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Формирование подхода к моделированию операций орбитальной сборки реконфигурируемого космического аппарата на геостационарной орбите

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Целью исследования является формирование подхода к моделированию операций орбитальной сборки реконфигурируемого космического аппарата (РКА) на геостационарной орбите. Реконфигурируемые космические аппараты представляют собой совокупность модульных космических аппаратов (МКА), где, в частном случае, на один МКА могут быть возложены функции модуля служебных систем (МСС), а на второй – функции модуля полезной нагрузки (МПН). Для обеспечения сборки РКА либо замены какого-то МКА, например, в случае его отказа, на новый, необходимо обеспечить решение задачи сближения МКА с РКА.

В статье проведен анализ и исследование работы системы управления движением МКА во время выполнения сближения МКА с РКА. Сформирован перечень необходимых математических моделей для осуществления операций при решении задачи сближения МКА с РКА, а также представлена структурная схема взаимодействия математических моделей. В работе представлено краткое описание математического аппарата, позволяющего осуществить моделирование операций сближения МКА с РКА. Данный математический аппарат включает в себя модель орбитального движения МКА и РКА, модели углового движения МКА и РКА, чувствительных элементов и исполнительных органов.

В данной работе математическое моделирование операций сближения МКА с РКА рассматривается как предмет исследования. Объектом исследования является система управления движением МКА, обеспечивающая реализацию сближения РКА на геостационарной орбите.

Ключевые слова: орбитальная сборка, реконфигурируемые космические аппараты, модульные космические аппараты, система управления движением.

Formation of an approach to modeling orbital operations assembly of a reconfigurable spacecraft on geostationary orbit

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The aim of the study is to form an approach to modeling the operations of the orbital assembly of a reconfigurable spacecraft (RS) in geostationary orbit. Reconfigurable spacecraft are a set of modular spacecraft (MS), where, in a particular case, one MS can be assigned the functions of the service systems module (MSS), and the second - the functions of the payload module (MPN). To ensure the assembly of the RC, or the replacement of some MC, for example, in case of its failure with a new one, it is necessary to provide a solution to the problem of bringing the MS with the RS.

The article analyzes and studies the operation of the motion control system of the MS during the convergence of the MS with the RS. A list of necessary mathematical models for performing operations in solving the problem of convergence of the MS with the RS is formed, and a block diagram of the interaction of mathematical models is presented. The paper presents a brief description of the mathematical apparatus that allows modeling the operations of convergence of the MS with the RS. This mathematical apparatus includes: a model of the orbital motion of the MS and the RS, models of the angular motion of the MS and the RS, sensitive elements and executive bodies.

In this paper, the mathematical modeling of the MS with the RS convergence operations is considered as the subject of research. The object of the study is the motion control system of the MS, which ensures the implementation of the approach of the RS in geostationary orbit.

Keywords: orbital assembly, reconfigurable spacecraft, modular spacecraft, motion control system.

Introduction

The volume of tasks performed with the help of spacecraft is gradually increasing, and the demand for space technologies is also grows up in both the civilian and military spheres. As a result, with an increase in the number of customers willing to pay, a number of space areas are already becoming profitable [1].

Great opportunities are promised by projects that require complex, large-sized and massive structures to be in geostationary orbit, such as solar and nuclear power plants, space communications antennas and radio telescopes, heavy interplanetary spacecraft, etc. However, the weight and size characteristics of the launched payloads are limited by the capabilities of launch vehicles.

The way out of this situation is to create in orbit reconfigurable spacecraft (RS), consisting of several modular spacecraft (MS). Each small spacecraft has its own design and is responsible for performing one or more target functions, for example, a reflector, fuel tanks, service system modules, payload modules, etc.

One of the key service systems of the small spacecraft that ensures the creation of the orbital assembly of the spacecraft is the angular and orbital motion control system (AOMCS) or, in other words, the motion control system (MCS). The appearance of the MCS and its capabilities determine the appearance of each MS, however, in order to determine the design appearance of the MCS and formulate technical requirements for the system, it is necessary to understand the basic principles of operation and control of MS in geostationary orbit when performing the target task. One of the ways to obtain information about the physical processes occurring during the orbital assembly is to carry out mathematical modeling, and it is also important to formulate an approach to carrying out this modeling [2].

