Dynamic characteristics modeling of rotary platform installed on board of a small spacecraft

A V Sedelnikov and A S Taneeva

Samara National Research University, 34, Moskovskoye shosse, Samara, 443086, Russia
E-mail: axe_backdraft@inbox.ru

Abstract. The paper analyzes the capabilities of an automatic rotary platform of the "Flyuger" type to reduce micro-accelerations in a protected area when it is installed on a small spacecraft of the "Aist-2" type. The micro-accelerations field of the working volume of scientific equipment of the "Growth installation" type has been modeled. The comparison with flight test data is made. The results of the work can be used in the design of small technological spacecraft.

1. Introduction
The unusual properties of materials obtained under reduced gravity were known back in the middle of the last century. Therefore, a drop tower 155 m high was put into operation at the Lewis Research Center (Ohio, USA) to study the behavior of various liquids in a state close to weightlessness in the early 60s of the last century. It allowed for a short time (just over 2 s) to obtain an almost uniform micro-acceleration field of about 10–100 µm / s² [1, 2]. However, this duration was not enough for full-scale studies. The ideas of increasing the duration of the low gravity period led to the creation of specialized laboratories based on the aircraft and the development of techniques for their piloting. Figure 1 shows the dynamic characteristics of the Airbus A300 laboratory aircraft during parabolic flight [3].

The state of low gravity (about 0,04 g) could be maintained for about 20 s [3, 4]. It is worth noting that neither the fall towers nor the aircraft of the laboratory have lost their significance these days and are widely used [5, 6]. However, their capabilities are significantly limited.

One of the first breakthroughs in the field of space technologies can be considered the project of the orbital space station "Skylab" implemented in 1973 [7]. More than 300 different series of technological experiments were carried out on board including gravitationally-sensitive ones, for example, growing crystals in a growth facility (Figure 2) [8].
Figure 1. There is time dependence of the components of the acceleration vector in the building axes of the measuring instrument during parabolic flight.

Figure 2. There is technological equipment on board the orbital station "Skylab".

The results analysis of technological experiments carried out on board the Skylab made it possible to conclude that the requirements for micro-accelerations are not always met even in near-earth conditions of orbital flight. Later estimates of the micro-acceleration module (for example, [9]) showed that its value in the telescope reorientation mode exceeded 5 mm/s². Despite the fact that...
these conditions were significantly better than in ground installations, not all planned experiments ended successfully. A number of specialized scientific groups were created to study the possibilities of space technology in terms of creating favorable conditions for the implementation of gravitational-sensitive processes. One of them, the Microgravity Science and Applications Division, operated within NASA. This group included the Principal Investigator Microgravity services division which measured micro-accelerations on space shuttles and provided information on the values of micro-accelerations in the areas of experimental equipment [10].

One of the most promising directions for meeting the requirements for micro-acceleration was the creation of specialized vibration protection platforms [11]. Technological equipment was located in the protected area of these platforms. One of the first such platforms was created and tested the Microgravity Isolation Mount (Figure 3) [12].

Tests of Microgravity Isolation Mount aboard the Mir orbital complex have shown that oscillations in the protected area are significantly lower than outside the protected area during normal operation (Figure 4).

Later, the Vibration Isolation Mounting System was developed on the basis of the Microgravity Isolation Mount [13]. It became the basis for the Microgravity Vibration Isolation Subsystem which is part of the Fluid Science Laboratory [14]. This minilab operates as part of the Columbus laboratory module on the International Space Station. It was possible to reduce the maximum values of micro-accelerations from 227 μm / s² to 40 μm / s² according to estimates [14] using the Microgravity Vibration Isolation Subsystem.

Thus, the direction for meeting the requirements for micro-accelerations for orbital space stations which include specialized laboratory modules ("Kristall" [15], "Columbus" [16], "KIBO" [17]), as well as laboratories of the class orbiting space stations "Tiangong" [18, 19]). This direction is actively developing at the present time [20, 21] since full-fledged pilot-scale production is possible only on large space objects. The capabilities of a modern Microgravity Isolation Mount are shown in Figure 5.
Figure 4. There are oscillations in the protected area and outside the protected area of the vibration protection platform Microgravity Isolation Mount [12]

Figure 5. There are requirements for micro-acceleration:
1 is document SSP41000D regulating micro-accelerations on the international space station;
2, 3, 4, 5 are test results of the MAIS vibration protection platform (Tiangong-2 [18]);
6 are requirements of Baikov Institute of Metallurgy and Materials Science [22].

