Problems of development motion control algorithms for a small spacecraft for technological purpose taking into account temperature deformations of solar panels

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Abstract. The paper considers the development of an algorithm for controlling the orbital motion of a small spacecraft using a control system that has flywheel engines and an electrothermal micromotor for unloading flywheels as executive bodies. It is assumed that a small spacecraft periodically falls into the shadow of the Earth. The temperature deformations of solar panels that affect the dynamics of evolution around the center of mass are taken into account. The restrictions on the internal environment micro-accelerations of a small spacecraft are taken into account when choosing the main parameters of the executive bodies. These restrictions are imposed when gravitationally sensitive technological processes are carried on board it. The aim is to reduce the level of micro-accelerations in the zone of technological equipment as possible while developing control algorithms.

1. Introduction

A specific feature of gravitationally sensitive processes implementation aboard a small spacecraft is the high requirements for the level of micro-acceleration of the internal environment [1-3]. We should take into account not only the vibrations of large elastic elements [6, 7], but also the temperature shock at the entrance and exit of a small spacecraft from the Earth’s shadow while carrying out such processes on board a small spacecraft as the studies [4, 5] show. If for a middle-class spacecraft the values of micro-accelerations from temperature shock are small [8, 9] then for a small spacecraft they can exceed the values acceptable for the favorable implementation of gravitationally sensitive processes [10, 11]. Therefore, it is necessary to develop algorithms for controlling the orbital motion of a small spacecraft that reduce the negative impact of temperature shock.

Temperature shock is accompanied by significant deformations of solar panels power frame in terms of the occurrence of micro-accelerations. Therefore, the first part of the problem to be solved in the work is to correctly describe the dynamics of the temperature field of the solar panels skeleton. Such a problem is a classical boundary-value problem with boundary conditions of the third kind that determine the possibility of radiation from the outer surface of the frame [12]. We have for the outer surface on which sunlight falls:
\[
\begin{cases}
    c \rho \frac{\partial T}{\partial t} = \text{div}(\lambda \text{grad} T) + q \\
    \lambda \frac{\partial T}{\partial n} + \alpha \sigma (T^4 - T_s^4) = 0 \quad (x, y, z) \in \Omega
\end{cases}
\]

where \( c \) is specific heat, \( \rho \) is density, \( \lambda \) is thermal conductivity, \( \varepsilon \) is degree of blackness, \( \sigma \) is the Boltzmann constant, \( T \) is temperature, \( T_s \) is ambient temperature, \( q \) is external heat flux (solar radiation), \( n \) is a normal to the surface of the solar panel power frame, \( \Omega \) is boundary surface of the frame.

We will simplify assuming that the temperature field is inhomogeneous only along the depth of the frame and \( \lambda = \text{const} \):

\[
\begin{cases}
    c \rho \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2} + q \\
    \lambda \frac{\partial T}{\partial n} + \alpha \sigma (T^4 - T_s^4) = 0 \quad (x, y, z) \in \Omega
\end{cases}
\]

We have for the outer surface on which sunlight does not fall taking into account the comments:

\[
\begin{cases}
    c \rho \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2} \\
    \lambda \frac{\partial T}{\partial n} + \alpha \sigma (T^4 - T_s^4) = 0 \quad (x, y, z) \in \Omega
\end{cases}
\]

And finally, we have for the inner layer of the frame:

\[
c \rho \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2}
\]

Significant nonlinearity of this problem is given by boundary conditions of the third kind. Figure 1 shows the dependences of the stationary external heat flux \( q \) (solar radiation) incident on the illuminated surface of the solar panel skeleton and the reflected heat flux satisfying the second equation of system (2).

![Figure 1. Dependences of the external incident and reflected heat fluxes](image-url)
This problem was solved in the ANSYS package. Figure 2 shows the maximum phase of the thermal deflection of the frame. Figure 3 shows the average compressive reaction at the attachment point of the solar panel into the small spacecraft body. It was believed during the simulation that the frame is rigidly attached to the body and has the characteristics presented in Table 1.

**Table 1. Characteristic of the small spacecraft solar panel frame.**

| Characteristic | Length, m | Cross-section dimensions, mm | Material | Initial temperature, °C | Number of layers |
|----------------|-----------|------------------------------|----------|------------------------|-----------------|
| Value          | 0.5       | 5x5                         | MA–2     | 0                      | 5               |

**Figure 2.** The curved shape of the power element frame with a maximum temperature gradient across the thickness of the element

**Figure 3.** Average compressive reaction in the attachment point of the solar panel power frame to the body of a small spacecraft
The dynamics of changes in the temperature of the carcass layers when a small spacecraft leaves the Earth’s shadow for an element of the solar panel power frame with the characteristics presented in Table 1 is shown in Fig. 4. In general, it can be stated that when a significant compression reaction occurs at the attachment point, the temperature of the layers change almost linearly. It greatly facilitates the solution of the compensation problem for micro-accelerations arising from thermal shock.

