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Evaluation of the Level of Microaccelerations on-Board of a Small Satellite Caused by a Collision of a Space Debris Particle with a Solar Panel

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Abstract

The present study aims at studying the effects of possible collision of a space debris particle with a solar panel of a small spacecraft designed to implement gravity-sensitive operating process on-board. We estimated the level of microaccelerations caused by a collision of a space debris particle with a solar panel. The results presented in this article may be useful in the design and operation of modern small spacecrafts and satellites.

Keywords: *Microaccelerations, Collision, Space Debris, Small Spacecraft, Solar Panel*.

1. Introduction

Modern requirements for the design of a new space technology for implementation of gravity-sensitive procedures in space suggest serious limitations of the level of microaccelerations in the area with technological equipment [1]. It is known that the reason for changes of angular velocity of small satellites cause microaccelerations in their internal space can include mechanical moments of various physical nature, effects of various physical fields and executive bodies of control systems, as well as a number of other phenomena [2-4]. Studies show that, depending on the basic parameters of the orbit of the spacecraft, the most significant contribution to the field of microaccelerations of its internal space is provided by the metastable component for low orbits [5-7] or the structural component for high orbits [8-10]. However, modern space projects (such as "OKA-T" [8]) suggest a high level of autonomy of a space lab during orbital flight. This, on the one hand, allows using of high orbits for the spacecraft, reducing the influence of the metastable component [10]. On the other hand, turning off all auxiliary systems on-board the spacecraft, except for the critical ones, for the duration of implementation of operating processes will significantly influence on the structural component. In this case, other disturbing factors may come to prominence in formation of the field of microaccelerations of the internal environment of the spacecraft. One such factor is the collision of a debris particle with the spacecraft.

Improvement of the technologies to control the level of microaccelerations in the technological equipment placement area [11], as well as application of the modern spacecraft control systems [10, 12] reduces the influence of the metastable and structural components on the microaccelerations level. And this, in turn, increases importance of the task of studies of the other disturbing factors influence, in particular, collisions with space debris.

Impact of the space debris particle according to the classification [13] causes, along with the other similar factors, the emergence of a random component of the microaccelerations field. This component is not paid enough attention in the literature. Thus, evaluation of the effect of space debris on microacceleration in the internal environment of large space stations shows that for the "Mir" orbital station the amplitude of such microaccelerations does not exceed 10^{-15} m/s^2 in the frequency range 5-50 kHz [14]. However, the use of small satellites, microsatellites and nanosatellites in the space industry, undoubtedly, will attract the attention of researchers to this problem.

1.1. Simple Evaluation of the Relevance of the Study

Negligible sensitivity of large space stations to impact of the space debris particles differs significantly from the reaction of small satellites caused by similar collisions. In addition, because of their structural complexity, multi-functionality, habitability and permanent need of orbital motion control, large space stations are of little use as prototypes for future space miniplants [8]. Quite the contrary, small spacecraft nowadays are not only capable of fulfilling the role of space minilabs, but also can perform pilot production.

In order to justify the relevance of the problem for small spacecraft, we choose the American spacecraft "Deep Space 1" (Figure 1) launched on 24.10.1998 as a model [15].

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Figure 1. The Deep Space 1 spacecraft and the comet Borelli

The case of a collision of the debris particle with the part of the solar cell mostly remote from the center of mass of the spacecraft area is considered. Spacecraft with solar cell and the space debris particle are considered to be rigid bodies. We estimate the inertial mass parameters of the spacecraft "Deep Space 1" (Table 1), using the data given in [15] and assuming the spacecraft body is a cylinder. As the radius of the cylinder, we take the average of the two characteristic lateral dimensions of the spacecraft. The solar cell is considered as a plate.

Table 1.Estimation of inertial-mass parameters Deep Space 1

Mass of the body, kg	Mass of the panel, kg	Moment of inertia of the body, kg·m^2	Moment of inertia of the panel, kg·m^2
428	58	2264	1099

Parameters of the space debris particles are shown in Table 2.

