Modeling the effect of temperature deformations of large elements on the dynamics of the orbital motion of a small spacecraft

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Abstract. The effect of temperature deformations of panels of solar battery of a small spacecraft like “Aist–2D” is modeling in this paper. Temperature deformations occur while a small spacecraft enters and goes into the shadow of the Earth. The effect of temperature deformations on the dynamics of the orbital motion of a small spacecraft is reviewed. Conclusions are made regarding the consideration of temperature deformations for efficient operation of orbital motion control system. The three-dimensional heat conduction problem was solved during the modeling. Computational modeling was made by the LS-Dyna package. The results of work may be used while creating a small spacecraft with large elastic elements control laws and the shadow segment of the orbit.

1. Introduction

Today a small spacecraft is becoming more widely used. Start of a launch vehicle is able to provide light of dozen small spacecraft [1]. The orbit with eclipse period is used for the exploitation of a small spacecraft at the same time. The presence in the structural layout of the spacecraft of large elastic elements (primarily panels of solar battery) leads to a stepwise change of dimensions of these elements when a spacecraft enters and goes into the shadow of the Earth due to temperature shock [2]. This factor can influence the dynamic of orbital motion [3]. This effect can be significant for a middle class spacecraft when gravitational sensitive processes are implemented on its board [4]. It can in some cases disrupt its orientation for a small spacecraft. It is especially relevant for a small spacecraft remote sensing of the Earth (for example, “Aist–2D” [5], Figure 1) or a small spacecraft for technological purposes (for example, “Vozvrat-MKA” [6]).

The effect of temperature shock for the middle class spacecraft should be taken into account only when implementing gravitationally sensitive technological processes according to studies [7–10]. Thus, an estimate of the micro-accelerations is given in the zone where the technological equipment of the NIKA – T spacecraft is located thrust due to temperature [10]. The maximum value of the micro-acceleration module is estimated at 20 $\mu m/s^2$. It is a valid value for the “NIKA–T” spacecraft [11]. However, this value significantly exceeds the micro-acceleration module allowed for the “OKA–T” spacecraft project [12].
Figure 1. General view of a small spacecraft for remote sensing of the Earth “Aist–2D”.

It is explained by the fact that the share of large elastic elements in the total mass of the middle class spacecraft is small. However, for a small spacecraft there are different situations. Requirements for the provision of power supply lead to the need for the use of large-area solar panels [13]. The mass ratio of elastic elements and the total mass for a small spacecraft are significantly higher than for a middle class spacecraft. Consequently, the effect of thrust due to the temperature on the motion of a small spacecraft around the center of mass will be more significant.

Thus, the task of research the effect of temperature deformations of large elastic elements of a small spacecraft on the dynamics of the orbital motion in the presence of shadow orbit regions is important and relevant. There is development of algorithms for controlling orbital motion in consideration of temperature deformations.

2. Tree-dimensional heat conduction of large elastic elements
Accept few simplifying assumptions to solve the problem of constructing a three-dimensional model of heat conduction.

– The model of the elastic element is orthotropic plate.
– The elastic element is rigidly fixed in the spacecraft body.
– The properties of the elastic element fulfill the conditions of homogeneity.
– The case of uniform stream is considered.
– The working temperature range is: \(-170^\circ C\) ... \(+110^\circ C\).
– The material properties of the elastic element are considered constant in the entire operating temperature range.
– A change in the orientation of the normal to the surface of an elastic element is neglected due to its natural oscillations.

Since there are no sources of heat generation inside the elastic element we will consider the equation of unsteady heat conduction parabolic type in the form [14]:

\[
\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2}
\]  

(1)

where 

\[a = \sqrt{\frac{\lambda}{\rho c}}\]

is thermal diffusivity; \(\rho\) is material density of large elastic elements; \(c\) is specific heat; \(\lambda\) is a coefficient of heat conductivity.

The initial conditions for this boundary value problem are the uniform distributions of temperature field:

\[T(M, t) \mid_{t=0} = T_{\text{min}}, (T_{\text{max}}) = \text{const}\]

(2)

depending on whether the small spacecraft is immersed in or out of the shadow of the Earth.

We use conditions related by infrared emission surface of panels of solar battery as the boundary conditions:
\[- \lambda \frac{\partial T}{\partial n} \bigg|_S = \varepsilon \sigma (T_i^s - T_{e}^s) \tag{3}\]

where \( S \) is the surface of body; \( \varepsilon \) is the integral coefficient of infrared emission of the body which characterizes its absorption or emissivity; \( \sigma \) is the Stefan-Boltzmann constant; \( T_s \) and \( T_e \) are the surface temperature of large elastic elements of a small spacecraft and the environment, respectively.