However, meeting the micro-acceleration requirements on a multifunctional orbital space station is a more difficult task than on specialized technological spacecraft. Since only one target problem is solved on the latter. It is the implementation of gravitational-sensitive processes. Therefore, another promising direction for meeting the requirements for micro-accelerations has arisen which consists in the creation of specialized space laboratories for technological purposes of the middle class. By now, quite a lot of experience has been accumulated and several series of such spacecraft have been implemented. The most famous of them are “Foton” (for technological purposes) [23, 24], “Bion” (for
biomedical purposes) [25, 26] and “SJ” [27]. A number of promising projects of technological space laboratories have been developed but have not yet been implemented (Makos-T [28], NIKA-T [9], OKA-T [29], Vozvrat-MKA [30]). This direction is also widely developing at the present time.

The miniaturization of space technology has led to the rapid development of small spacecraft and their widespread use in various fields of space activities. Low cost and short term of implementation of small spacecraft projects are their indisputable advantages, thanks to which they can successfully compete with spacecraft of other classes. The use of small spacecraft in the field of space technology is still limited by two factors. The first of these is that it is more difficult to meet the micro-acceleration requirements on a small spacecraft than on a middle class spacecraft [24, 30]. It is primarily due to the fact that the proportion of elastic elements in the total mass is higher for a small spacecraft than for a spacecraft of another class. Therefore, natural vibrations [9] or temperature shock [30] of elastic elements significantly affect the dynamics of the rotational motion of a small spacecraft around the center of mass. It creates additional micro-accelerations. The second important reason is the small internal space for the placement of technological equipment. However, despite it, this direction is promising and will be actively developed in the future.

The first steps in this direction can be considered the small spacecraft Volan and Bolid (Volan-M) [31] developed at the end of the last century at the Makeyev Design Bureau (Figure 6).

![Small spacecraft Volan and Bolid](image)

**Figure 6.** It is general view of small spacecraft "Volan" (a) and "Bolid" (b)

They made a suborbital flight (Figure 7) while theoretically providing for about 30 min values of the micro-acceleration modulus 10–100 µm / s².
In total, four small spacecraft of this type were launched. The last launch took place on 07.06.1995. The Volna launch vehicle launched the Volan small spacecraft which carried a payload in the form of a thermal convection module (developed by the University of Bremen) was launched into suborbital flight (Figure 7) from a water launch. It made a soft landing 40 minutes after the start. Onboard measuring instruments recorded that the favorable period for carrying out gravitational-sensitive lasted 20.5 minutes at a level of micro-accelerations from 100 to 1000 μm / s².

At present, there are all conditions for the creation and successful launch of small technological spacecraft. Of course, they will not be able to compete with space laboratories in organizing pilot production in space. However, they are quite suitable for conducting experiments and will soon take their place.

2. Materials and methods.
This work considers a platform of the "Aist-2" type (Figure 8) as a prototype of a small spacecraft for technological purposes [32].

Figure 7. It is suborbital flight of the small spacecraft "Volan"

![Figure 7](image1)

Figure 8. There is an experimental and technological small spacecraft "Aist-2D"

![Figure 8](image2)
The mass of the target and scientific equipment is at least 145 kg with a total mass of 530 kg. The only significant structural difference of the considered small spacecraft for technological purposes from the platform of the "Aist-2" type is the presence of four rather than two solar panels, as in the project of the "Vozvrat-MKA" spacecraft (Figure 9).

**Figure 9.** There is a spacecraft "Vozvrat-MKA"

It significantly reduces the effect of natural vibrations and thermal shock of elastic elements on the micro-acceleration modulus in the internal environment of a small spacecraft. The "Growth installation" [33] is considered as scientific equipment (Figure 10).

**Figure 10.** There is scientific equipment of the Growth installation on the automatic rotary vibration-protective platform "Flyuger"

It is intended for growing highly homogeneous and perfect germanium crystals with a diameter of about 25-30 mm by directional crystallization by the Bridgman method. It is assumed that this technological equipment will be installed on the automatic rotary vibration protection platform "Flyuger" [34] (Figure 10). The total mass of this equipment is about 90 kg which does not exceed the maximum value for a platform of the "Aist-2" type.
The research method is mathematical modeling of the rotational motion of a small spacecraft with an automatic rotary vibration protection platform. The assessment of the micro-acceleration field inside the technological container of scientific equipment is constructed using this method.

