INFLUENCE OF ASYMMETRY OF SOLAR PANELS ON THE MICROACCELERATION LEVEL IN A SPACE LABORATORY ENVIRONMENT

ВЛИЯНИЕ АСИММЕТРИИ ПАНЕЛЕЙ СОЛНЕЧНЫХ БАТАРЕЙ НА УРОВЕНЬ МИКРОУСКОРЕНИЙ ВНУТРЕННЕЙ СРЕДЫ КОСМИЧЕСКОЙ ЛАБОРАТОРИИ

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Abstract: *There are viewed the following types of asymmetry: mass, linear and asymmetry of fixing points of big elastic elements to the spacecraft' body. There is shown increase of the microacceleration module while asymmetry of the mentioned types appears. The conclusions about importance of geometrical symmetry of space laboratory for successful realization of gravity-sensitive technological processes on its board were made.*

Keywords: MICROACCELERATION FIELD, SOLAR PANELS, SPACE LABORATORY, GRAVITY-SENSITIVE PROCESSES, ASYMMETRY

1. Introduction

Modern requirements for design of new space technic, which is intended for realization of gravity-sensitive processes in space, such as growing of monocrystals, foamed metal, creating of specific medicines etc., presuppose serious limits of microacceleration level in area with technological equipment. It is very important to provide near zero gravity conditions into the inner environment of space laboratories for successful gravity-sensitive experiments and technological processes. The features of some of them are described in [1-4]. The maximum permissible microacceleration level in the facilities hosting technological equipment is a requirement provided in the preliminary technical design for the development of the space laboratory. This level is one of the most important operational and technical features of the future laboratory [5]. For instance, during the design study program of the “NIKA-T” spacecraft a microacceleration level less than 20 µm/s2 was prescribed [6], while for the perspective spacecraft “OKA-T” the requirement was less than 10 µm/s2 [7]. These requirements will become increasingly stringent with the evolution of space technologies [8].

One of the important factors to meet microgravity acceleration requirements is to avoid asymmetries of solar panels of the space laboratory during the developmental stage. This article is devoted to the analysis of consequences of possible asymmetries of solar panels in three forms:

- mass asymmetry, caused by differences in mass of solar panels;
- linear asymmetry, due to different lengths of solar panels;
- asymmetry of connection points of solar panels to spacecraft's body (connection points are not aligned with the mass center of the spacecraft).

It is known that orbiting space laboratories have been launched into space by Russia and China. Russian spacecraft from “BION” family provide a platform for conducting fundamental space biology or bio-medical experiments [9, 10]. The “FOTON” family program is dedicated to physical science and technological experiments [8, 11]. Chinese spacecraft from SJ family are used as a platform for conducting gravity-sensitive processes in space [3]. Spacecraft «FOTON – M» № 4 launched on 19th of July 2014 [11] was applied as a prototype of space laboratory for the research.

2. Source data for modelling

The spacecraft model is represented by a perfectly rigid central body with two elastic elements rigidly fixed to it (figure 1).

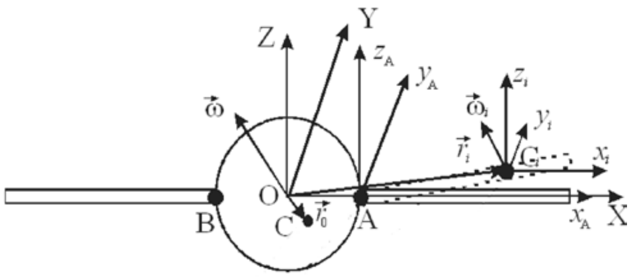

Fig. 1 *Model of spacecraft*

Elastic elements are represented by Euler–Bernoulli beam. Studies performed according to such simplified model show that a rigid connecting lug of the elastic element to the spacecraft's body gives some overestimation because some energy of elastic elements' oscillations would be dispersed by elastic attaching lug [12]. It is proved that a beam-model of elastic elements also gives rather inflated estimate in comparison with the model of homogeneous plate [13]. Therefore, application of the above mentioned model of the spacecraft provides some overestimation resulting in some safety margin for microacceleration disturbances that are very undesirable for certain gravity-sensitive processes on board the space laboratory. Data corresponding to the reference spacecraft, chosen for modelling, are shown in table 1.

Table 1: *Main characteristic of spacecraft, chosen for modelling*

Parameter	Notation	Value	Dimension
Mass	*m*	6535	kg
Centroidal moment of inertia of spacecraft	I_x; I_y; I_z	10000; 11000; 10000	kg·m^2
Length of elastic elements	l_1; l_2	4; 4	m
Thickness of elastic elements	h_1; h_2	0,003; 0,003	m

Mass of elastic elements	m_1; m_2	60; 60	kg
Centroidal moment of inertia of elastic elements	I_{x1}; I_{y1}; I_{z1}	0; 830; 850	kg·m^2
Coordinates of fixing point of elastic elements	x_A; x_B; y_A; y_B; z_A; z_B	2; -2; 0; 0; 0; 0	m
Disturbing moment of orientation engine of spacecraft	M_x; M_y; M_z	1; 5; 1	N·m

3. Equations for modelling and calculation results

The following coordinate systems have been used for derivation of the equations of mathematical model (figure 1): OXYZ – the main coordinate system; A xA yA zA – local coordinate system, centered at the fixing point of elastic element to spacecraft's body; Ci xi yi zi – local coordinate system, centered at the mass center of i-section of elastic element.