Table 2. Parameters of space debris particle

Size, mm	Speed, km/s	Impulse, kg·m/s	Impact force, N
0,5	16	0,03	0,15

The reaction time of the collision was estimated as 0,2 s. For example, NASA scientists recorded a meteorite impact on the Moon surface with the duration of about 0,4 seconds, making a 3 m deep crater with a diameter of 14 m [16]. In case of a collision of such a particle with a solar cell (at a distance of 5,9 meters from the center of mass [15]) it causes a moment about 1 N·m. This value is comparable with a moment generated by the orientation engine of «NIKA-T» project (6 N·m [8]) or «SPOT-4» (4 N·m [17]) spacecraft. In this case the resulting tangential microacceleration at the moment of the collision will exceed 100 μm/s^2 at a distance of 0,3 m from the center of mass. This is more than 10 times higher than the permissible microacceleration for "OKA-T" project (10 μm/s^2 [8]). It should be noted that speeds of micrometeoroid particles of natural origin in the vicinity of the Earth's orbit are estimated to be 11-75 km/s [17], so the actual level of microaccelerations caused by the collision may be significantly higher.

For comparison, the same space debris particle with a similar collision with a solar cell of the "Foton-M4" spacecraft will cause tangential microacceleration of two orders of magnitude smaller than the estimate presented above, which corresponds to values close to half of the level of allowable accelerations. Thus, the problem of taking collisions with space debris into account is of practical importance for modern and future small satellites to be used for the purpose of production in space. An example of such a spacecraft is the "Vozvrat-MKA" project [8].

2. Probability of a Collision with a Space Debris Particle

Correct evaluation of the probability of a collision with a space debris particle on the solar cell is a rather difficult task. All natural and man-made particles are divided into observed (with the characteristic size of about 100 mm or more) and unobserved particles. Only a few percent of the total are monitored with optical and radar aids, and the total mass of the man-made objects orbiting the Earth already significantly exceeds 5000 tons [17].

Evaluation of the probability of a collision with a space debris particle with the parameters described in Table II or greater, showing that it will not exceed 10^{-9} per one revolution around the Earth of a spacecraft at a height of the orbit of about 600 km [18]. However, long active lifetime of spacecraft makes this event quiet probable. As evidence, we can point to well-known facts of damage of outer cover (Figure 2) and the solar cell of the International Space Station (Figure 3), and the results of the study of the solar cell dismantled from the Hubble Space Telescope [19], which also has visible micrometeorite craters (Figure 4).

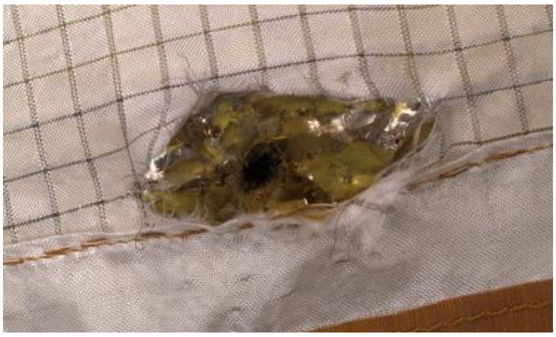

Figure 2. Detail of the damaged outer cover of the International Space Station

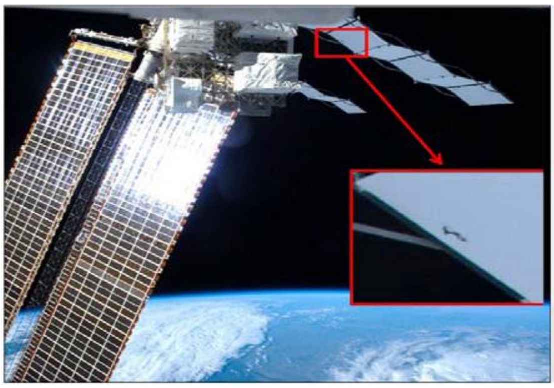

Figure 3. Solar panel of the International Space Station, damaged by a micrometeorite

