Intelligent Assessment of the Impact of Hypervelocity Anthropogenic Particles on a Spacecraft

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Abstract

A methodology for intelligent evaluating the parameters of impacts of hypervelocity anthropogenic particles on the elements of Space Apparatus is proposed combining data on complex physical processes obtained using two types of complementary methods of estimation-experimental and computer modeling.

The structure has been developed and functions of an integrated intelligent information system that assess and predict the results of the impact of hypervelocity anthropogenic particles on the elements of the spacecraft have been described.

The proposed intelligent assessment of the impact of hypervelocity anthropogenic particles on the spacecraft can be used for developing theoretical and applied foundations for creating an intelligent control system for the protection of spacecrafts from particle impacts, as well as for optimizing the composition and design of elements of perspective spacecraft.

Keywords

spacecraft, hypervelocity anthropogenic particles, impact, damage, integrated intelligent system, fuzzy logic, experiments, modeling.

1. Introduction

One of the actual directions of the modern stage of space exploration is to ensure the efficiency and durability of orbital spacecraft (SC) under conditions of constant accumulation of space "debris" in near-earth space. This "debris" consists of *anthropogenic* (*technogenic*) particles that have arisen because of the space activities of the mankind: operational elements of rockets and spacecrafts and their wrecks.

According to analysts' forecasts the passive continuation of rocket launches can over the next 50 years lead to complete screening of the Earth by space debris at altitudes up to 2000 km and significantly impair the possibilities of effective and long-term use of spacecrafts.

The leading countries of the world carry out space activities: in Russia (Roscosmos State Space Corporation, a number of research and specialized institutions and enterprises), as well as in the United States and China, active attempts are being made to reduce the negative effect of particles, as well as to increase the survivability of spacecraft.

The survivability of a spacecraft as a system means its property to maintain the ability to function with the required efficiency during or after the impact of unfavorable external factors of outer space. Survivability is a complex property including *resistance* to adverse factors, the *security* of the spacecraft, as well as its *invulnerability* --- which characterizes the spacecraft's ability to avoid the impact of unfavorable factors on vulnerable elements by maneuvering and actively countering to unfavorable factors.

Therefore, the problem of increasing the survivability of a wide class and purpose spacecraft for long-term operation under the influence of anthropogenic particles due to optimal integration into the

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spacecraft design of an intelligent maneuvering control system and active counteraction to particle impacts is urgent but at the same time extremely difficult.

2. The problem of creating an intelligent maneuvering control system and active response to particle impacts

This work is a continuation and development of the research carried out in 2017-2019 in accordance with the task of the Ministry of Education and Science of the Russian Federation on the topic "Theory and adaptive algorithms for detecting anthropogenic particles and objects, and the assessment of dynamic interaction with spacecrafts based on the data intelligent analysis " [1].

The carried complex of works on the theoretical analysis of data about the space environment, the analysis of the known characteristics of anthropogenic particles, the results of simulation and experimental research made it possible to draw a number of fundamental conclusions.

Firstly, the greatest threat to the spacecraft can be posed by metal anthropogenic particles 0.5 - 5 cm in size moving in orbit with hypersonic space velocity at headings colliding with the spacecraft, or rather quickly approaching it in pursuit or tangentially from loop to loop on close orbits. The sizes of these particles the probability of the collision of which with the spacecraft is high do not allow to reliably monitor them by ground-based radar at long ranges due to the low level of radar cross-section (RCS) of particles (less than $0.0001 m^2$), as well as by ground-based optical means.

Secondly, based on the analysis of the characteristics of hazardous particles the most preferable method of their detection, selection and recognition against the background of other particles and interfering emissions from space is the use of onboard optical-electronic devices (OEDs) of the visible wavelength range the detection quality of which does not depend on distortion of signals caused by inhomogeneity of the transmission medium. However, for their implementation new methods and algorithms are needed to ensure the solution of information problems with the required quality for a large number (more than 1000) of simultaneously observed small-sized targets with restrictions on the time and number of OEDs on spacecraft board. The theoretical foundations for the development of such methods are considered in paper [2].

