The simulation results of the operation of a small spacecraft motion control system with an electrothermal microdrive

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Abstract. The work simulates the operation of the motion control system of a small spacecraft. The main Executive body of this system is the engine-flywheel. It is proposed to use an electrothermal micro-motor to reduce the kinetic moment of the flywheel motor. In emergency situations, it can be used as the main Executive body of the management system. A comparative analysis of the advantages and disadvantages of using magnetic actuators and electrothermal micro-motor to reduce the kinetic moment of the flywheel motor. Conclusions are drawn on the feasibility of their application for various small spacecrafts.

1. Introduction
Currently, the miniaturization of space technology and the mass use of small spacecraft for solving a wide range of tasks requires optimal revisions of approaches. They were optimal for a middle-class spacecraft., The significant effect on magnetic measuring instruments and equipment of a spacecraft from space thus is noted in comparison with a middle-class spacecraft [1]. It can lead to incorrect operation of the executive bodies of the orbital motion control system of a small spacecraft [2]. There are many complex aspects due to the small mass of a small spacecraft and a spacecraft [3]. The moving parts of a small spacecraft largely influence on the movement of its central masses. The introduction of gravitationally-sensitive technological processes should be due to the influence of magnetic interactions of a small spacecraft with the earth's field [4]. The work of the target and supporting equipment can therefore disrupt the favorable conditions for the implementation of such processes. [5]. Moreover, the requirements for micro-accelerations in the internal environment of the spacecraft are becoming tougher every year. It can lead to the need for successful implementation of already developed gravitationally-sensitive technological processes that can be obtained on board the space station at the micro level (Figure 1) [6]. Despite the fact that the international space station is a multifunctional space research as well as, for example, Foton - M No. 4 [7], the possible problems of this problem are obvious. For this purpose, special laboratory modules are used to implement gravity-sensitive technological processes [8].

The upper curve in the figure 1 is taken from an official document SSP41000D [9] which formulates the requirements to the level of microgravity environment to conduct gravity-sensitive experiments and processes for the international space station, and the lower curve shows the desired requirements of the specialists of the Institute of metallurgy and material science named after A.A.
Baykov of the Russian Academy of Sciences, presented by the processes they have developed which are still unattainable [10].

![Figure 1](image)

**Figure 1.** Required and achievable levels of micro-accelerations.

The problem of controlled motion of a small spacecraft in the light of the requirements for micro-accelerations thus is relevant and timely. One of the possible solutions is creating a control system based on the executive bodies that can both solve the problems of orientation and stabilization of a small spacecraft, and allow the implementation of gravitational-sensitive processes on board.

The purpose of the paper is simulation of the operation of a small spacecraft motion control system with an electrothermal microdrive. In this case, an electrothermal micromotor is used to reduce the angular momentum of flywheel engines. It is a replacement for a low-thrust liquid-propellant rocket engine used in the control system of a middle-class spacecraft [11].

New results were obtained for assessing the level of micro-accelerations in the area of the proposed placement of technological equipment for conducting gravity-sensitive technological processes. The results indicate the possibility of successful implementation of most gravitationally sensitive processes [12–14] and correspond to the data obtained by other authors [15–18].

2. **Statement of the problem of developing a control system for the orbital motion of a small spacecraft**

Providing a high power-to-power capability of a modern spacecraft while maintaining a low level of micro-accelerations in the zone of gravitational-sensitive processes is a difficult task. The most efficient and environmentally friendly source of electrical energy in the near-earth space continues to be solar energy, so the requirements for energy efficiency are met by the presence of extended solar panels in the design and layout scheme of the spacecraft. Their effective operation involves the solar orientation of the spacecraft. This problem is usually solved in two stages [19]:

- orientation of the spacecraft after its launch into the working orbit;
- stabilization of the spacecraft position relative to the Sun.

The first stage should be implemented in a compressed time interval. The middle-class spacecraft is often used in liquid rocket engines of small thrust to do it [7] (figure 2 a). However, their minimum thrust can theoretically reach about 400 mN [8]. It is too much for most small spacecrafts. The thrust created by liquid rocket engines of small thrust is in the range of 1–10 N [20].