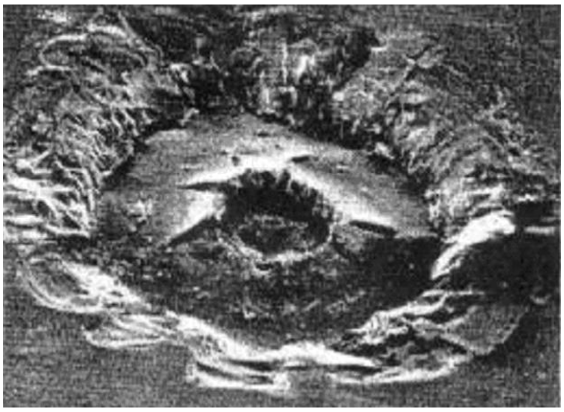

Figure 4. Micrometeorite crater on the surface of the Hubble Space Telescope solar panel

Thus, despite the low probability of a collision with space debris particles in a solar cell of a spacecraft, the considered problem of evaluating accelerations caused by such collisions does not lose its relevance. Firstly, there were actual cases of collisions with such particles in cover of spacecraft, as well as in solar cells. Secondly, the development of the near-Earth space at the present stage leads to the growth of the number of man-made objects, which increases the probability of collisions of spacecraft with space debris particles.

In such a way, this rather weak evaluation of microaccelerations that occur in collisions with space debris particles shows a danger of significant excess of permissible microaccelerations for small spacecraft. On the other hand, during continuous operation of spacecraft in orbit, there is a real possibility of a collision. This justifies the construction of a more complex model of spacecraft for improvement of the earlier evaluation of the resulting microaccelerations.

In addition, at the present time a significant amount of debris particles hinders the effective development of near-Earth space and becomes one of the fundamental problems of the mankind. Space flight experience shows that a high-speed collision of space debris particles with a satellite can lead to the destruction of the individual components of the satellite [20]. Other consequences of a collision may include changes in the angular velocity of the satellite and on-board microaccelerations. For these reasons, the study of the effects of collisions and the development of means of protection of satellites from the space debris is one of the most important international problems [21]. The calculations presented in [22] show that for a collision of a nanosatellite with high-speed particles less than one millimeter in diameter, there is a significant change in the magnitude and direction of rotation of the nanosatellite.

3. Simulation of a Collision of a Particle and a Satellite in the Form of a Rigid Body

There is viewed motion of the satellite about its center of mass on the example of a small "Deep Space 1" spacecraft with mass of 486 kg and dimensions 2.1x1.7x1.5 m (Table 1). Small interplanetary station "Deep Space 1" was intended for a long flight through the solar system, and could be open to collision with micrometeorite or space debris. Assume that a collision of "Deep Space 1" with a space debris particle takes place in a circular near-Earth orbit at the altitude of 600 km. This formulation is relevant for development of space miniplants that are expected to operate in the near-Earth space. The simulation takes into account a number of different positions of the point of collision in different directions of the vector of the relative collision velocity [23]. It is assumed that the debris particle is a ball of 0.5 mm in diameter. Before the collision with the satellite, the particle moves with a relative speed of 16 km/s.

A mathematical model describing the rotational motion of the satellite as a rigid body after the collision with the high-speed particle includes a system of three dynamic Euler equations and a system of four equations for determining the Rodrigues-Hamilton parameters [24].

Dynamic Euler equations describing the change in the angular velocity of the satellite, written in a vector form, are as follows:

$$I\frac{d\vec{\omega}}{dt} + \vec{\omega}\times I\vec{\omega} = \vec{M}, \qquad (1)$$

Here I is the tensor of inertia of the satellite; $\vec{\omega} = (\omega_x,\ \omega_y,\ \omega_z)$ is the vector of the angular velocity of the satellite including projections on the axes of the associated XYZ coordinate system; $\vec{M} = (M_x,\ M_y,\ M_z)$ is the vector of external mechanical moments acting on the small satellite. With a disabled control, the vector of the mechanical moment includes perturbing gravitational and aerodynamic moments recorded in known forms.