Thirdly, the input information for the supposed onboard intelligent control system of the spacecraft is not only the trajectory characteristics of particles but also the selection of particles from their set which are most dangerous for the survivability of the spacecraft and which can damage the coatings or structure, or disable vital units. For this, the data on the vulnerability of structures are needed, as well as the data on the assemblies and coatings of spacecrafts of various types as the targets of damage from impacts of hypersonic particles in vacuum.

Obtaining such data in natural space conditions is practically impossible. The possibilities of physical modeling of the characteristics of the vulnerability of materials and structures of real spacecrafts are limited by the mass and the speed of the accelerated elements. The approach proposed in this work is based on the use of combined estimation-experimental and computational methods using mathematical models of a high degree of adequacy on a supercomputer that were calibrated according to the results of experiments at lower speeds.

To achieve this goal it is necessary to solve the problem of developing theoretical and practical foundations that provide a justification for creating an intelligent system to increase the survivability of spacecrafts for long-term operation under the influence of anthropogenic particles.

The solution of the problem and the creation of a complex of new and improved theoretical and experimental methods, principles of constructing the systems under consideration is the development of achievements in this subject area of well-known scientific schools of Russia.

Decomposition of the problem of creating intelligent on-board systems to ensure the survivability of a spacecraft under the influence of space debris involves solving the following main tasks:

1. Development of theoretical and applied foundations for creating an intelligent control system for the protection of a spacecraft from impacts of anthropogenic particles with substantiation of possible options for the structure and composition of the system, assessment of its effectiveness on simulation models.

2. Development of methods and algorithms for the detection and selection of onboard OEDs from a large set (more than 1000) of the most dangerous hypersonic anthropogenic particles of small size (0.5–5 cm), which are not detected by ground-based national space control facilities in difficult background conditions of external illumination of particles by the Sun and the Moon, mechanical noises of instruments.

3. Development of experimental and theoretical methods that provide verification of computer models for studying anthropogenic particles and the vulnerability of materials and structures of spacecrafts as objects of hypervelocity damage.

The purpose of this article is an intelligent assessment of the impact of hypersonic anthropogenic particles on a typical spacecraft to substantiate the construction of its onboard intelligent control system for protection against anthropogenic particles.

3. Fundamentals of creating a system of intellectual analysis of the results of hypervelocity anthropogenic particles impact on spacecraft elements

An important aspect of the problem of controlling the protection of a spacecraft from the impact of hypervelocity anthropogenic particles is the development of the foundations for creating an information system for assessing and predicting the results of the impact of particles on spacecraft elements.

The main tasks in creating a system for intelligent analysis of the results of the impact of hypervelocity anthropogenic particles on the spacecraft are:

- investigation of the impact of hypervelocity particles on spacecraft elements by methods of physical and mathematical modeling;

- experimental study of the impact of hypervelocity particles on spacecraft elements in a wide range of parameters;

- integral analysis of the simulation results and experimental data using digital image processing (optical, X-ray, etc.) of the impact of hypervelocity particles on the spacecraft elements.

Experimental methods and mathematical modeling were used to study the hypervelocity interaction of particles with a spacecraft [2-7].

The main results in the field of experimental research were obtained by a full-scale experiment using barrel throwing of solids at targets. The disadvantage of experimental methods is their high cost, the complexity of the registration of parameters and the difficulty or impossibility of accelerating bodies to speeds of 7-14 km/s.

Mathematical modeling uses: a) flow models and ballistic limit equations to determine the parameters of damage and penetration of the spacecraft walls and b) modeling in modern software environments including the SPH method [3-8]. The main problem for mathematical models and their software implementations is the accuracy of setting the parameters that need to be corrected upon the analysis of experiments and model verification.

The main purpose of the proposed integrated information intelligent modeling system (IIIS) is to combine and analyze the results of experiments and different types of modeling, as well as to generate knowledge structures used in the formation of formalized hypotheses about the relationship between input and output variables. The IIIS system includes three software blocks (SB) [9-11], Figure 1: SB-1 focused on the tasks of estimation-experimental and computational modeling and field experiments; SB-2 which solves the problems of mathematical modeling and setting up computational experiments taking into account the results of the experiment, and SB-3 which processes and analyzes the simulation results.