The boundary value problem with external non-linearity in the formulation (1)-(3) was solved taking into account the assumption that the substructure of the panel of solar battery was made of MA-2 material [15].

The problem of heat conduction in bodies of classical forms under boundary conditions (3) for which the direction of the outward normal \( n \) coincides with the direction of the current coordinate \( \xi \), reduced to the form:

\[ \frac{\partial T}{\partial \xi} = Bi (Fo) \cdot \varphi (Fo) \tag{4} \]

\[ \frac{\partial T}{\partial Fo} = \frac{1}{\xi^2} \frac{\partial}{\partial \xi} \left( \xi^2 \frac{\partial T}{\partial \xi} \right) ; \quad [T (\xi , Fo) ]_{T=0} = T_0 \tag{5} \]

where \( Bi (Fo) = \alpha_a (Fo) R / \lambda ; \varphi (Fo) = T_e \).

The approximate solution of the task will find in the community of a linear composition of the form:

\[ T_i (\xi , Fo) = \varphi (Fo) + a_i (Fo) \left[ \frac{Bi (Fo) + 2}{Bi (Fo)} - \xi^2 \right] + \sum_{k=1}^{n} a_k (Fo) (1 - \xi^2) \xi^{2(k-1)} \tag{6} \]

which for any non-stationary coefficients is projections \( a_i (Fo) \) exactly satisfies the boundary conditions (3). These coefficients \( a_1 (Fo), a_2 (Fo), ..., a_s (Fo) \) are found as a solution to a linear system differential equations of the first order. In turn, it is composed by the requirement of the orthogonality of the residual of equation (4) with \( T (\xi , Fo) = T_i (\xi , Fo) \) to all base functions. We limit the definition of a solution in the first approximation. For expression

\[ T_i (\xi , Fo) = \varphi (Fo) + a_i (Fo) \left[ \frac{Bi (Fo) + 2}{Bi (Fo)} - \xi^2 \right] \tag{7} \]

we make residual

\[ \varepsilon_i \left[ a_i (Fo) , \frac{da_i (Fo)}{dFo} \right] = \frac{\partial}{\partial \xi} \left( \xi^2 \frac{\partial T}{\partial \xi} \right) - \xi^2 \frac{\partial T}{\partial Fo} = 0 \tag{8} \]

The magnitude of this discrepancy can control the accuracy of the conducted numerical simulation. If necessary, increase the accuracy should take into account the additional terms of the sum in equation (6). We thus obtain an equation that can be used to calculate micro-accelerations and angular velocity of a small spacecraft from due to temperature deformations of large elastic elements.

\[ \Theta (\xi , Fo) = 1 - \frac{3 Bi}{2(Bi + 3)} \left( \frac{Bi + 2}{Bi} - \xi^2 \right) e^{-A(Bi)fo} \tag{9} \]

where \( A(Bi) = \frac{6 Bi (Bi + 4)}{Bi^3 + 6 Bi + 12} \).

Thus, equations have been obtained for numerical simulation in order to assess the significance of the temperature impact of large elastic elements when immersed in the Earth’s shadow and exit from it for the rotational mode of a small spacecraft around the center of mass.

### 3. Computational modeling results

A mathematical package LS-Dyna was used in furtherance of computational modeling of the task. In this package, a plate was modeled the parameters of which accept the panel of solar battery of the small spacecraft “Aist-2D” (Figure 1). The plate was divided using the finite element method into
small rectangular in shape elements. The thickness of the plate was divided into five sections. It corresponds to five layers of heating (cooling). Heating each layer gives a picture of the dynamics of heating the entire plate. The incident heat flux was considered normal to the plate surface. This condition corresponds to the minimum warming-up time. Three schemes of heating were precedence: the heating of the plate without taking into account thermal conductivity, taking into account the thermal conductivity and taking into account the radiant heat exchange.

The first variant of the plate warming up scheme is presented in Figure 2.

![Figure 2. The plate heating scheme without thermal conductivity: 1,2,3,4,5 are corresponding layers into which the plate was divided.](image)

Only the surface layer of the plate is heated without heat conduction (Figure 2). The law of such heating practically does not differ from linear. The temperature further remains constant reaching the maximum value when the energy due to solar emission and the energy of its own emission according to the law (3) become equal to each other. Accounting for thermal conductivity in layers of the plate makes this process more complicated. Such a model is a test of numerical simulation correctness. Analysis of Figure 2 shows that the dynamics of heating of all layers are the same. In this case, it is believed that all the heat supplied is spent on heating the surface layer. Then the next layer begins to heat up when the surface layer is heated to the final equilibrium temperature and so on.