3. **Mathematical model.**

Let us consider the problem of assessing the dynamic characteristics of a vibration protection platform in the following setting. Let the geometric center of the Growth installation coincide with the axes intersection point of its own rotation of the outer and inner frames of the automatic rotary vibration protection platform. In turn, this point coincides with the center of mass of the spacecraft (point C in Figure 11). Let us introduce the following coordinate systems (shown in Figure 11): CXYZ is the main connected coordinate system of the small spacecraft; Cx1y1z1 is coordinate system associated with the outer frame of the platform and the axis of its own rotation (z1) coincides with the Z axis of the main associated coordinate system; Cx2y2z2 is coordinate system associated with the inner frame of the platform where the x1 and x2 axes coincide. The position of the x1 and x2 axes relative to the X axis will be described by the angle $\phi$ and the position of the z1 axis of the inner frame relative to the Z and z1 will be described by the angle $\psi$ (Figure 11).

Then the absolute acceleration of an arbitrary point M of the internal environment of the working area of the Growth installation in some fixed coordinate system can be determined as follows [35]:

\[
\ddot{\mathbf{w}}_M = \ddot{\mathbf{w}}_C + (\ddot{\mathbf{e}}_1 + \ddot{\mathbf{e}}_2) \times \ddot{\mathbf{r}}_M + (\dddot{\varphi}_1 + \dddot{\varphi}_2) \times \ddot{\mathbf{r}}_M + (\dddot{\psi}_1 + \dddot{\psi}_2) \times (\ddot{\varphi}_1 + \ddot{\varphi}_2) \times \ddot{\mathbf{r}}_M
\]

where $\ddot{\varphi}_1$ and $\ddot{\varphi}_1$ are vectors of the angular velocity and angular acceleration of the small spacecraft, respectively (transfer rotation); $\ddot{\psi}_2$ and $\ddot{\psi}_2$ are vectors of angular velocity and angular acceleration of rotation of the Growth installation relative to a small spacecraft, respectively (relative rotation); $\ddot{\mathbf{r}}_M$ is radius vector of point M relative to point C.

**Figure 11.** There is diagram of an automatic rotary vibration protection platform with coordinate axes
The transition matrices between coordinate systems were obtained in [35]. Then we have in the main connected coordinate system:

\[
\phi_2 = (\psi', \phi \sin \psi, \phi \cos \psi) \quad \text{and} \quad \phi_2 = (\dot{\psi}, \dot{\phi} \sin \psi + \dot{\phi} \psi \cos \psi, \dot{\phi} \cos \psi - \dot{\phi} \psi \sin \psi). \tag{2}
\]

It is possible to estimate the micro-accelerations in the entire working area of the Growth installation knowing the values of the rotational motion parameters of a small spacecraft and projecting (1) on the axis of the associated coordinate system taking into account (2). The micro-acceleration field will be the most important dynamic characteristic that determines the possibility and feasibility of implementing one or another gravitationally sensitive process.

We will use the d'Alembert's principle to connect the kinematic parameters of the rotational motion of the small spacecraft and the platform:

\[
\ddot{M} (\ddot{R}) + \ddot{M} (\ddot{R}) + \ddot{M} (\ddot{\Phi}) = 0, \tag{3}
\]

where \( \ddot{M} (\ddot{R}) \), \( \ddot{M} (\ddot{R}) \) and \( \ddot{M} (\ddot{\Phi}) \) are respectively the main moments of active, reactive and fictitious forces.

We will assume that all connections are ideal, therefore, in the equation (3) \( \ddot{M} (\ddot{R}) = 0 \). We get instead of (3) in the simplest case (\( \ddot{M} (\ddot{R}) = 0 \)):

\[
\ddot{M} (\ddot{\Phi}) = 0. \tag{4}
\]

Then it follows from equation (4) that:

\[
\ddot{e}_1 = -\ddot{e}_2. \tag{5}
\]

We obtain integrating (5):

\[
\ddot{a}_h = -\ddot{a}_2. \tag{6}
\]

We will have substituting (5) and (6) into expression (1):

\[
\ddot{w}_M = \ddot{w}_C. \tag{7}
\]

We can come to the conclusion that the automatic rotary vibration protection platform in this case fully compensates for the acceleration from the rotational motion of the small spacecraft analyzing expression (7). The absolute acceleration of the working zone points of the Growth installation will be determined by the acceleration of the center of mass in its orbital motion.