![Figure 4. Dynamics of changes in temperature of the inner layers of the solar panel frame element of a small spacecraft](image)

The next step in solving the problem was to assess the normal micro-accelerations arising from thermal shock. Tangential micro-accelerations will also occur due to deflection during thermal deflection of the frame. However, they were not studied in this work since they can be neglected in comparison with normal micro-accelerations. The transverse reaction and the reactive moment in the attachment site as the simulation shows are significantly less than the compressive reaction.

The micro-acceleration can be estimated using Newton’s second law since the compressive reaction in the attachment site will affect the translational part of the motion of a small spacecraft:

\[
\omega_n = \frac{R_1}{m_0},
\]

where \(m_0\) is mass of a small spacecraft including solar panels.

These values of micro-accelerations are unacceptably high because at \(m_0 = 1000\) kg and \(R_1 = 0.1\) N the induced micro-accelerations are two orders of magnitude higher than those allowed for the OKA – T middle-class technological spacecraft [13]. Therefore, the next stage of work is the development of the law governing the executive body of the orientation and motion control system of a small spacecraft which contributes to a significant reduction in micro-accelerations. In fact, the task is to minimize the objective function:

\[
|R_1 - F_c| \rightarrow \min_{F_c} \ , \quad (5)
\]

In this work, an electrothermal micromotor is proposed as the executive body of the control system. The solution to the problem of controlling micro-accelerations is associated with the design of the main parameters of the electrothermal micromotor and the development of the control law of this engine. The body of the electrothermal micromotor was manufactured using additive technologies in order to optimize the design by weight and the exact execution of complex elements. The nozzle, the
outer casing, the inner casing, the gas flow former, the micromotor attachment unit were formed in one casing (Figure 5) [14, 15].

![Image](image_url)

**Figure 5.** The electrothermal micromotor assembly with a heating element

The main design parameters of the electrothermal micromotor include:
- thrust;
- specific impulse of thrust;
- flow rate of the working fluid;
- power of the gas stream at the nozzle exit.

The values of the applied voltage to the heating element at different output powers were used as the initial data for the design. The experiments were conducted to assess the dependence of the electrothermal micromotor thrust on time. They were carried out according to the “cold” scheme for switching on the electrothermal micromotor which means the simultaneous supply of voltage to the heating element, the evaporator and the supply of the working fluid [16, 17]. The results of evaluating the dependences of the main parameters on the power supplied to the electrothermal micromotor are shown in table 2.

**Table 2.** The simulation results of the main parameters dependence of the electrothermal micromotor from the power supplied to the engine.

| №  | Parameters                                      | Power |
|----|------------------------------------------------|-------|
|    |                                                 | 3 W   | 4 W   | 5 W   | 10 W  | 15 W  | 20 W  | 25 W  | 30 W  |
| 1  | Voltage on the heating element, V               | 6,84  | 7,90  | 8,83  | 12,49 | 15,30 | 17,66 | 19,75 | 21,63 |
| 2  | Current strength on the heating element, A      | 0,44  | 0,51  | 0,57  | 0,80  | 0,98  | 1,13  | 1,27  | 1,39  |
| 3  | Resistance of the heating element, Ω            | 15,6  |       |       |       |       |       |       |       |
| 4  | Working body                                    | nitrogen |         |       |       |       |       |       |
| 5  | Pressure in the fuel tank (at the beginning of the test), MPa | 1,3 |       |       |       |       |       |       |       |
| 6  | Maximum temperature in the electrothermal micromotor $T^\circ$, °C | 291,18 | 369,98 | 445,82 | 643,86 | 774,34 | 771,09 | 797,37 | 823,98 |
| 7  | Operating time, s                               | 1210  | 1210  | 1210  | 1200  | 1200  | 205   | 70    | 80    |
The dependence of the electrothermal micromotor thrust on time taking into account the power supplied to the motor is shown in Figure 6.
Experimental studies show that the electrothermal micromotor thrust in the framework of the problem to be solved can be considered constant.

The variable parameters were the on and off times and the electrothermal micromotor thrust to solve the problem (5). This problem was solved by the gradient descent method [18] in the Mathcad mathematical package. The results are presented in Figure 7.

Figure 6. The dependence of the electrothermal micromotor thrust on time

Figure 7. The optimal constant thrust of the electrothermal micromotor taking into account the transient process from the point of view of minimizing the normal micro-accelerations arising from a temperature shock is: \( t_1 \) is the moment the electrothermal micromotor is turned on; \( t_2 \) is the moment of shutdown the electrothermal micromotor
Optimum moments of turning on and off the electrothermal micromotor of constant traction taking into account the transient process: \( t_1 = 0 \), \( t_2 = 6 \text{ s} \). The dependences of normal micro-accelerations using control and without control are shown in Figure 8.

![Figure 8](image)

**Figure 8.** The dependence of the electrothermal micromotor thrust on time

Thus, it is possible to reduce the maximum value of micro-accelerations by more than 2 times thanks to the control. However, it is necessary to control the thrust value of the electrothermal micromotor to meet modern requirements for micro-acceleration for the developed gravitationally sensitive processes [10, 11].

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