Of course, the actual bake-out process is more complicated. Firstly, the heat supplied will not only heat the surface layer but also penetrate into other layers due to thermal conductivity. Due to this fact they will heat up before the surface layer reaches the final equilibrium temperature. And secondly, part of the solar energy incident on the surface layer will be reflected. Accounting for these factors significantly complicates the model. The heat transfer is shown in Figure 3. The scheme of heating the plate with regard to thermal conductivity and radiant heat transfer is shown in Figure 3.

The solid lines in Figure 3 show warming up provided that there is no radiant heat exchange with the medium. And the intermittent lines show warming up taking into account radiant heat transfer. Calculations showed that the time of full heating of the plate in both cases is almost the same due to the small thickness of the plate. Thus, we can conclude that the value of the pulse taking into account radiative heat transfer does not deviate much from the results obtained without taking it into account. Accordingly, the module of additional micro-accelerations will remain practically unchanged. Therefore, influence from the surface of the solar battery can be ignored when assessing the effect of thrust due to temperature on the dynamics of the rotational motion of a small spacecraft. It has no significant effect.

Figure 4 shows the deformation shape of the plate. The upper layer undergoes the greatest change in size in the first seconds of warming up (immediately after a temperature strike). It stretches under heat flux action. In turn, the lower layer for some time retains the original state. Thus, the plate is bent
in the negative direction \( y \). The temperature inside the entire plate is equalized upon further heating and it is restored to its original form. The final temperature distribution is shown in Figure 5.

**Figure 3.** The plate heating circuit with regard to thermal conductivity and radiant heat exchange.

**Figure 4.** Deformation of the solar panel during thrust due to temperature.

**Figure 5.** Final temperature distribution over the layers of the plate.
At the same time, the displacement of the center of mass of the panel can reach 1.5 cm. It was estimated in accordance with the division of the plate into five layers of equal thickness and assumption that the enter layer is heated as shown in Figure 2. The displacement of the layers causes inertial forces that create a moment around the center of mass of the small spacecraft and lead to the appearance of the angular acceleration of the rotation of the small spacecraft. So, for example, the small spacecraft will receive a micro-accelerations equal to 9.921 μm/s² knowing the displacement of the centers of mass of each layer equal to 5 kg. And the maximum angular velocity will be 0.361 deg/s. The angular velocity value should not exceed 0.005 deg/s according to the technical characteristics of the small spacecraft “Aist–2D” to ensure the three-axis orientation of the small spacecraft [16].

The small spacecraft with large elastic elements can only be operated in a controlled flight mode since solar panels must be oriented relative to the Sun. Thermal shock due to the presence of the shadow portion of the orbit can cause significant deformation of elastic elements. It affects the orientation of the small spacecraft. This effect should be taken into account when developing control laws and choosing the executive bodies of the small spacecraft orbital motion control system. The phenomenon of radiative heat transfer can be neglected when assessing the influence of angular velocity on the dynamics of orbital motion and the orientation of the small spacecraft since its contribution to the plate heating dynamics is small.

4. Conclusion

Thus, following conclusions are made as result of the research.

1. The efforts have shown that thrust due to temperature for the small spacecraft “Aist–2D” can cause micro-accelerations around $10 \ \mu m / s^2$. It results in an angular velocity of approximately 0.4 deg/s. This angular velocity is unacceptably large for the mode of shooting the surface of the Earth. Therefore, modeling and accounting for thrust due to temperature is important and relevant for the effective solution of the problems of remote sensing of the Earth.

2. For the mechanization of gravitational sensitive processes on board a small spacecraft taking into account thrust due to temperature is also relevant. Micro-accelerations in size $10 \ \mu m / s^2$ are the maximum allowable for the technological design of the middle class spacecraft “OKA–T”.

3. The heat conductance between the layers must be taken into account for correct modeling of the heating or cooling of large elastic elements when immersed in the Earth’s shadow and leaving it. It is a significant process in terms of the problem to be solved. Its account significantly changes the impact assessment of the effect of thrust due to temperature on the dynamics of the rotational motion of a small spacecraft around the center of mass.

4. Accounting for radiation from the surface of an elastic element significantly complicates the mathematical model of heating. But it has little effect on the assessment of the significance of the temperature impact on the dynamics of the rotational motion of a small spacecraft. If it is not taken into account then, obviously, the heating of the elastic element occurs faster. It somewhat overestimates the micro-accelerations and the attitude rate of rotation. This situation is quite allowable, since the assessment is given a certain margin.

5. References

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