The gravitational action is considered as an external disturbing factor in [35]. It is shown that the inhomogeneity of the gravitational field will not allow creating micro-accelerations close to zero in the entire working zone [35]. However, magnetic perturbations are decisive for small spacecraft [32]. Therefore, the d'Alambert's principle (3) has the form in this work:

\[
\ddot{M} (\ddot{\Phi}) = -\ddot{M}_{mag}. \tag{8}
\]

It is possible to obtain recurrent formulas for estimating the parameters of the rotational motion of the platform using the measurement data of the induction vector of the Earth's magnetic field in the main connected coordinate system CXYZ (Figure 11), using (8):
Three more recurrent equations express an obvious relationship between the rotational motion parameters of the platform:

\[
\begin{align*}
\mathcal{E}_{x_i} &= \frac{M_{mag \; x_i}}{I_x} \cdot I_x - I_y (\omega_{1yi} + \omega_{2yi}) (\omega_{1zi} + \omega_{2zi}) - \mathcal{E}_{1xi}; \\
\mathcal{E}_{y_i} &= \frac{M_{mag \; y_i}}{I_y} \cdot I_y - I_z (\omega_{1xi} + \omega_{2xi}) (\omega_{1zi} + \omega_{2zi}) - \mathcal{E}_{1yi}; \\
\mathcal{E}_{z_i} &= \frac{M_{mag \; z_i}}{I_z} \cdot I_z - I_x (\omega_{1xi} + \omega_{2xi}) (\omega_{1yi} + \omega_{2yi}) - \mathcal{E}_{2zi},
\end{align*}
\]

(9)

where \(i\) is serial number of measurement.

Then it is possible to obtain the field of absolute accelerations in the working area of the Growth installation estimating \(\vec{\omega}_1, \vec{e}_1\) and \(\vec{M}_{mag}\) according to measurements, but evaluating \(\vec{\omega}_2\) and \(\vec{e}_2\) according to formulas (10) and (9), respectively, using expression (1).  

4. Numerical simulation results and their analysis.

We will assume that the first term in expression (1) is equal to zero for simplicity of analysis. Consider the controlled motion of a small spacecraft by magnetic actuators. In this case, the magnetic disturbing moment is maximum. In this case, the control torque is aimed at reducing the angular velocity of rotation of the small spacecraft and corresponds to the "-Bdot" algorithm.

We will select the data of measurements of the Earth's magnetic field on the flight sample of the small spacecraft "Aist" from 02.05.2013 (Figure 12) for numerical analysis.

**Figure 12.** There is measurement data of the Earth's magnetic field on the flight sample of the small spacecraft "Aist" from 05/02/2013 (\(t = 0\) means 01:14:07 Moscow time)
Let us estimate the angular velocity according to the measurement data (Figure 12) using the well-known Boer formula:

$$ \ddot{\omega}_t = \frac{\dot{\tilde{B}} \times \left( \tilde{B} - \frac{d\dot{B}}{dt} \right)}{\tilde{B}^2}. $$

(11)

The estimated angular velocity is shown in Figure 13 for the data presented in Figure 12.

Figure 13. There is the rotation angular velocity of the flight sample of the small spacecraft "Aist" from 05/02/2013 (t = 0 means 01:14:07 Moscow time)

The angular acceleration was determined by time differentiation $\ddot{\omega}_t$ and is shown in Figure 14.

A current was applied to the magnetic actuators (electromagnets) to create a magnetic control torque. Moreover, its value is determined by the expression:

$$ M_{mag} = \sum_{j=1}^{n} \tilde{p}_j \times \tilde{B}, $$

(12)

where $\tilde{p}_j$ is magnetic moment of current of an actuator or circuit with current; $n$ is total number of magnetic actuators and current circuits.

We will assume that the magnetic moment of the current of the actuators is significantly higher than the magnetic moments of the circuits of the target and providing equipment. Therefore, we will take into account only the magnetic moments of electromagnets neglecting the rest of the magnetic disturbances. The strength of the current supplied to the magnetic actuators is shown in Figure 15.
Figure 14. There is the rotation angular acceleration of the flight sample of the small spacecraft "Aist" from 05/02/2013 (t = 0 means 01:14:07 Moscow time)

![Figure 14](image1)

Figure 15. There is strength of the current supplied to electromagnets, the axes of which are parallel:

![Figure 15](image2)

The magnetic control torque was formed when current was applied to the electromagnets, shown in Figure 16.