Estimation-experimental modeling of the hypervelocity impact of solids

The SB-1 block is designed for estimation-experimental modeling of the hypervelocity impact of particles and for information support of experiments carried out at the special experimental complex. The experimental study of the impact of hypervelocity particles was carried out on a complex containing a light-gas accelerator that provides acceleration of particles with the size up to 2 cm in diameter to a speed of 5 km/s and equipped with a high-speed X-ray camera.

A mathematical model was made using the relations and parameters characteristic of the energy approach to assessing the process of high velocity interaction. The main characteristic of the process is the energy absorbed by an obstacle when it is penetrated by a particle considering the parameters of the fragment and obstacles and the kinetics of their change, as well as the mechanism of high-rate deformation.

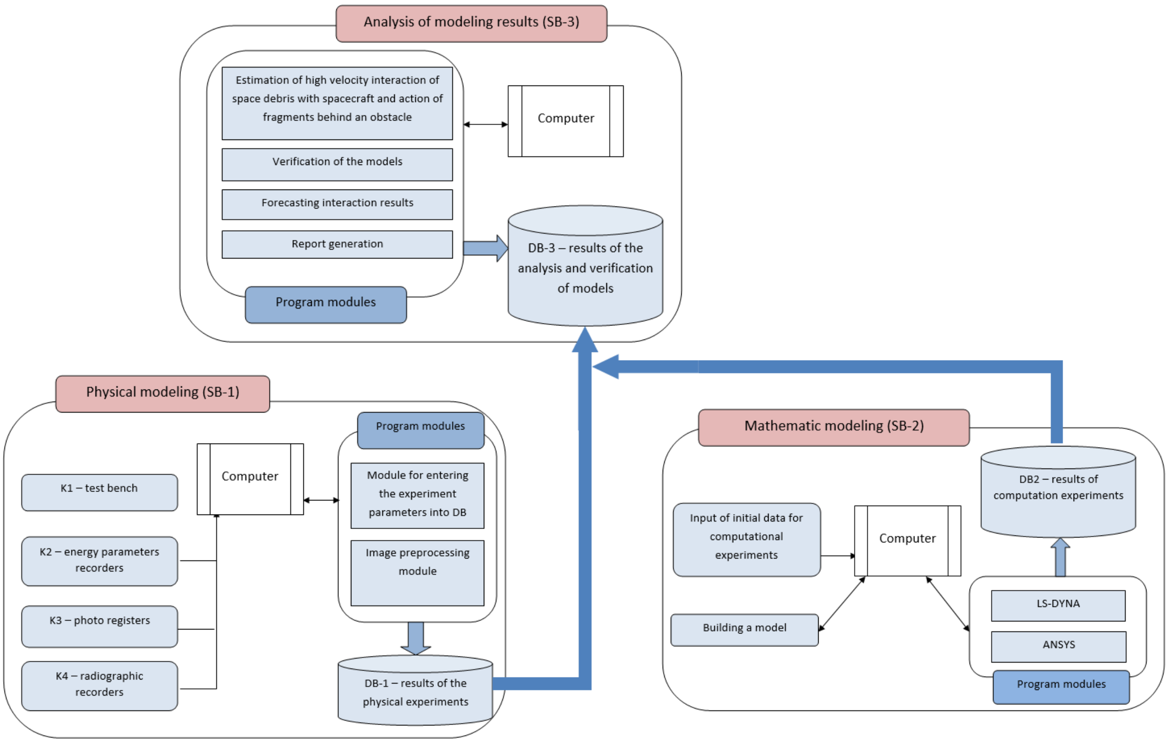


Figure 1: Principal structure of an integrated information intelligent system for assessing the impact of hypervelocity particles on a spacecraft

The block diagram of the object of estimation-experimental modeling makes it possible to establish quantitative relationships characterizing the relationship between the input variables of the process under study and the main characteristics of the impact results.

The obtained calculated and experimental dependences made it possible to create an algorithm that allows to carry out calculations for shielding schemes consisting of various materials and structures.