The equations of the mathematical model of the spacecraft dynamics around its mass center are shown below:

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

$$\hat{I}_i=\begin{pmatrix} I_{ix} & 0 & 0 \\ 0 & I_{iy} & 0 \\ 0 & 0 & I_{iz} \end{pmatrix} \qquad (1)$$

where $\hat{I}$ is the inertia tensor of i-section of elastic element in the coordinate system located at the mass center of the section with axes are parallel to the axes of the main coordinate system (figure 1); $\vec{\omega}_i(\omega_{ix}, \omega_{iy}, \omega_{iz})$ is the angular velocity vector (relative to the central body) in the main coordinate system (figure 1); $\vec{\omega}(\omega_x, \omega_y, \omega_z)$ is absolute angular velocity vector of the central body in the inertial coordinate system; m_i is the mass of i-section of elastic element; $\vec{r}_i(x_i, y_i, z_i)$ is the vector radius of mass center of i-section of elastic element in the main coordinate system (figure 1); $\vec{r}_0(x_0, y_0, z_0)$ the vector radius of the mass center of the spacecraft in the main coordinate system (figure 1); N is the number of the elastic elements of the spacecraft; $\vec{M}(M_x, M_y, M_z)$ is the moment vector provided by the attitude control thrusters used to keep the spacecraft at the desired orientation.

In this model, as opposed to the article [6], elastic elements are represented by a finite number of separated rigid elements. Such approach allows observing of the system's motion as a whole and not to divide it into rigid and elastic parts.

Components of the angular acceleration vector of the spacecraft are derived from (1) in an explicit form:

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

Estimation of the module of microaccelerations is shown below:

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

where $\vec{r}_M(x_M, y_M, z_M)$ is the vector radius of the displacement point of the facility where microaccelerations are estimated.

The case of ideally symmetrical positions of elastic elements and also ideally geometrical symmetry of elastic elements is considered below (figure 2). At the time $t=0$ the thruster is switched off. According to calculations, microacceleration level become less than $|\vec{w}|=1\ \mu m/s^2$ approximately in 73 seconds after the thruster is switched off.

It is then considered that elastic elements are asymmetrical in mass (masses of two solar panels are different) while the elements have linear symmetry and are symmetrically attached to the spacecraft's body. Mass of solar panel attached to the point A has the nominal value reported in table 1. Mass of another panel is reduced from the nominal value in Δm. Furthermore, lengths of both elastic elements are the same and equal to the value shown in table 1. Connection points of elastic elements to the body of spacecraft A and B are located symmetrically relative to the center of mass of the spacecraft. This leads to asynchronous vibrations of big elastic elements. It should be mentioned that synchronous vibrations in symmetrical spacecraft lead to negligibly small displacement of the overall center of mass, but asynchrony is responsible for significant (relatively to estimated microaccelerations) movements of the center of mass, and this causes additional microaccelerations. Trends of relationships of the maximum microaccelerations values after switching off the orientation engine and time-periods to achieve threshold value of microacceleration's module, as functions of the value of mass asymmetry of elastic elements can eventually demonstrate some increase of microaccelerations. This increase can be estimated quantitatively by two dimensionless parameters. The first is the relative importance of the times needed to achieve a critical microacceleration value w_{cr} for the same spacecraft with asymmetrical (T_a) and symmetrical (T_s) mass distributions. The second is the relative importance of the amplitude values of the microaccelerations for asymmetrical (w_a) and for symmetrical (w_s) mass distribution after the same time, shown in figure 2b). Figure 3 shows the dependences of the relative periods to achieve the threshold value ($|\vec{w}|=1\ \mu m/s^2$) with asymmetry and without asymmetry, as a function of the mass unbalance Δm. Similar relationship is shown for the ratio of the microaccelerations modules w_a and w_s 50 seconds after switch off of the orientation thruster. The asymmetry was achieved reducing the mass of the elastic element attached in point B from the value mentioned in table 1.

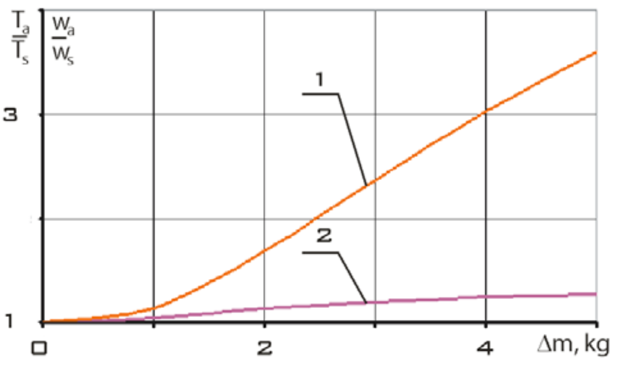

Fig.2 *Trends of relationships of the maximum microaccelerations values 50 seconds after switching off the orientation engine (1) and time-periods to achieve threshold value of microacceleration's module (2), as functions of the value of mass asymmetry of elastic elements*

As shown in figure 2, significant mass asymmetry ($\Delta m = 4\ kg$) can increase the amplitude of the microacceleration disturbances more than three times; the waiting time for favorable conditions corresponding to relatively small microaccelerations compatible with gravity-sensitive processes is increased to almost 20%.