Further, the parameters of the rotational motion of the automatic rotary vibration protection platform were estimated using formulas (9) and (10) and the dependences of micro-accelerations on time were obtained (Figures 17 and 18) taking into account only the second term of expression (1). The sums of angular velocities (third and fourth terms) are squared and are negligible compared to the second term.
**Figure 16.** There is the control torque of the magnetic actuators of the flight sample of the small spacecraft "Aist" from 05/02/2013 (t = 0 means 01:14:07 Moscow time)

**Figure 17.** There is the module of micro-accelerations from the rotational motion of the small spacecraft "Aist" (corresponding to the magnetic disturbing moment in Figure 16) at a point 10 cm from the center of mass:

1 is outside the protected area of the platform;
2 is on an automatic rotary vibration protection platform
Figure 18. There is the module of micro-accelerations from the rotational motion of the small spacecraft "Aist" (corresponding to the magnetic disturbing moment in Figure 16) at a point 10 cm from the center of mass on an automatic rotary vibration protection platform. It can be seen that the automatic rotary vibration protection platform reduces micro-accelerations from rotary movement by about two orders of magnitude from Figures 17 and 18.

5. Conclusions.
Thus, small spacecraft are already prepared to find their application in space technologies. The developed equipment makes it possible to provide a micro-acceleration level of 10 μm / s². It is this value that is determined by the terms of reference for the space laboratory of the middle class "OKA-T" [29]. Therefore, the competitiveness of small spacecraft is beyond doubt. We can say that the concept of "OKA-T" also does not provide for the delivery of results to Earth as for the lack of the possibility of such delivery using the return vehicle. It interacts with a base space station as a reusable space object. And from there, the results are delivered to Earth. The same scheme is quite efficient in the case of a small spacecraft. From this point of view, the lack of direct delivery is not a significant drawback.

This work did not consider the possibility of controlling the rotary motion of an automatic rotary vibration-protective platform. The development of control laws that reduce micro-acceleration will make it possible to obtain even better dynamic characteristics than those presented in Figure 18. This problem is solved with high efficiency in a number of works [30, 35]. Therefore, there are enough developments for the implementation of a technological project based on a small spacecraft at present.

References
[1] Lekan J, Neumann E S and Sotos R G 1993 Capabilities and constraints of NASA’s ground-based reduced gravity facilities, in Second International Microgravity Combustion Workshop (CP-10113 – NASA)
[2] Lekan J 1996 Users Guide for the 2.2 Second Drop Tower of the NASA Lewis Research Center (TM 107090 – NASA)
[3] Pletser V 2004 Short duration microgravity experiments in physical and life sciences during parabolic flights: the first 30 ESA campaigns (Acta Astronautica vol 55 № 10) pp 829–854
[4] Frank D J 1996 Dynamics of superfluid Helium in low gravity, Progress report (CR-201072. – California: NASA, Jet Propulsion Laboratory)

[5] Zhang X et al 2005 Some key technics of drop tower experiment device of National Microgravity Laboratory (China) (NMLC) (Science in China Ser. E Engineering & Materials Science vol 48 № 3) pp 305–316

[6] Bishk K S and Dreyer M E 2020 Phase Separation in Porous Media Integrated Capillary Channels (Microgravity Science and Technology vol 32 №6) pp 1001–1018

[7] Leland F Belew and Washington D C 1997 Skylab, our first space station (Scientific Technical Information Office) p 164

[8] Schneider W C and William D Green Jr 1972 The Skylab Experiment Program (Advances in Space Science and Technology vol 11) pp 329–436

[9] Sedelnikov A V and Kireeva A A 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

[10] Gregory L Vogt et al 1992 Microgravity A Teacher's Guide With Activities Secondary Level (National Aeronautics and Space Administration) p 64

[11] Thomas V A, Prasad N S and Ananda Mohan Reddy C 2000 Microgravity Research Platforms – A Study (Current Science vol 79 № 3 ) pp 336–340

[12] Owen R G et al 1990 Integration of a microgravity isolation mount within a Columbus single rack (Acta Astronautica vol 22) pp 127–135