Analysis and study of MCS of MS during the orbital assembly of the RS from several MS

The orbital operation of the MS can be conditionally divided into several stages (Fig. 1).

The stages of the operation of the MS correspond to the stages of the operation of the MCS of MS. The MCS of MS operates from the moment the MS separates from the upper stage until the end of the active existence period of the MS or RS.

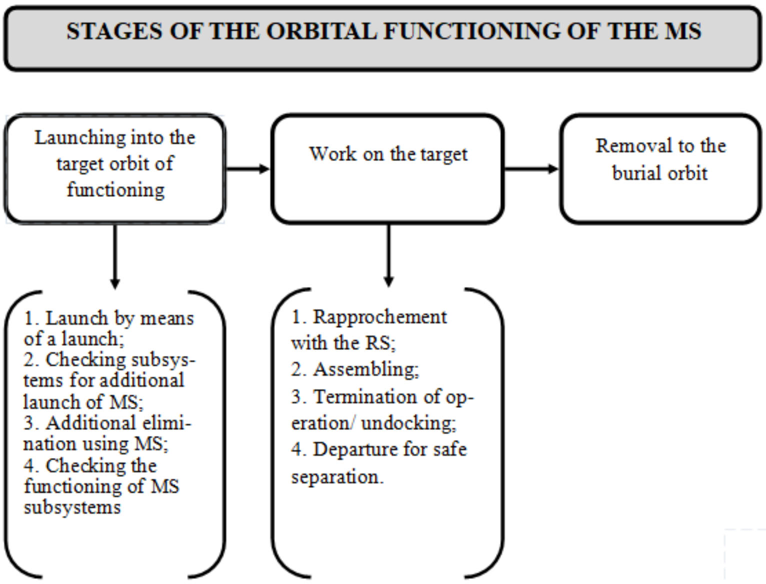

Рис. 1. Этапы орбитального функционирования МКА

Fig. 1. Stages of orbital construction of a modular spacecraft

The work of the MCS of MS at the stage of rendezvous with the RS, depending on the type of equipment used, is divided into two large substages:

– far-field rendezvous;

– approach in the near zone or local navigation zone (Fig. 2).

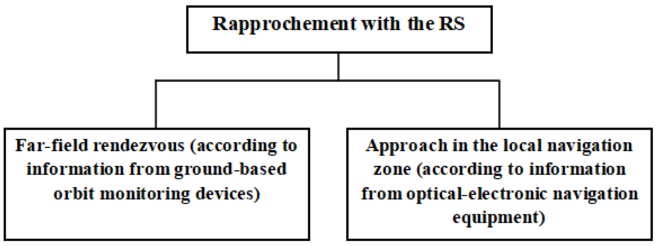

Рис. 2. Подэтапы работы СУД МКА при сближении с РКА

Fig. 2. Sub-stages of the motion control system of a model spacecraft when approaching a reconfigurable spacecraft

The task of far-field rendezvous is to bring the MS into an orbit close to the RS orbit, with the expectation that the distance between the MS and the RS does not exceed the range of the local navigation system of the MS. At this stage, the approach is carried out using ballistic data obtained both from ground-based measuring instruments, and from navigation spacecraft [3]. Far-field control involves a series of corrections of orbital parameters by creating an acceleration of the center of mass of the MS using low-thrust jet engines. In this case, the device provides the necessary orientation both during orbital correction and during the period of time when correction is not carried out.

In the near zone (local navigation zone), the position of the MS is controlled using information received from the local navigation equipment of the MS. The position of the center of mass of the MS is controlled using jet engines. Movement around the center of mass can be carried out both using jet engines and using electromechanical actuators.

The following operations are performed in the near zone:

1. RS Inspection. This operation involves identification (recognition) of the RS in order to select the required approach object.
2. Approach to a safe distance in order to clarify the orbital parameters of the RS and MS and formulate a further flight mission.
3. Flight of the RS for the purpose of primary diagnostics of the RS and determination of the required docking plane and response devices.
4. Docking.
5. Undocking to replace the module or place it into a disposal orbit.

