The micrometeoroid influence estimate on the microaccelerations level onboard small spacecraft

G P Anshakov, A I Belousov, A V Sedelnikov and A S Gorozhankina
Samara National Research University, 34, Moskovskoye shosse, Samara, 443086, Russia
E-mail: axe_backdraft@inbox.ru

Abstract. The problem of estimating the impact of a particle of a space debris or a micrometeoroid in the solar cell panel of a small spacecraft is considered. Numerical modeling of the impact of particle penetration into the solar cell panel on the dynamics of a small spacecraft and the level of microacceleration of its internal environment have been simulated. As a prototype for numerical modeling, a small spacecraft "Aist-2D" was chosen. The obtained results testify to the significant influence of particle penetration into the solar cell panel on the level of microacceleration of the internal environment of a small spacecraft and the need to take this influence into account when carrying out gravitationally sensitive processes on its board.

1. Introduction
Micrometeorites and debris of space debris are now a significant threat to the regular functioning of the spacecraft [1]. During the operation of space technology, statistics of damage to the plating and solar panels of space vehicles have been accumulated. In the zone of significant risk are space objects, the life of which is sufficiently long. Figures 1 and 2 show the damaged elements of the international space station. Figure 3 shows dismantled from the Hubbl Space Telescope fragments of solar panels [2], which also show micrometeorite craters.

Figure 1. Fragment of damaged skin international space station
Therefore, for effective operation of space technology, it is necessary to develop new ways to protect structural elements of spacecraft from debris of space debris and micrometeorites. At the same time, it is important to study the impact of a collision of a spacecraft with such particles not only on its ability to function properly, but also on the change in the dynamics of their rotational motion, which in particular affects the conditions for the realization of gravitationally sensitive processes on board.
The purpose of this study is to investigate the impact of a debris or micrometeoroid particle entering the solar cell panel on the level of microacceleration of the internal environment of a small spacecraft, as the object for which it is the most significant. The importance of such influence makes even more urgent the development of ways to protect the structural elements of a small spacecraft when gravitationally sensitive technological processes are implemented on its board.

A correct estimate of the probability of a particle of debris falling into the solar cell panel is a rather complicated task. All natural and anthropogenic particles are subdivided into observables (a characteristic size of about 100 mm and more) and unobservable particles. Moreover, only a few percent of the total number is tracked by optical and radar means, and the total mass of objects of anthropogenic nature in near-earth orbits is already significantly higher than 5000 tons [3].

Consider a particle with certain parameters (Table 1).

| Parameter          | Value |
|--------------------|-------|
| Size, mm           | 0.5   |
| Speed, km/s        | 16    |
| Impulse, kg m/s    | 0.03  |
| Impact strength, N | 0.15  |

The collision of such a particle with the edge of the solar cell panel at a distance of 2 m from the center of mass produces a perturbing moment of the order of 0.5 N m. This value is only an order of magnitude less than the moment created by the low-thrust liquid-fuel thruster in the NIKA-T project (6 Nm [5]) or the Spot-4 spacecraft (4 Nm [6]). Then the values of the induced tangential microacceleration at the moment of impact at a distance of 40 cm from the center of mass can be estimated as 50 μm/s². It is 5 times greater than the maximum permissible microacceleration for the technological project "OKA-T" (10 μm/s² [7]). The value of a real pulse from a micrometeorite can be significantly higher, since the velocities of micrometeoroid particles of natural origin in the region of the Earth’s orbit are estimated at 11-75 km/s [2]. Consequently, the microacceleration excited by the collision may exceed this estimate.

For a spacecraft of the middle class "Foton-M", the micrometeoroid particle under consideration, if hit in the same direction as the edge of the solar cell panel, will cause tangential microacceleration two orders of magnitude smaller than the estimate given above. This corresponds to values less than half the level of allowable microacceleration. Thus, the problem of taking into account the collisions of space vehicles with particles of micrometeorites and space debris is of great practical importance precisely for modern and promising small space vehicles that will in future be used for space production. A vivid example of such a spacecraft can serve as the currently implemented project "Vozvrat-MKA" [8].