The linear asymmetry is discussed below. In what follows the masses of both panels are the same and equal to the nominal value (reported in table 1), and points A and B are symmetric relative to the center of mass of the spacecraft. The length of the elastic element attached to the point A is also equal to the nominal value in table 1. The length of the elastic element attached to the point B is reduced from the nominal value in Δl . Such asymmetry will also lead to asynchrony of vibrations of elastic element resulting in additional microaccelerations related to the displacement of the spacecraft center of mass. The quantitative impact of the linear asymmetry on the microacceleration level has been identified. Time dependences of microaccelerations, analogous to those shown in figure 2, demonstrate that disturbances, in the presence of linear asymmetry of elastic elements, are higher than in the case of symmetric spacecraft. The same above mentioned parameters considered to investigate the influence of mass asymmetry have been evaluated.

Figure 3 shows the behavior of the relative times and relative microacceleration amplitudes versus the value of linear asymmetry.

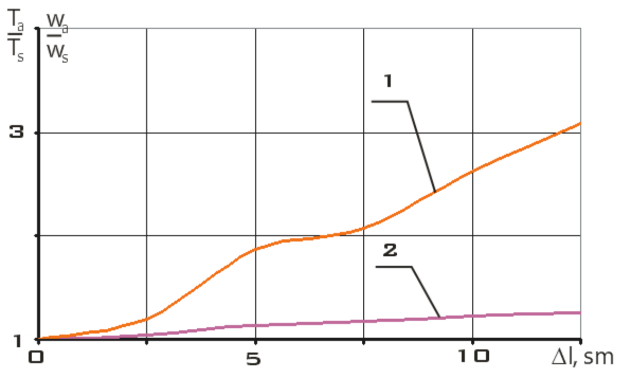

Fig.3 *Trends of relationships of the maximum microaccelerations values 50 seconds after switching off the orientation engine (1) and time-periods to achieve threshold value of microacceleration's module (2), as functions of the of linear asymmetry of elastic elements*

4. Results and discussion

In summary, all the discussed results show that almost each asymmetry is a source of acceleration disturbances in the microgravity environment. This can be explained by the constant position of the mass center of the spacecraft when elastic elements and their oscillations are symmetric, because displacements of separated parts along axes of the main coordinate system have equal magnitudes and opposite directions. Microaccelerations are caused by inertia moments excited by displacements of separated parts of elastic elements synchronously clockwise or anticlockwise. Appearance of mass asymmetry caused by reduced mass of one elastic element, in the present case, excites the displacement of the center of mass of the spacecraft while solar panels oscillate. The resulting microaccelerations are higher than the corresponding reduction caused by rotational motion. This reduction is conditioned by decrease of inertia moment of elastic elements while mass of one of them is reduced. An increase of mass of elastic element causes even larger microaccelerations caused by the combination of the rotational contribution (increase of inertia moment of elastic elements) with the displacement of the mass center of spacecraft.

A similar situation occurs when linear asymmetry appears. The length of an elastic element was reduced providing reduction of microaccelerations caused by rotational movement of the spacecraft. However, the overall microaccelerational level increases because of the displacement of the center of mass. Increase of the length of elastic element makes this growth even more significant.

5. Conclusion

The study provides the following conclusions.

1. The level of microaccelerations is underestimated when they are evaluated based only on the platform characteristics assuming symmetrical oscillations of symmetric elastic elements, because only evolution of the spacecraft around the mass center is taken into account. Displacements of the center of mass, caused by fluctuations of asymmetric elastic elements, give rise to additional constructive microacceleration. Despite the fact that the model (rigid attachment of elastic elements to the spacecraft body the beam-models of elastic elements), as shown in [13], overestimates the microaccelerational level, it is shown that neglecting significant asymmetries the microgravity disturbances can be underestimated leading to incorrect decisions about the feasibility of gravity-sensitive processes aboard the space laboratory.

2. Mass and linear asymmetry negatively influence the microgravity environment, especially in cases when the length or weight of the elastic element is greater than its designed value. Therefore, in the development stage of a space laboratory it is necessary to minimize these types of asymmetries.

3. The mathematical model used in this research allows a qualitative estimation of the impact of the considered types of asymmetries on the microaccelerational level. For reliable quantitative estimations a significantly more complicate model of the spacecraft must be developed. However, even a qualitative analysis is very useful to design a new generation of space laboratories.

4. The effects of the asymmetry of solar panels and, consequently, the microgravity disturbances can be reduced with ad hoc spacecraft asymmetries, for instance the center of mass of the spacecraft should be removed closely to heavier or longer panel. The effect of such asymmetry is opposite to the influence of mass or linear asymmetries of solar panels.

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