Formation of a list of necessary mathematical models for modeling the operations of orbital assembly of MS with RS

To indicate the interaction of these mathematical models, a block diagram was developed, presented in Fig. 3.

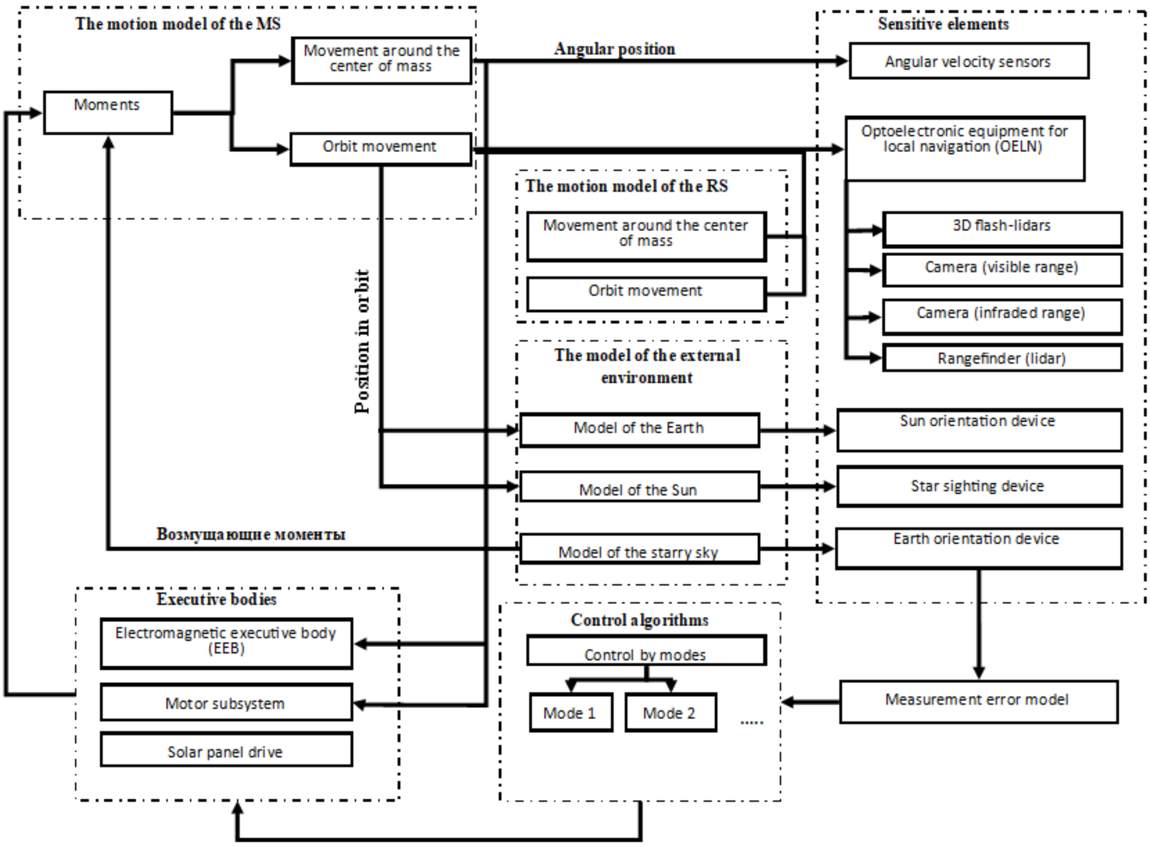

Рис. 3. Структурная схема взаимодействия необходимых математических моделей

Fig. 3. Block diagram of the interaction of the necessary mathematical models

Analysis and research of the main stages and operations performed by the MS to achieve its target task allows us to formulate the following list of mathematical models necessary for modeling orbital assembly operations:

– model of orbital motion of the spacecraft center of mass;

– environmental or disturbance model:

a) model of the Sun, including:

solar pressure model;

model of change in the position of the Sun in relation to the spacecraft orbit;

b) model of the Earth, including:

model of the Earth's gravitational field;
magnetic field model;
– model of angular motion relative to the spacecraft center of mass;
– spacecraft model, taking into account overall, mass and inertial characteristics, models of elastic structural elements;
– model for generating information from the ballistic center and ground stations;
– model of spacecraft sensitive elements:
a) Solar Orientation Device (SOD);
b) Star Orientation Device (SOD);
c) Earth orientation device (EOD);
d) speed sensor (SS);
e) local navigation equipment (LNE);
– executive model:
a) model of end organ;
b) correction jet engine unit (CJEU);
c) electromechanical executive body (EMEB).