For the second stage, a complex of control flywheel motors is most often used. Its main advantage is the absence of a working body (figure 2 b). This advantage makes it possible to operate a small spacecraft for a long time. The thrust of flywheel motors is 1–20 mN [21]. However, to maintain their performance, periodic compensation of the kinetic moment of the flywheels is necessary. It is also necessary to replace the liquid rocket engines of low thrust to solve the problem of orientation, since its solution by the forces of the complex of control flywheel engines can take a long time.

The task therefore is to develop a new orbital motion control system for a small spacecraft that does not use low-thrust liquid-propellant rocket engines as the main executive body. It should be taken
into account in solving this problem that the use of magnetic executive bodies gives significant limitations. Despite their undoubted advantage (the lack of a working body), solving the problem of orientation for an acceptable period of time with their help will also fail. There are serious restrictions on the angular velocity of rotation of a small spacecraft on their performance and in the direction of the control torque [13]. While the thrust of the executive body must be less than liquid rocket engines of small thrust but more than the reaction wheels.

Figure 2. Executive bodies of the system of orientation and traffic control: a) low-thrust liquid rocket engines; b) flywheel engines.

3. Justification of the use of electrothermal microdrive as the main executive body

It is proposed to use an electrothermal micro-engine developed by the production Association "Polet" (Omsk) [22] as the main executive body for solving the problem of orientation in this work. Advantages of electrothermal micromotors are [22]:

- high efficiency in the class of electric rocket engines;
- a wide range of potential types of working fluid for the functioning of the electrothermal microdrive;
- simple design;
- high reliability;
- the possibility of multiple switching on for a long service life;
- high resource (up to hundreds of hours);
- high efficiency (up to 80%);
- the ability to control the amount of traction in a wide range (10–200 mN).

The appearance of the electrothermal microdrive is shown in the figure 3 [22].

However, it should be noted that the warm-up time of the design of the electrothermal microdrive before the start of ammonia is about 300 s according to the experimental results [22]. It imposes restrictions due to the fact that the use of an electrothermal microdrive requires a reserve for the kinetic moment of the flywheel. If you use an electrothermal microdrive at a time when the flywheel
reached a critical angular velocity of rotation, then for some period the control system with a complex of control motors-flywheels will be inoperative. Therefore, it is proposed to duplicate the electrothermal microdrive with magnetic actuators which will allow less use of the electrothermal microdrive saving the working fluid and thereby increasing the period of its regular operation. On the other hand, the use of an electrothermal microdrive will allow to neutralize the shortcomings of magnetic actuators which consist in the inefficiency of their work at angular velocities of rotation of a small spacecraft above 15 deg/s as well as the possibility of creating a control torque only perpendicular to the earth's magnetic field induction vector. In fact, the electrothermal micro-engine in the proposed system of orientation and motion control of a small spacecraft will play the same role as the liquid rocket low-thrust engine for a middle-class spacecraft. The scheme of operation of such a system of orientation and orbital motion control using an electrothermal microdrive is shown in figure 4.

![Figure 3](image-url)

**Figure 3.** Scheme of electrothermal micromotors: 1 – nozzle; 2 – glass tube; 3 – the cavity of the gas outlet; 4 – hollow nut; 5 – the cavity of the placement of the heating element; 6 – channel ceramic tube; 7 – cylindrical glass.

![Figure 4](image-url)

**Figure 4.** Scheme of operation of the orbital motion control system of a small spacecraft using an electrothermal microdrive.

The unloading of flywheels refers to the reduction of their kinetic moment. Restrictions on the use of an electrothermal microdrive may be related, for example, to the requirement of technological processes carried out on board of a small spacecraft or other restrictions not related to the non-standard operation of the electrothermal micro-engine itself. For example, gravity-sensitive technological processes require a significant limitation of the level of micro-accelerations in the area of technological equipment placement (figure 1). If the use of magnetic actuators prevents the values of the angular velocity of rotation of the flywheel from approaching the critical values, then the electrothermal micromotor is also not used.
Thus, the function of the electrothermal microdrive is to solve the problem of orientation and significant unloading of flywheels provided that the m & E do not cope with this task. At the same time, the electrothermal microdrive can, if necessary, perform those functions that were assigned to it earlier and implemented in various space projects [22]:

- breeding in the orbits of the functioning of a number of small satellites;
- correction of the orbit of a small spacecraft.