The estimation of the probability of collision of a particle, the parameters of which are presented in Table 1, shows that it does not exceed 10⁻⁹ for one turn of a small spacecraft around the Earth with an orbit altitude of about 600 km [9]. A long period of active existence of a small spacecraft in orbit makes this event quite likely.

We perform numerical simulation for spacecraft "Aist-2D" (Figure 4), launched on April 28, 2016 [10]. Let the case of a small spacecraft with panels of solar batteries and a particle of space debris represent solid bodies. Let's estimate the inertial-mass parameters of the small spacecraft "Aist-2D" (Table 2), using the data given in [10] and considering the spacecraft body as a cube. Solar panels are considered homogeneous plates.
Figure 4. Appearance of the small spacecraft "Aist-2D"

Table 2. Evaluation of inertia-mass parameters of spacecraft of the type "Aist-2D".

| Parameter               | Body weight, kg | Solar panel weight, kg | Minimum axial body moment of inertia, kg·m² | Maximum panel moment of inertia, kg·m² |
|-------------------------|-----------------|------------------------|---------------------------------------------|----------------------------------------|
| Value                   | 530             | 120                    | 200                                         | 200                                    |

To estimate the parameters of the panel vibrations after its collision with the particle, we use the assumptions.

2. Model of solar panel – Euler-Bernoulli beam. Such a model gives an overestimation of microacceleration [11], since beam oscillations are possible only in the longitudinal direction, unlike the plate. It is shown [11] that at the same value of the potential energy of deformation, the amplitudes of these oscillations are higher than the oscillation amplitudes of the plate, where longitudinal and transverse oscillations are possible.

3. The model of fixing the solar panel to the body of the spacecraft – a rigid fit. This model also overestimates the estimation of microacceleration, since part of the oscillation energy will be scattered in the elastic assembly of the solar panel panel to the body. Most often, the performance requirements of solar panels dictate the need for their rigid attachment to the body. Otherwise, it is impossible to guarantee its solar orientation. If it is not required to provide high power availability, for example, when surveying the Earth's surface with a high resolution, then it is possible to resiliently fasten the solar panels. An example of this approach is a series of French spacecraft "Spot-4,5" [12]. However, for spacecrafts for technological purposes (for example, "NIKA-T", "OKAT-T"), the cosine of the angle between the normal to the solar cell surface and the direction to the Sun should be above 0.9 [5].

4. The displacement of the center of mass of the body of the spacecraft is negligible compared to the movements of the center of mass of the solar cell panel. This simplification makes it possible to reduce the oscillations of the solar panel to the case when the fixing point of the panel is stationary. We will estimate the error of this simplification. So for the "Aist-2D" spacecraft considered in the work, the ratio of the movements of the centers of mass of the
solar battery and the hull of the spacecraft will correspond to the ratio of the mass of the panel to the entire mass of the spacecraft, i.e. . Moreover, the estimate itself is substantially simplified. The oscillations of a rigidly embedded beam are determined up to an arbitrary constant C by the following equation [13]:

\[
y(x; t) = \sum_{i=1}^{N} C_i \left[ U(k,x) - \frac{V(k_x)}{S(k_x)} V(k_x) \right] \cos(\omega_i t)
\]  

(1)

where is the deviation of points of the solar panel from the undeformed position; N is the number of self-oscillations that are taken into account; is the natural frequencies of oscillation; is the part of the constant C, attributable to the i-th form of vibration; Krylov functions:

\[
U(k,x) = 0.5(chk_x - \cos k_x), \quad V(k,x) = 0.5(shk_x - \sin k_x), \quad S(k,x) = 0.5(chk_x + \cos k_x);
\]

where \( k_i = \frac{\mu \omega_i^2}{EI} \); \( \mu \) and EI are accordingly mass per unit length and rigidity of the solar panel.

To determine the constant C, it is necessary to estimate the dynamic deflection of the extreme point of the beam. Consider the most dangerous case of a particle falling into the extreme end point of the panel when the maximum perturbing moment is created. According to the studies carried out in [14], in the case of high-speed impact, the dynamic deflection exceeds the static deflection by approximately 1.57 times.