Description of the mathematical apparatus that allows for modeling operations of orbital assembly of MS with RS

3.1. Approach to the formation of a model of orbital motion of MS and RS

The description of the mathematical apparatus should begin with a description of the used motion model of the MS and RS. The motion model must have the following properties:

1. Provide continuous modeling of the motion operations of two spacecraft in all rendezvous sections.
2. Allow for correction of orbital parameters and maneuvers of MS using low-thrust engines.
3. 3. Allow to take into account the disturbing forces acting on the apparatus and caused by the influence of outer space (impacts from the Sun, Earth, Moon) and the functioning of the end organs.
4. Provide a convenient initial position of the MS and RS and generate informative data about the relative position of the two devices.

To fulfill all the specified restrictions imposed on the models, it is advisable to describe the motion of MS and RS using two sets of equations: equations of motion in the ocular elements for modeling the far zone and equations of motion of the spacecraft in a geocentric coordinate system for modeling maneuvers in the near zone [4– 5].

When modeling low-thrust maneuvers in the far zone, it is advisable to use a_r, a_t, a_n mathematical model of spacecraft motion in osculating elements. In this case, it is assumed that the spacecraft orbit changes due to the action of the control acceleration, which has the components a_r, a_t, a_n (a_r – radial component of control acceleration directed along the instantaneous position of the spacecraft radius vector; a_t – transversal component oriented in the spacecraft orbital plane perpendicular to the spacecraft radius vector; a_n – component of the control acceleration normal to the orbital plane (Fig. 4).

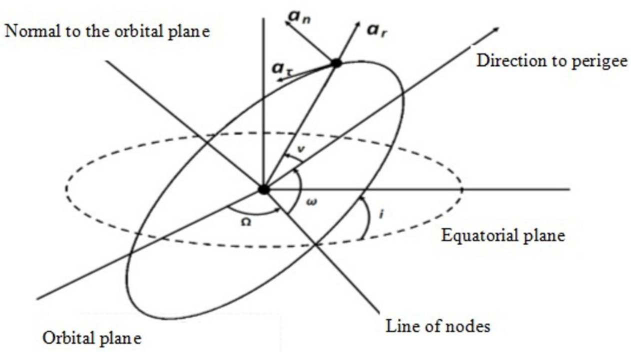

Рис. 4. Составляющие ускорения

Fig. 4. Component acceleration

$$
\begin{gathered}
\frac{dp}{dt} = a_t \sqrt{\frac{p}{\mu}} 2r, \\
\frac{de}{dt} = \sqrt{\frac{p}{\mu}} \left\{ a_r \sin\vartheta + a_t \left[\left(1 + \frac{r}{p}\right) \cos\vartheta + e\frac{r}{p} \right] \right\}, \\
\frac{d\omega_n}{dt} = \sqrt{\frac{p}{\mu}} \left[-\frac{a_r \cos\vartheta}{e} + a_t \frac{1}{e}\left(1 + \frac{r}{p}\right) \sin\vartheta - a_n \frac{r}{p} ctgi \sin u \right], \\
\frac{d\Omega}{dt} = a_n \sqrt{\frac{p}{\mu}} \frac{r}{p} \frac{\sin u}{\sin i}, \\
\frac{di}{dt} = a_n \sqrt{\frac{p}{\mu}} \frac{r}{p} \cos u, \\
\frac{d\vartheta}{dt} = \sqrt{\frac{p}{\mu}} \left[\frac{\mu}{r^2} + a_r \frac{\cos\vartheta}{e} - a_t \frac{1}{e}\left(1 + \frac{r}{p}\right) \sin\vartheta \right],
\end{gathered} \tag{1}
$$

where

$$
r = \frac{p}{1 + e\cos\vartheta}, \ \frac{r}{p} = \frac{1}{1 + e\cos\vartheta}, \ u = \omega_n + \vartheta, \tag{2}
$$