[13] Jones D I, Owens A R and Owen R G 1987 A microgravity isolation mount (Acta Astronautica vol 15 № 6–7) pp 441–448

[14] Labib M et al 2010 The Fluid Science Laboratory's Microgravity Vibration Isolation Subsystem Overview and Commissioning Update (SpaceOps 2010 Conference) DOI:10.2514/6.2010-2007

[15] Kundrot C E et al 2001 Microgravity and Macromolecular Crystallography (Crystal Growth & Design vol 1 № 1) pp 87–99

[16] Kuch T and Sabath D 2008 The Columbus-CC—Operating the European laboratory at ISS (Acta Astronautica vol 63 № 1–4) pp 204–212

[17] Yano S et al 2013 Improvements in and actual performance of the plant experiment unit onboard KIBO, the Japanese experiment module on the International Space Station (Advances in Space Research vol 51 № 5) pp 780–788

[18] Dong W et al 2019 Microgravity disturbance analysis on Chinese space laboratory (npj Microgravity vol 5) 18

[19] Li X L et al 2014 A Compact Device for Colloidal Crystal Studies on Tiangong-1 Target Spacecraft (Microgravity Science and Technology vol 25 № 6) pp 375–381

[20] Liu W et al 2018 Flight Test Results of the Microgravity Active Vibration Isolation System in China's Tianzhou-1 Mission (Microgravity Science and Technology vol 30 № 6) pp 995–1009

[21] Wu Q et al 2019 Tracking Control of a Maglev Vibration Isolation System Based on a High-Precision Relative Position and Attitude Model (Sensors vol 19) 3375

[22] Sedelnikov AV 2012 Fractal quality of microaccelerations (Microgravity Science and Technology vol 24 № 5) pp 345–350

[23] Abrashkin V I et al 2016 Rotational motion of FOTON M-4 (Cosmic Research vol 54 № 4) pp 296–302

[24] Abrashkin AV 2020 Accuracy assessment of microaccelerations simulation on the spacecraft “Foton-M” no. 2 according to magnetic measuring instruments data (Microgravity Science and Technology vol 32 № 3) pp 259–264

[25] Abrashkin V I et al 2015 Determining the rotational motion of the BION M-1 satellite with the GRAVITON instrument (Cosmic Research vol 53 № 4) pp 286–299

[26] Belousov A I and Sedelnikov A V 2013 Probabilistic Estimation of Fulfilling Favorable Conditions to Realize the Gravity-Sensitive Processes Aboard a Space Laboratory (Russian Aeronautics vol 56 № 3) pp 297–302
[27] Hu W R et al 2014 Space Program SJ–10 of Microgravity Research (Microgravity Science and Technology vol 26 № 3) pp 159–169
[28] Lukashchenko V et al 1996 «MAKOS–T» A New Spacecraft for Conducting Experiments in Microgravity (Russian Space Bulletin vol 1 № 4) pp 13–15
[29] Ivanov A et al 2014 Served by ISS free-flying spacecraft OKA-T and its usage for microgravity experiments and technological exploration of space (65th International Astronautical Congress (IAC 2014) vol 1) pp 607–612
[30] Gorozhankina A S, Orlov D I and Belousova D A 2020 Problems of development motion control algorithms for a small spacecraft for technological purpose taking into account temperature deformations of solar panels (Journal of Physics: Conference Series 1546) 012015
[31] Ivanov S 2002 Weapons and technologies of Russia. XXI Century. Encyclopedia. Vol 5 Space Weapons (Arms and Technology publishing house) p 703
[32] Kirilin A N 2017 Small spacecrafts of a Aist series (design, tests, operation, development) (Samara: publishing house of the Samara scientific center) p 348
[33] Shikova I A et al 2017 Scientific apparatus for obtaining highly homogeneous and perfect semiconductor crystals by the vertical bridgman method in space conditions (All-Russian Youth Scientific and Practical Conference "Orbit of Youth" and Prospects for the Development of Russian Cosmonautics) pp 173–174
[34] Akulenko L D et al 2019 Orientation control of an object on a rotating base by using a two-stage electric drive (Journal of Computer and Systems Sciences International vol 58 № 6) pp 829–843
[35] Akulenko L D et al 2012 Control of the apparent acceleration of a rigid body attached to a movable base by means of a two-degree-of-freedom gimbal (Journal of Computer and Systems Sciences International vol 51 № 3) pp 339–348