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Selecting the Parameters of the Orientation Engine for a Technological Spacecraft

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Abstract. This work provides a solution to the issues of providing favorable conditions for carrying out gravitationally sensitive technological processes on board a spacecraft. It is noted that an important role is played by the optimal choice of the orientation system of the spacecraft and the main parameters of the propulsion system as the most important executive organ of the system of orientation and control of the orbital motion of the spacecraft. Advantages and disadvantages of two different orientation systems are considered. One of them assumes the periodic impulsive inclusion of a low thrust liquid rocket engines, the other is based on the continuous operation of the executing elements. A conclusion is drawn on the need to take into account the composition of gravitationally sensitive processes when choosing the orientation system of the spacecraft.

1. Introduction

Low-thrust liquid-fuel rocket engines (LT LRE) are one of the output links of a complex motion control system (MCS) of many modern spacecraft (SC).

The MCS carries out the following functions:

- navigation – control of the movement of the center of mass of the spacecraft;
- stabilization – parrying possible turns of the spacecraft relative to the center of mass, keeping its body in the position set by the orientation system;
- orientation –rotation the spacecraft at specified angles to perform assigned tasks, including the implementation of space technologies in orbit.

Space technologies have led to the emergence of a number of unique materials and products. Thus, monocrystals are used in the manufacture of high-temperature turbines blades of aircraft engines. However, growing such monocrystals is a gravitationally sensitive process: the impact of even a small force field in the process of crystallization is capable of deflecting the axis of the grown monocrystal. This can give rise to a significant heterogeneity and anisotropy of the mechanical properties of the monocrystal [1]. For example, the anisotropy of the modulus of elasticity of grown single crystals will contribute to the dispersion of the natural oscillation frequencies of such blades, which leads to a decrease in the resource of the turbine. It was shown in [2] that such anisotropy is capable of reducing the limit of the long-term strength of monocrystalline blades to 40%.

Having a porous structure and good mechanical strength characteristics metallic foam is another perspective material. When implementing the process, it is necessary that the gaseous component of the foam metal be thoroughly mixed with the melt. Otherwise, during crystallization, inhomogeneities arise, which substantially worsen the strength properties.



Most gravitationally sensitive processes are energy-intensive. To successfully conduct them in space, it is necessary to make serious demands on the orientation of the spacecraft (SC) at the stage of its operation. Effective orbital stabilization of spacecraft relative to the Sun allows to obtain the required electric power from solar panels (SP).

The most common is the orientation scheme, which involves the use of active-passive orientation devices (APOD). Such devices include power gyroscopes and gyrodynes. With the perturbing effect of internal and external factors on the orbital motion of the spacecraft, the angular velocity of rotation of the APOD flywheels increases. This prevents disorientation of the spacecraft itself [1]. However, such an increase cannot be unlimited. At a certain value of the angular velocity taken as critical, in view of the asymmetry of the flywheels, radial runout occurs. It consists in the fact that the alternating centrifugal force of inertia, caused by asymmetry, causes an alternating reaction in the flywheel shaft supports. This, in turn, provokes a significant vibration disturbance. Such a situation is unacceptable in the realization of gravitationally sensitive processes, since favorable conditions for their flow are disrupted. There is a need for the orientation engine to unload the angular momentum of the APOD[3].

2. The role of LT LPRE in the MCS of a technological SC

As an orientation engine for a medium-class spacecraft, as a rule, LT LPRE is used. When the critical angular velocity of the flywheel rotation is attained, the APOD turns on the liquid-propellant engine in the pulsed mode, discharging the kinetic moment of the flywheels. The change of the pulsed thrust of the engine with time is shown in 'Figure 1' [4].