The mass and velocity parameters of the particle (Table 1) make it possible to estimate the force at the time of impact interaction at 0.2 N. Then the static deflection is determined by the universal equation of the elastic axis of the beam [14], which for the case under consideration has the form If:

\[
EI \frac{M_l^2}{2} + \frac{F_l^3}{6 EI} = 0
\]

where \( M \) and \( F \) are static termination reactions when the beam is loaded with a force of 0.2 N at its free end.

Substituting the value: for the time instant in equation (1), we can get the calculated value of the constant C.

The results of the numerical simulation taking into account the first five forms of natural oscillations are shown in Fig. 5.

Figure 5. Dynamics of microacceleration, caused by fluctuations in the solar panel taking into account damping when the panel frame is made from the material MA-8.
Figure 5 demonstrates a significant violation of favorable conditions for the successful implementation of gravitational-sensitive processes in terms of the level of microacceleration. Thus, at the maximum permissible value of the microacceleration modulus of 10 μm/s², the unfavorable period lasts about 200 s after a collision.

Thus, the conducted studies show that the hit of a small high-speed particle in the solar cell panel of a small spacecraft can violate the conditions for microacceleration. The estimates of the level of microacceleration due to collision with a particle for a small spacecraft such as Aist-2D show the possibility of microacceleration, the modulus of which is up to 35 μm/s². This exceeds the permissible level of microacceleration for the OKA-T project by 3.5 times [15]. On the other hand, gravitational-sensitive processes have already been developed that require, for their successful implementation, a level of microacceleration not more than 1 μm/s² [16]. And in the future these requirements will only get tougher.

Consequently, the problem of disturbing favorable conditions for the flow of gravitationally sensitive processes on a small spacecraft due to the entry of a high-speed particle into the solar panel is very important and requires close attention.

Acknowledgments
This work is done in accordance with the Agreement No. 14.578.21.0229 of September 26, 2017 between the Ministry of Education and Science of the Russian Federation and Samara University (a unique identifier of the project is RFMEFI57817X0229).

References
[1] Deluca L T et al 2013 Active space debris removal by a hybrid propulsion module Acta Astronautica 91 pp 20–33
[2] Rival M 1997 Proc. of the 7 Int. Simp. on Space Environment (Toulouse) pp 16–20
[3] Vorobyov A A 2011 Electromechanical matters. VNIIEM studies vol 120 pp 27–30
[4] Blinov V N 2010 Small spacecraft. Book 3. Minisatellites. The unified space platforms for small spacecrafts ed (Omsk: Publishing house of OMGTU) p 348
[5] Sedelnikov A V 2012 The problem of microaccelerations: from comprehension up to fractal model (Moscow: Russian Academy of Sciences: The Elected Works of the Russian school) p 277
[6] Belousov A I 2014 Problems in formation and control of a required microacceleration level at spacecraft design, tests, and operation (Russian Aeronautics vol 57) pp 111–117
[7] Belousov A I 2015 International Review of Aerospace Engineering vol 8 pp 157–160
[8] Sedelnikov A V 2016 Microgravity Science and Technology vol 28 pp 491–498
[9] Anghileri M 2005 Development of Orbital Debris Impact Protection Panels 3rd European LS-DYNA Users Conference. Methods and Technique pp 1–10
[10] Kirilin A N 2017 «Aist–2D» small spacecraft (Samara: Publishing house of the Samara scientific center of the Russian Academy of Sciences) p 324
[11] Sedelnikov A V 2016 International Review of Aerospace Engineering vol 9 1 pp 9–12
[12] Sedelnikov A V 2011 Alternative solution to increase the duration of microgravity calm period on board the space laboratory (Acta Astronautica vol 69(6–7) pp 480–484
[13] Babakov I M 2004 Theory of oscillations (Moscow: Drofa) p 592
[14] Olshanskii V P 2012 Oscillations of rods and plates with mechanical impact (Kharkov: Urban printing) p 318
[15] Sedelnikov A V 2017 (Jordan Journal of Mechanic and Industrial Ingeneering vol 11(2) pp 121–127
[16] Anshakov G P, Belousov A I and Sedelnikov A V 2017 Russian Aeronautics vol 60(1) pp 83–89