4. Simulation results of the orbital motion control system with an electrothermal microdrive

Choose as a prototype of a small spacecraft "Aist–2D" (figure 5) [23].

![Figure 5. General view of the small spacecraft "Aist–2D".](image)

Small spacecraft "Aist–2D" was launched from the spaceport Vostochny 28.04.2016 in a circular orbit with a height of about 480 km and an inclination of 97.30. It is a promising small spacecraft for solving problems of remote sensing of the Earth and scientific problems. "Aist–2D" can be considered as a platform for the implementation of gravity-sensitive processes having a mass of 530 kg and an active life of about 3 years. Therefore, it was chosen as a prototype in this work.

To construct a model of the rotational motion of the spacecraft around the center of mass, we take a number of simplifying assumptions.

- The model of motion of a small spacecraft is spatial rotation around the center of mass.
- The spacecraft is a completely solid symmetrical body with two elastic rigidly attached to it.
- The model of elastic elements (solar panels) is Euler-Bernoulli beam.
- The change in the longitudinal coordinate of the elastic element points along the beam axis with fluctuations in solar panels is negligible.
- The first two forms of natural oscillations of elastic elements are taken into account.
- The model of damping the natural vibrations of elastic elements due to internal friction in the material is viscous friction.

The assumptions made to simplify the simulated situation slightly overestimate the resulting estimate of micro-accelerations in the internal environment of a small spacecraft.

We apply the theorem on the change of the kinetic moment to derive the equations. The expression for the kinetic moment in the general case will have the form:

\[
\vec{L} = \hat{I} \cdot \vec{\omega} + \sum_{i=1}^{N} \hat{I}_i \cdot (\vec{\omega} + \vec{\omega}_i) + m \vec{r}_n \times \vec{\alpha}_n + \sum_{i=1}^{N} \left( \vec{r}_i - \vec{r}_n \right) \times \left( \vec{\alpha}_i - \vec{\alpha}_n \right),
\]

(1)

where \( \hat{I}_i = \begin{pmatrix} I_{ii} & 0 & 0 \\ 0 & I_{ii} & 0 \\ 0 & 0 & I_{ii} \end{pmatrix} \) is the inertia tensor of the i-th section of the elastic element in the coordinate system, the beginning of which is located in the center of mass of the section, and the axes are parallel to the axes of the main bound coordinate system (Figure 6); \( \vec{\omega}_i = (\omega_i, \omega_i, \omega_i) \) is the vector of relative
angular velocity (relative to the central body) in the main bound coordinate system; \( \dot{\omega}(\omega_x, \omega_y, \omega_z) \) is the vector of the absolute angular velocity of the central body of a small spacecraft in the inertial coordinate system; \( m_i \) is the mass of the i-th section of the elastic element; \( \vec{r}_i (x_i, y_i, z_i) \) is the radius-vector of the center of mass of the i-th portion of the elastic element in the main bound coordinate system; \( \vec{r}_0 (x_0, y_0, z_0) \) is the radius-vector of the center of mass of a small spacecraft in the main bound coordinate system; \( N \) is the number of sites into which the elastic elements of a small spacecraft are broken; \( \vec{M} (M_x, M_y, M_z) \) is the vector of the control torque of the engine orientation of a small spacecraft.

The designations in Figure 6: 1 is the center of mass of a small spacecraft; 2 is the point of attachment of the elastic element to the body; 3 is the undeformed position of the elastic element; 4 is the center of mass of the i-th section of the elastic element; OXYZ is the main bound coordinate system; \( A_X A_Y A_Z \) – local coordinate system associated with the point of attachment of the elastic element to the body; \( C_{x_i y_i z_i} \) – a local coordinate system associated with the center of mass of the i-th portion of the elastic element.