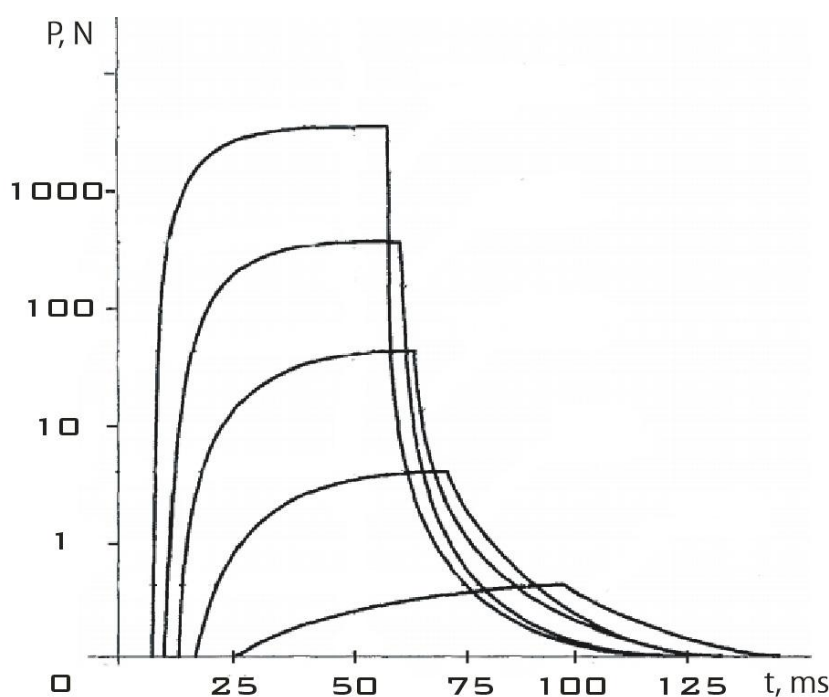


Figure 1. The rate of change of thrust of the LT LRE with time

The field of micro acceleration causes the appearance of anisotropy of the properties of the obtained materials and can significantly worsen their quality. Figure 2 shows the dependence of the level of micro acceleration on time in the location of the technological equipment when using liquid rocket engines in impulse mode [5].

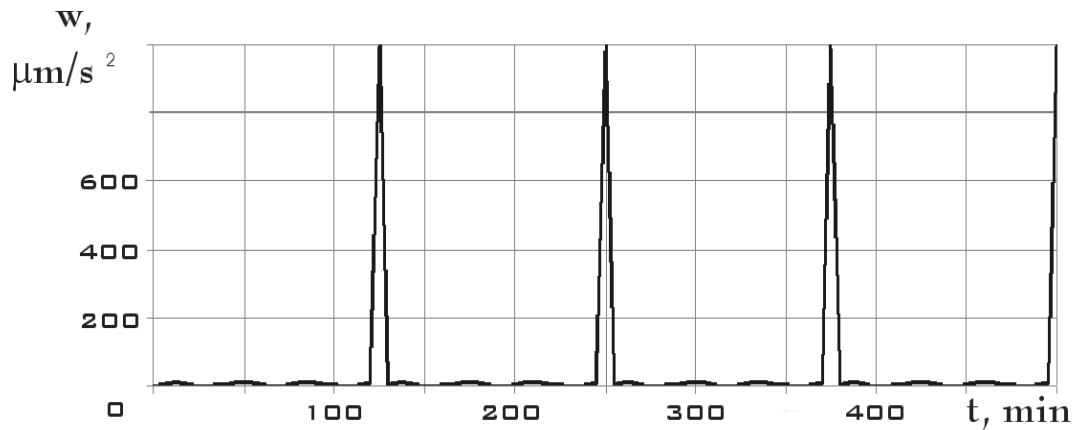


Figure 2. The rate change of micro acceleration with time when using a LT LPRE

The peak value of microaccelerations, as well as the waiting time of favorable conditions for the realization of gravitational-sensitive processes, directly depend on the thrust of the orientation engine. The equations of controlled motion of the spacecraft in the decomposition of elastic elements into individual rigid sections have the form [6]:

$$\left\{ \begin{array}{l} \dot{\omega}_x = \frac{M_x - \sum_{i=1}^N I_{ix} \dot{\omega}_{ix} - m(y_0 \ddot{z}_0 - \ddot{y}_0 z_0) - \sum_{i=1}^N m_i [(y_i - y_0) \cdot (\ddot{z}_i - \ddot{z}_0) - (\ddot{y}_i - \ddot{y}_0) \cdot (z_i - z_0)]}{I_x + \sum_{i=1}^N I_{ix}}; \\ \dot{\omega}_y = \frac{M_y - \sum_{i=1}^N I_{iy} \dot{\omega}_{iy} - m(\ddot{x}_0 z_0 - \ddot{x}_0 z_0) - \sum_{i=1}^N m_i [(\ddot{x}_i - \ddot{x}_0) \cdot (z_i - z_0) - (x_i - x_0) \cdot (\ddot{z}_i - \ddot{z}_0)]}{I_y + \sum_{i=1}^N I_{iz}}; \\ \dot{\omega}_z = \frac{M_z - \sum_{i=1}^N I_{iz} \dot{\omega}_{iz} - m(x_0 \ddot{y}_0 - \ddot{x}_0 y_0) - \sum_{i=1}^N m_i [(x_i - x_0) \cdot (\ddot{y}_i - \ddot{y}_0) - (\ddot{x}_i - \ddot{x}_0) \cdot (y_i - y_0)]}{I_z + \sum_{i=1}^N I_{iz}}, \end{array} \right. \quad (1)$$