Differential equations for Rodrigues-Hamilton parameters $\lambda_1,\ \lambda_2,\ \lambda_3, \lambda_4$ are as follows [25]:

$$2\frac{d\lambda_0}{dt} = -\omega_x\lambda_1 - \omega_y\lambda_2 - \omega_z\lambda_3,$$

$$2\frac{d\lambda_1}{dt} = \omega_x\lambda_0 - \omega_y\lambda_3 + \omega_z\lambda_2, \qquad (2)$$

$$2\frac{d\lambda_2}{dt} = \omega_x\lambda_3 + \omega_y\lambda_0 - \omega_z\lambda_1,$$

$$2\frac{d\lambda_3}{dt} = -\omega_x\lambda_2 + \omega_y\lambda_1 + \omega_z\lambda_0.$$

The numerical integration of the dynamic Euler equations (1) and the kinematic equations (2) allows us to find the components of the angular velocity of the satellite and the values of the Rodrigues-Hamilton parameters, respectively. To calculate the quasi-static component of the microaccelerations on-board of a small satellite considered as a rigid body in a fixed point relative to the satellite, we apply a well-known expression [5, 14, 26]:

$$\vec{w} = \vec{r} \times \frac{d\vec{\omega}}{dt} + \left(\vec{\omega} \times \vec{r}\right) \times \vec{\omega} + \frac{\mu_e}{\left|\vec{R}\right|^3}\left(\frac{3\left(\vec{R}\cdot\vec{r}\right)\vec{R}}{\left|\vec{R}\right|^2} - \vec{r}\right) + \vec{w}_a, \quad (3)$$

where $\vec{w}$ is the microacceleration vector including the effect of inertia (first two terms), gravity (the third term) and air resistance force (the fourth term); $\vec{r}$ – radius vector defining the position of the point with respect to the center of mass of the satellite; $\vec{R}$ – radius vector of the center of gravity position in the geocentric coordinate system; μ_e – Earth's gravitational parameter. During disabled active control of the satellite orientation it is assumed that the value $\vec{w}_a$ is determined, taking into account the disturbing action of air resistance force.

It is known [27] that in the process of collision of a particle and a rigid body, penetration of the former into the body material is observed, accompanied by release of crushed material from the body structure. In this case, the ratio of jet impulse at ejection to the particle impulse can be calculated, for example, as follows [27]:

$$\frac{J_0}{J_p} = \frac{3u_0}{5u_k}, \quad (4)$$

Here u_0 is the relative velocity of collision of the particle and the body, u_k is the minimum value of the collision speed causing fine crushing of the body material. According to our supposition, u_0 = 16 km/s, and u_k = 1 km/s. In this case, we obtain from the expression (4) that the jet impulse at ejection of material J_0 exceeds the impulse of the space debris particle J_p by about 10 times.

4. Numerical Simulation

Figures 5-6 show the results of the numerical simulation of the process of changes in the components of the angular velocity and microaccelerations on-board the "Deep Space 1" satellite. The horizontal axis shows the time of orbital flight of the "Deep Space 1" satellite, measured in hours.

In the process of numerical simulation it was assumed that the initial angular velocities are due solely to the impact of high-speed particles. In drawing of Figures 5-6 it was taken into account that the collision takes place in the most remote from the center of mass point of the deployed solar cells. In this case, the angular moment of the space debris particle becomes completely transformed into kinetic moment of the "Deep Space 1" satellite.

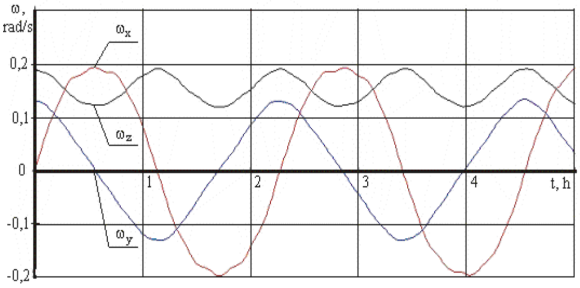

Figure 5. Change in components of the angular velocity of the satellite Deep

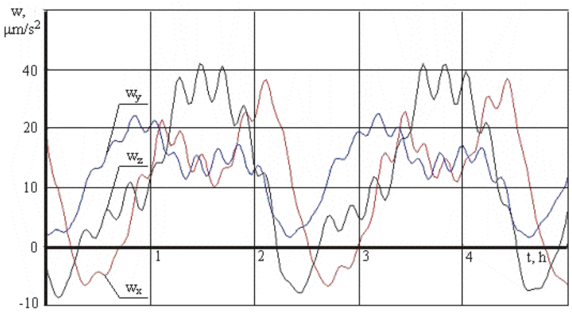

Figure 6. Change in components of the vector of the on-board quasi-static microaccelerations of the satellite Deep Space 1 as a rigid body