$a_r = a_{rDK} + a_{rV}$; $a_n = a_{nDK} + a_{nV}$; $a_t = a_{tDK} + a_{tV}$; $e, p, i, \Omega, \omega_{n,}\ \vartheta$ – osculating values of eccentricity, focal parameter, orbital inclination, longitude of the ascending node, perigee argument and true spacecraft anomaly; $\mu = 398600{,}448 \frac{км^3}{с^2}$ – Earth's gravitational parameter; $a_{rDK}, a_{nDK}, a_{tDK}$ – acceleration projections caused by the operation of the correction and orientation engines. Acceleration data comes from the "Propulsion Subsystem" model.

In further modeling, we assume that the propulsion system of the MS does not generate accelerations; therefore, for the MSV $a_{rDK} = a_{nDK} = a_{tDK} = 0$.

a_{rV}, a_{nV}, a_{tV} – projections of accelerations caused by various disturbances acting on the apparatus (from the non-centrality of the Earth's gravitational field, the attraction of the Moon and the Sun, light pressure). The acceleration data comes from the "Environmental Model" [6].

Modeling of near-field maneuvers in a geocentric coordinate system makes it possible to simplify the transition to the coordinate systems of spacecraft equipment (orbital and sighting coordinate systems). In addition, this allows you to more clearly specify the initial data on the position of the small spacecraft in relation to the spacecraft, as well as display the simulation results. The description of the motion model using equations in the geocentric coordinate system is discussed in detail in [7]. When using this model, it is assumed that spacecraft maneuvers are carried out due to the action of the control acceleration on the axis of the geocentric coordinate system, which has the components a_x, a_y, a_z.

The equation of motion in a rectangular geocentric coordinate system is (3):

$$
\ddot{x} = a_x - \frac{\pi_0 x}{r^3}, \quad \ddot{y} = a_y - \frac{\pi_0 y}{r^3}, \quad \ddot{z} = a_z - \frac{\pi_0 z}{r^3}. \tag{3}
$$

$$
a_x = a_{xDK} + a_{xV}, \ a_y = a_{yDK} + a_{yV}, \ a_z = a_{zDK} + a_{zV},
$$

where $a_{xDK}, a_{yDK}, a_{zDK}$ – projections of acceleration acting on the axes of a geocentric coordinate system caused by the operation of coordinate, correction, or orientation motors. The acceleration data comes from the "Propulsion Subsystem" model.

As when using the model in osculating elements, we assume that the MS performs a free orbital flight, and, therefore, $a_{xDK} = a_{yDK} = a_{zDK} = 0$.

a_{xV}, a_{yV}, a_{zV} – projections of accelerations on the axis of the geocentric coordinate system caused by various disturbances acting on the apparatus (solar, gravitational, magnetic). The acceleration data comes from the "Environmental Model" model.

3.2. Approach to forming a model of the angular motion of MS

Using the orbital motion model provides calculation of the position of the center of mass of the MS and allows you to control the position of the center of mass of the MS in orbit. However, to solve the problems of orbital assembly, it is also important to control the angular position of the small spacecraft. To do this, it is necessary to use a mathematical model of the angular motion of the spacecraft [8–10].

For orbital assembly operations, it is sufficient to use a mathematical model of the angular motion of the MSV, obtained taking into account the following assumptions:

– the MS body is absolutely rigid;

– BS panels and antennas are elastic;

– the position of the center of mass and the moments of inertia of the small spacecraft remain unchanged during the rotation of the solar panels.

