always greater than slug mass. That opens wide possibilities for increasing fragment mass in laboratory tests.

There are many of other variants of the projectile and charge geometry. The scheme of a jet-charge with a variable-thickness sharp angle conical liner is the most suitable for forming massive but high-velocity projectiles. In this case the conical liner collapse, velocity is constant, which, in turn, allows for the reduction of the velocity gradient of various parts of the jet and for the formation of a high-velocity projectile.

3. Theoretical assessment and experimental modeling

Fig. 1 presents the scheme of the gradient-free jet-charge for attaining the high-velocity portion of the jet with the minimum velocity gradient. In the case when a centered jet-charge is used, the load, $R = M_{he}/M_v$, is constant for all its cross sections, where M_{he} and M_v are the mass of the high explosive rings and the conical liner rings in each cross section, respectively. The constant load of each conical ring provides the stationary velocity of the conical liner collapse and the resulting jet. At the cone compression, a projectile of approximately of the jet cone length is explosively formed. Concurrently, a low-velocity portion of the conical liner (slug) is generated; the slug should be cut-off.

The shell collapse velocity *W*, can be found from [28]:

$$W = D(1 - f\ sin(A_f))(2R/((2+R)(n^2-1)))^{0.5} \tag{1}$$

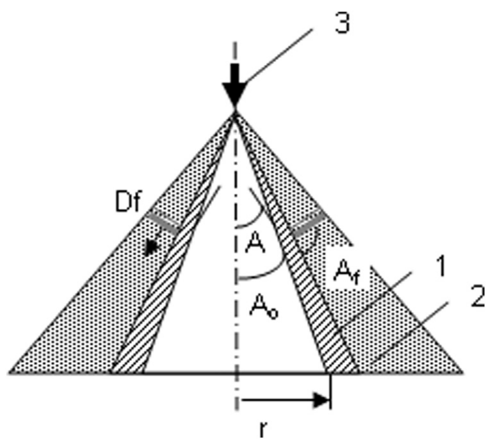

Fig. 1. Scheme of the jet-charge for the formation of the gradient-free jet: 1–the jet metallic cone, 2–the high explosive charge, 3–the initiation location, A_0–the initial angle of the liner cone; $A_f = 90°$–the angle between the detonation wave and the conical liner; A–the angle of the conical liner collapse forming the jet; r–radius of the cone; D_f–sliding detonation wave velocity.