The investigation of the phenomena arising from a hypervelocity impact with the only help of physical experiments does not often give the expected result despite the large material and technical costs. The solution of this problem is possible by using computer simulation.

Computer simulation of the impact of hypervelocity particles on a spacecraft.

To accomplish this task the SB-2 block is included in the IIIS and it is intended for the numerical implementation of computer models of the process of impact of a hypervelocity particle on a spacecraft element.

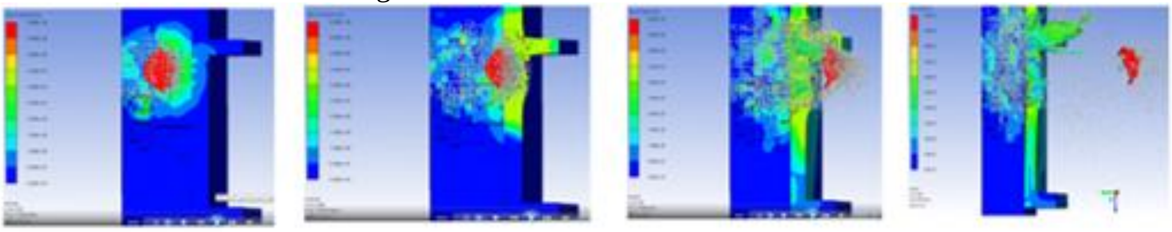
The use of finite element methods and SPH in the ANSYS/LS-DYNA/AUTODYN and FLOWVISION environments makes it possible to study the damage and the kinetics of changes in the stress-strain state and temperature field of a technogenic particle and a hybrid element of the spacecraft's real shell at the impact, Figure 2. Based on the results of the numerical simulation for any time instant it is possible to estimate:

- the rate and the parameters of destruction, defects and cracks in the element, as well as the effect of small fragments (less than 0.5 mm) on damage of the spacecraft element and internal equipment,

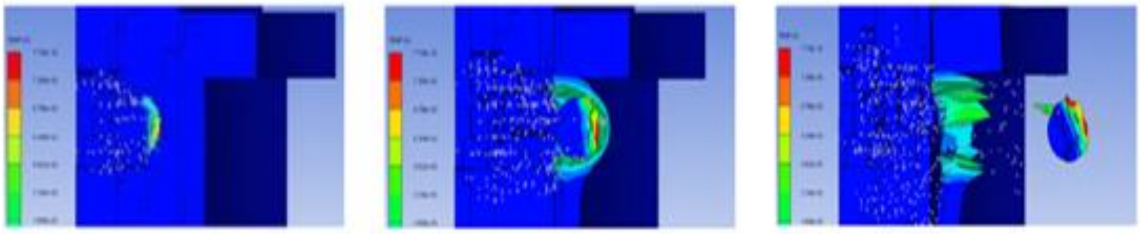
- the kinetics of changes in the stress-strain state and temperature field of the spacecraft element and particle,

- the kinetic energy of the spacecraft element and particle, as well as time 3D-dependences of average velocities of fragments in a cloud.

Test 4: V=2961 m/s m=8.4 g



a)



$T_{max} = 450^0$ C $T_{max} = 500^0$ C $T_{max} = 500^0$ C b)

Figure 2: Kinetics of changes in stress-strain state (a) and temperature field (b) at impact of a hypervelocity particle on a hybrid element of the spacecraft's real shell

The study of the peculiarities of the complex physical processes occurring during the impact of a hypervelocity particle on a spacecraft element makes it possible to substantiate the composition and design of real spacecraft elements and, within certain limits, to predict spacecraft damage depending on changes in the material, size and speed of anthropogenic particles and to form a data bank that can be updated and supplemented by new data.

Computer modeling also makes it possible to expand the limited set of results of computational and experimental modeling and field experiments. In turn, this allows to develop the basics of using the data bank in the development of protection and protection control systems for perspective spacecraft.

Processing and analysis of the results of computational-experimental and computer modeling

The tasks of processing the results of experiments obtained using different types of modeling are solved in the SB-3 block which includes: a) a database with vector models built on the basis of the results of estimation-experimental and computer modeling, b) calculation modules that make it possible to analyze the results of full-scale and computational experiments including high-speed radiography and model verification using fuzzy logic algorithms [10,11].