Where, $\vec{M}(M_x, M_y, M_z)$ – the moment created by the thrust vector of the motor relative to the center of mass of the spacecraft in the main coupled coordinate system (Figure 3). The torque generated by the thrust vector of the motor in the main coupled coordinate system (Figure 3); I_{ix}, I_{iy}, I_{iz} – the diagonal components of the inertia tensor of the i -th section of the elastic element in the coordinate system, whose origin is located at the center of the mass of the section, and the axes are parallel to the axes of the principal coupled coordinate system (Figure 3); I_x, I_y, I_z – the diagonal components of the inertia tensor of the hull in the principal coupled coordinate system; $\vec{r}_0(x_0, y_0, z_0)$ – the radius vector of the center of mass of the spacecraft in the main coupled coordinate system (Figure 3); $\dot{\vec{\omega}}(\dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z)$ – the vector of angular acceleration of the spacecraft body in the main coupled coordinate system; $\vec{\omega}_i$ – the vector of relative angular velocity (relative to the central body) in the main

coupled coordinate system (Figure 3); m_i – mass of i -th section of a part of an elastic element; $\vec{r}_i(x_i, y_i, z_i)$ – the radius vector of the center of mass of the i -th section of the elastic element in the principal coupled coordinate system (Figure 3); N – the number of sections into which the elastic elements of the spacecraft are divided.

$$\begin{cases} w_x = \dot{\omega}_y z_M - \dot{\omega}_z y_M + \omega_x(\omega_x x_M + \omega_y y_M + \omega_z z_M) - (\omega_x^2 + \omega_y^2 + \omega_z^2)x_M; \\ w_y = \dot{\omega}_z x_M - \dot{\omega}_x z_M + \omega_y(\omega_x x_M + \omega_y y_M + \omega_z z_M) - (\omega_x^2 + \omega_y^2 + \omega_z^2)y_M; \\ w_z = \dot{\omega}_x y_M - \dot{\omega}_y x_M + \omega_z(\omega_x x_M + \omega_y y_M + \omega_z z_M) - (\omega_x^2 + \omega_y^2 + \omega_z^2)z_M, \end{cases} \quad (2)$$

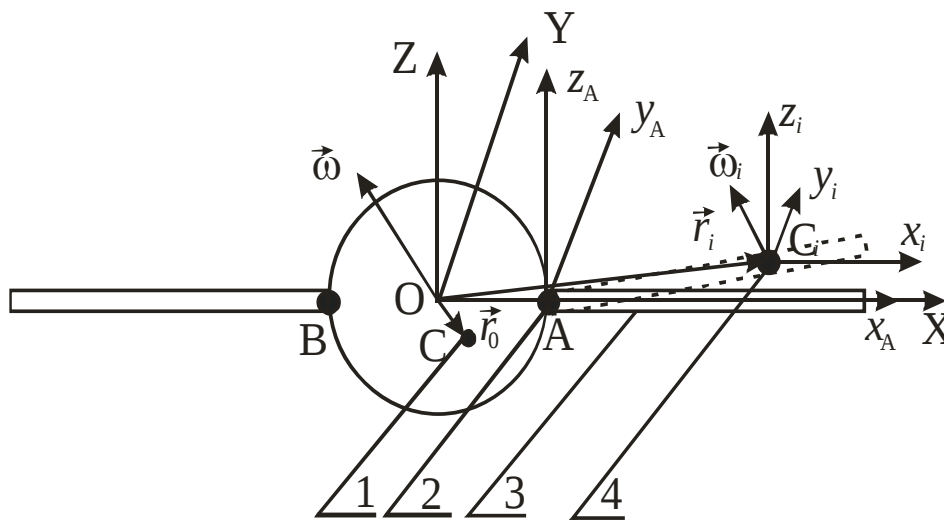


Figure 3. Schematic diagram of the SC

Then the components of micro accelerations can be defined as follows:

- 1 – is the center of mass of the spacecraft;
- 2 – the point of attachment of the elastic element to the body of the spacecraft;

3 – undeformed position of the elastic element;

4 – center of mass of the i -th part of the elastic element;

OXYZ is the main connected coordinate system;

$Ax_Ay_Az_A$ – is the local coordinate system associated

With the point of attachment of the elastic element to the body of the spacecraft;

$C_i x_i y_i z_i$ – is the local coordinate system associated with the mass center of the i -th part of the elastic element

Analysis in expressions (1) and (2) shows that for the technological assignment, low thrust values should be selected. So, for SC "Spot-4" this value is 4 N [7], for the spacecraft "Foton" - up to 6 N [8]. Such a value of thrust increases the duration of the engine operation and the time for the release of the flywheel angular momentum of the APOD. For example, for a space remote sensing satellite, this shortcoming is significant. However, from the point of view of the realization of gravitationally sensitive processes, large values of thrust will cause significant oscillations of large elastic elements. Therefore, in spite of the fact that the time for unloading flywheels of APOD will be reduced, the waiting time of favorable conditions for microacceleration will significantly increase. Thus, for the successful implementation of gravitational-sensitive processes, it is necessary to choose the thrust of the orientation engine to 10 N, depending on the inertial-mass characteristics of the spacecraft.

The wide application of small spacecraft (MCS) for the solution of technological problems dictates the necessity of using the orientation of micromotors for performing tasks [9]. Thus, the electrothermal micromotor, tested for the dilution of five different MCSs along the orbits of functioning, produced a thrust of 30 *mN* and was also effective for solving orientation problems [10]. Due to minimal impact, the use of such engines does not create such significant microaccelerations, as in the case of the LT LRE. For the orientation of MCA, both pulsed motors similar to the LT LRE can be used, as well as continuously operating, for example, electric rocket engines (ERE) [11] or a set of flywheel control motors (SFCM) [12, 13]. In the second case, there will be no peaks of microacceleration caused by impulsive switching of the engines, however, the constant operation of the ERD or SFCM will lead to the appearance of other microaccelerations (Figure 4).

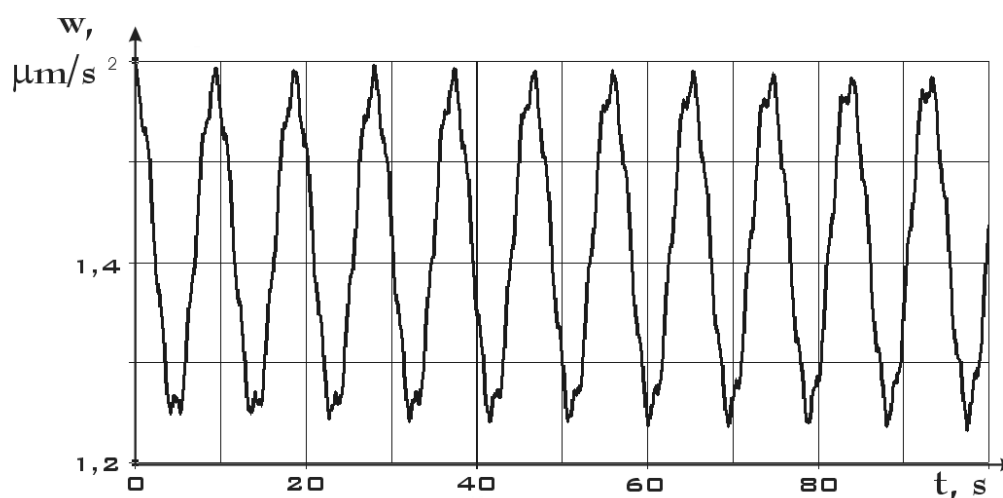


Figure 4. The rate of change of microacceleration, caused by the continuous operation of thrust 30 *mN*

3. Conclusion

Analysis of Figures 2 and 4 shows that for a short-term gravitational-sensitive processes requiring a micro-acceleration level below 1 $\mu\text{m/s}^2$, a pulse control scheme for orbital orientation is more appropriate. Since at a certain time interval between the peaks of the microacceleration (Figure 2), the level can drop to the required values. For a constantly operating ERE, this effect is not observed (Figure 4).

Thus, when choosing the scheme and parameters of the orientation engine, it is important to take into account not only the class of spacecraft and the requirements for its orientation, but also the composition of the gravitationally sensitive processes realized on its board.

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