The simulation results show that for an aluminum particle with a diameter of half a millimeter, having a relative velocity before the collision of 16 km/s, the components of angular velocity of the satellite after the collision do not exceed 0,2 radians per second. In this case, the microacceleration in most remote point from the center of mass does not exceed 35 μm/s^2.

In the numerical simulation of the rotational motion of the satellite we take into account the effect of the jet moment on the satellite design. Furthermore, it is assumed that the collision does not occur through failure of the satellite structure, and the action of the jet impulse only results in the rotation of the satellite.

It should be noted that these assumptions lead to an overestimation of the results of estimates of magnitudes of angular velocities and microaccelerations. Indeed, in general case the process of high-speed collision in vacuum is a complicated multiphysical phenomenon [28].

In this formulation of the problem of a collision with a space debris particle the small satellite was supposed to be a rigid body. Assessment of the accelerations values that occur in collision of a high-speed space debris particle with an elastic deformable solar panel is also of practical concern.

5. Simulation of Oscillations of a Solar Cell Caused by a Collision with a Space Debris Particle

For evaluative calculations we use the following assumptions:

1. Model of a Solar Panel as an Euler-Bernoulli Beam

This model suggests an overestimation of microaccelerations [8], because the oscillations of the beam are only possible in the longitudinal direction. At the equal value of the potential energy of deformation the amplitudes of the oscillations are higher than the amplitudes of the oscillations of a plate where both longitudinal and transverse oscillations are possible.

2. Model of a Solar Panel Mounted to the Spacecraft Body-Rigid Mounting

This model also overestimates the microaccelerations, as part of the oscillation energy dissipates in the elastic attaching fitting. However, the requirements of the effective use of solar panels necessitate a quite rigid mounting to the body. Otherwise, it would be impossible to ensure the right orientation of the solar panel to the Sun. If we exclude energy-intensive processes, e.g. high resolution imaging of the Earth's surface, panel's resilient mounting to the body becomes possible. A striking example of such design can be «SPOT 4/5», a series of French spacecraft [1]. However, for space labs (for example, «NIKA-T») the cosine of the angle between the normal line to the surface of the solar panel and the direction towards the Sun must be greater than 0.9 [8].

On the other hand, some spacecraft use active dampers of natural oscillations of solar cells, reducing the oscillation damping duration from 90 s to 18 s [29]. However, in this case, this means not only an overestimation of the amplitudes of the microaccelerations, but also the period during which the favorable conditions for gravity-sensitive experiments will be disrupted.

3. Movements of the Center of Mass of a Spacecraft Body are Negligible Compared with the Movements of the Center of Mass of the Solar Panel

This simplification allows us to consider oscillations of a solar panel, the fastening point (fitting) of which is rigid. Accuracy of this simplification can be easily estimated. For the considered "Deep Space 1" spacecraft the ratio between the displacements of the centers of mass of the solar panel and the spacecraft body will correspond to the ratio of the mass of the cell to the whole mass of the spacecraft, i.e., $29/486 \approx 0{,}0597$. At that, the evaluation is greatly simplified.

It is known [30] that oscillations of rigidly attached beams are determined with accuracy up to an arbitrary constant *C* with by the following equation:

$$y(x;t) = \sum_{i=1}^{N} C_i \left[U(k_i x) - \frac{V(k_i l)}{S(k_i l)} V(k_i x) \right] \quad (5)$$

$$Cos(\omega_i t)$$

where $y(x;t)$ is the deviation of points of the solar cell from the non-deformed position; *N* is the number of accounted natural modes; ω_i are natural frequencies; C_i is a part of the constant *C* attributable to the *i*-waveform; Krylov functions: $U(k_i x) = 0{,}5(chk_i x - \cos k_i x)$; $V(k_i x) = 0{,}5(shk_i x - \sin k_i x)$; $S(k_i x) = 0{,}5(chk_i x + \cos k_i x)$; $k_i = \frac{\mu \omega_i^2}{EI}$; μ and *EI* are accordingly mass per unit length and rigidity of the solar panel.