The use of two types of modeling (estimation-experimental and computer) in the study of the same object let solve such problems as:

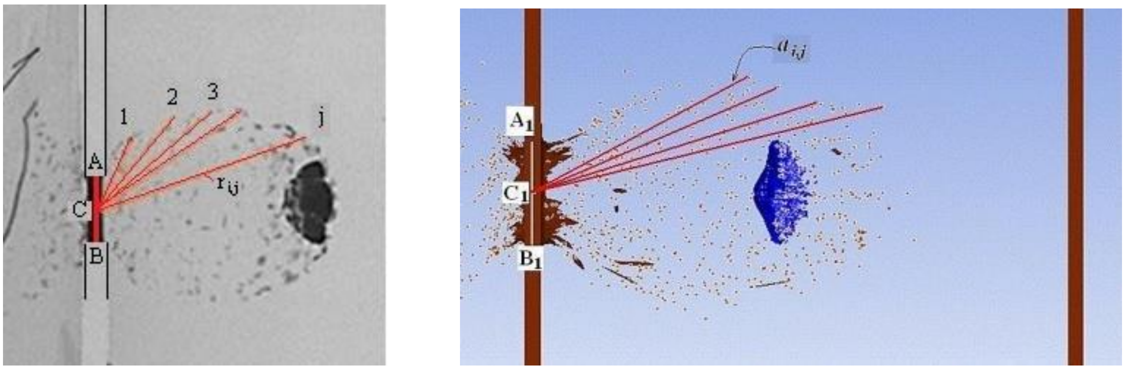
- verification of mathematical models by comparing vector models built on the results of full-scale and computational experiments if the experiments were performed under the same conditions,

- formation of training samples for the subsystem for predicting the results of particle impact on spacecraft elements,

- the formation of generalizing statements with estimates of the simulation results which will be used in the construction of the knowledge base of the integrated information intelligent system for assessing the hypervelocity impact of particles on spacecraft element.

Analysis of images of the results of computer modeling and experiments by the method of fuzzy sets

The reliability of the results obtained using the finite element model implemented in the ANSYS environment depends on the results of its verification. The solution of this problem is carried out by comparing images on optical and pulsed X-ray images obtained in a full-scale experiment with the results of computer simulation. To compare the parameters of images the methods of fuzzy sets are used [9, 10], Figure 3.



a) b)

Figure 3: Image of a cloud of debris behind the first broken obstacle obtained on the X-ray diffraction pattern (a) and when simulated in the ANSYS environment (b)

The finite result of evaluating the differences in the optical and X-ray images of the holes formed at the impact in the process of the experiment and computer simulation is formed by logical conclusions using well-known algorithms. The analysis of the results of comparing the parameters of experimental (optical and X-ray) and computer images allows us to conclude that it is possible to use a computer model in the ANSYS program for describing damage of a spacecraft element at the impact of a hypervelocity particle, as well as for subsequent verification of the model in the SB-3 complex.

4. Conclusion

The structure and functions of the integrated intelligent information system that assess and predict the results of the impact of hypervelocity anthropogenic particles on spacecraft elements have been developed and described.

A new methodology for evaluating the parameters of the impact of hypervelocity particles on spacecraft elements is proposed combining the results of complementary methods of estimation-experimental and computer modeling. A fuzzy logic apparatus was used, as well as an original procedure for switching to an index scale when forming a general assessment of differences for a set of points of the corresponding optical and X-ray images. The use of the apparatus of fuzzy logic makes it possible to form generalizing statements with estimates of the simulation results. These generalizing statements can be used to make a knowledge base in an integrated information intelligent system for assessing and predicting the consequences of dynamic impact of particles on a spacecraft in the range of velocities and masses of particles that are not available in experiments.

The proposed intelligent assessment of the impact of hypervelocity anthropogenic particles on a spacecraft can be used for developing theoretical and applied foundations for creating an intelligent control system for protecting spacecraft from particle impacts, as well as for optimizing the composition and design of elements of perspective spacecraft.

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