Given the simplifying assumptions, the model of the motion of a small spacecraft with elastic elements is:

\[
\begin{align*}
I_x \dot{\omega}_x + \sum_{i=1}^{N} l_i (\dot{\omega}_x + \dot{\omega}_z) + m \left( y_0 \dot{y}_0 - y_0 \dot{y}_0 \right) + \sum_{i=1}^{N} m_i \left[ (y_i - y_0) \cdot (z_i - z_0) - (y_i - y_0) \cdot (z_i - z_0) \right] &= M_x; \\
I_y \dot{\omega}_y + \sum_{i=1}^{N} l_i (\dot{\omega}_y + \dot{\omega}_z) + m \left( \dot{x}_0 \dot{x}_0 - x_0 \dot{z}_0 \right) + \sum_{i=1}^{N} m_i \left[ (x_i - x_0) \cdot (z_i - z_0) - (x_i - x_0) \cdot (z_i - z_0) \right] &= M_y; \\
I_z \dot{\omega}_z + \sum_{i=1}^{N} l_i (\dot{\omega}_z + \dot{\omega}_y) + m \left( \dot{y}_0 \dot{y}_0 - x_0 \dot{x}_0 \right) + \sum_{i=1}^{N} m_i \left[ (x_i - x_0) \cdot (y_i - y_0) - (x_i - x_0) \cdot (y_i - y_0) \right] &= M_z;
\end{align*}
\]  

Then the components of the micro-acceleration vector at point M with the radius-vector of the orbital motion of a small spacecraft with an electrothermal micromotor are determined by the dependencies:

\[
\begin{align*}
w_x &= \dot{\omega}_x z_m - \dot{\omega}_z y_m + \omega_y x_m + \omega_z x_m + \omega_x y_m + \omega_z y_m - \left( \omega_x^2 + \omega_z^2 + \omega_z^2 \right) x_m; \\
w_y &= \dot{\omega}_z x_m - \dot{\omega}_x z_m + \omega_y x_m + \omega_z x_m + \omega_x y_m + \omega_z y_m - \left( \omega_x^2 + \omega_z^2 + \omega_z^2 \right) y_m; \\
w_z &= \dot{\omega}_x y_m - \dot{\omega}_z x_m + \omega_y x_m + \omega_z x_m + \omega_x y_m + \omega_z y_m - \left( \omega_x^2 + \omega_z^2 + \omega_z^2 \right) z_m.
\end{align*}
\]  

The software package in the Delphi language was developed for numerical modeling of the micro-acceleration level. The user interface of it is shown in Figure 7.
Figure 7. User interface of the program complex for calculation of micro-debris in the internal environment of a small spacecraft using a motion control system with an electrothermal microdrive.

Figure 8 shows the dependence of micro-accelerations on time with a constantly running complex of control flywheel motors, the inclusion of an electrothermal microdrive at a time of 500 s and its shutdown at a time of 1000 s.

Figure 8. The dependence of modulus of accelerations at point M (0.2; 0.2; 0.1) from time to time.

The parameters of a small spacecraft of the "Aist 2D" type were chosen for numerical simulation. It was shown that it is possible in principle to use an electrothermal micromotor as the main executive body for solving the problem of orienting a small spacecraft instead of a liquid-propellant rocket engine in modeling the operation of the orbital motion control system.

5. Conclusion
A number of conclusions can be drawn from the results of this work.

- It is possible to develop a new system of orientation and motion control of a small spacecraft for technological purposes using an electrothermal microdrive.
- The operation of the electrothermal microdrive will eliminate the shortcomings of the magnetic actuators and increase the reliability of the orientation and motion control system.
- The resulting microaccelerations when the electrothermal micro-motor is switched on can be brought into compliance with the requirements for the successful implementation of gravity-sensitive
technological processes by selecting the design parameters of the electrothermal microdrive for a particular small spacecraft and the requirements for micro-accelerations.

6. References
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