To determine the constant C it is necessary to calculate the dynamic deflection of the end point of the beam [31]. We shall consider the most dangerous case, when the particle collides with the extreme end point of the panel. This situation is similar to the formulation of the problem of evaluation of accelerations in the previous sections of the present study. According to a study [32], in the case of high velocity impact the dynamic deflection is about 1,57 of the static deflection.

Mass and velocity parameters of the particles used in the previous section determine the force at the moment of impact interaction that is equal to 0,2 N [33]. After that, we can determine the static bending, using this value and the universal equation of the elastic axis of the beam [31], which for this case will be:

$$y_{st} = \frac{Ml^2}{2EI} + \frac{Fl^3}{6EI},$$

here *M* and *F* are static reactions of the fitting at loading beam strength of 0,2 N on its free end. Substituting the value: $y(x;t) = 1{,}57 y_{st}$ for $t_0 = 0$ in (5), we can obtain a constant value *C*.

After that, we performed further numerical simulation taking into account the different number of natural modes. Figure 7 shows the dependence of the change of microaccelerations caused by fluctuations in the solar panel at collision with a space debris particle, taking into account the first five forms of natural oscillations.

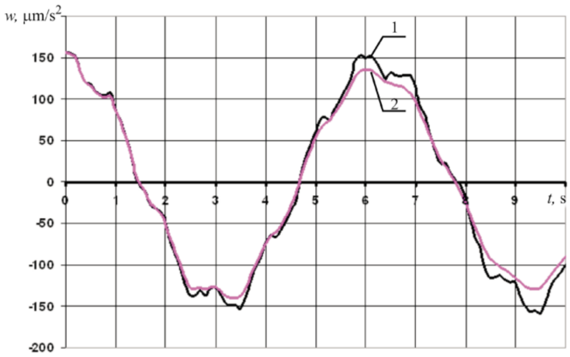

Figure 7. Change in the accelerations caused by oscillations in the solar cell:

1 - without taking into account the damping; 2 - taking into account the damping when the cell frame is made of MA-2 material

As seen in Figure 7, the caused microacceleration substantially disrupts favorable conditions for the successful implementation of gravity-sensitive processes. Taking into account the damping, the period of unacceptably high microaccelerations in respect of "OKA-T", a perspective Russian space laboratory project (the maximum value of the magnitude of microaccelerations is 10 μm/s^2 [8]) is about 200 s.

6. Conclusion

Thus, the conducted researches show that collision of a small high-speed particle with a solar panel may disrupt favorable conditions for gravity-sensitive processes in a small spacecraft. The estimates of on-board quasi-static microaccelerations caused by the collision with a space debris particle for the parameters of "Deep Space 1" spacecraft demonstrate the possibility of quasi-static microaccelerations up to 35 μm/s^2. This exceeds the permissible level of microaccelerations for "OKA-T" project in 3,5 times [8]. Given the fact that the quasi-static microaccelerations are hardly damped over time, it can become a serious problem for the implementation of gravity-sensitive processes.

On the other hand, recently developed processes require for their successful implementation accelerations is no greater than 1 μm/s^2 [34]. Of course, in the future these requirements will only increase.

Simulation of the solar panel oscillations shows a possibility of microaccelerations with amplitude close to 150 μm/s^2. Their frequency depends on the parameters of the solar cell (in this example, "Deep Space 1" spacecraft dominant frequency is about 0,2 Hz). In this case the permissible values for "OKA-T" project will be exceeded in about 200 seconds. This will cause failure of all the gravity-sensitive processes taking place in this period. As collisions with a space debris particle are random phenomena, there is a doubt that no production processes or orientation maneuvers of the satellite would be taking place at the moment of the collision.

Thus, the problem of disruption of favorable conditions for gravity-sensitive processes in a small spacecraft due to collision of a solar cell with high-speed space debris particles or other particles is of high importance and requires close attention.

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