For a MS consisting of an absolutely rigid body, 2 elastic wings of solar panels and 2 elastic reflectors, the equations of angular motion have the form

$$
\begin{gathered}
M\dot{V}_0 + \omega \times MV + \omega \times \left(2A_p\dot{q}_{np} + \omega \times A_p q_{np} + 2A_a\dot{q}_{na} + \omega \times A_a q_{na}\right) + \\
+\dot{\omega} \times \left(A_p q_{np} + A_a q_{na}\right) + A_p\ddot{q}_{np} + A_a\ddot{q}_{na} = P_B + P_y, \\
J\dot{\omega} + \omega \times \left(J\omega + B_p\dot{q}_{np} + B_a\dot{q}_{na}\right) - \left(\dot{V}_0 + \omega \times V_0\right) \times \left(A_p q_{np} + A_a q_{na}\right) + B_p\ddot{q}_{np} + B_a\ddot{q}_{na} = M_B + M_y, \\
\ddot{q}_{np} + D_p\dot{q}_{np} + W_p q_{np} + B_p^T\dot{\omega} + A_p^T\left(\dot{V}_0 + \omega \times V_0\right) = 0, \\
\ddot{q}_{na} + D_a\dot{q}_{na} + W_a q_{na} + B_a^T\dot{\omega} + A_a^T\left(\dot{V}_0 + \omega \times V_0\right) = 0,,
\end{gathered}
\tag{4}
$$

where M(3×3) – matrix, along the diagonal of which the mass of the MS is located; $\omega = (\omega_x, \omega_y, \omega_z)$ – angular velocity vector of MS relative to the center of mass; $V_0 = (V_{0x}, V_{0y}, V_{0z})$ – linear velocity vector of the center of mass of MS; J(3×3) – inertia tensor of MS in the undeformed state; np, na – number of tones taken into account for each solar panel and antenna; q_{np}, q_{na} – vector of generalized elastic coordinates of motion of solar panels and antennas; $\begin{matrix} A_p(3\times 2np) = \left[A_{1i}\ldots A_{1np} \quad A_{2i}\ldots A_{2np}\right] \\ B_p(3\times 2np) = \left[B_{1i}\ldots B_{1np} \quad B_{2i}\ldots B_{2np}\right] \end{matrix}$ – matrices of inertial coupling coefficients in the state coordinates, characterizing the dynamic interaction of the MS body and the elastic solar panels; $\begin{matrix} A_p(3\times 2na) = \left[A_{1i}\ldots A_{1na} \quad A_{2i}\ldots A_{2na}\right] \\ B_p(3\times 2na) = \left[B_{1i}\ldots B_{1na} \quad B_{2i}\ldots B_{2na}\right] \end{matrix}$ – matrices of inertial coupling coefficients in the state coordinates, characterizing the dynamic interaction of the MS body and elastic antennas; $D_p(2np\times 2na), D_a(2np\times 2na)$ – diagonal matrices of dissipation coefficients; $W_p(2np\times 2na), W_a(2np\times 2na)$ – diagonal matrices of squared natural frequencies of the wings of solar panels and antennas, respectively; $A_p{}^T(2np\times 3)$, $B_p{}^T(2np\times 3)$, $A_a{}^T(2na\times 3)$, $B_p{}^T(2na\times 3)$, – transposed matrices A_p, B_p respectively; $P_в$, P_y, $M_в$, M_y – vectors (in state coordinates) of external and control forces and moments acting on the small spacecraft.

3.3 Approach to the formation of models of sensitive elements and actuators

The functionality of models of sensitive elements for assessing ongoing processes can be limited only to the formation of output information suitable for control, namely:

– the model of solar orientation device (SOD) forms angles and , characterizing the deviation of the device axis from the direction to the Sun, a sign of the presence of the Sun in the field of view of the device;

– the model of Earth orientation to device (EOD) forms the angles and , which characterize the deviation of the device axis from the direction to the Earth, a sign of the presence of the Earth in the field of view of the device;

– the model of the star sighting device (SSD) forms angles ψ , φ , θ , characterizing the position of the device in the inertial coordinate system, the rate of change of the angles $\dot{\psi}$, $\dot{\varphi}$, $\dot{\theta}$;

– the model of rate generator generates speed through the channels of the device $\dot{\psi}$, $\dot{\varphi}$, $\dot{\theta}$;

– model of optical-electronic local navigation equipment (OELNE) forms angles α, β , characterizing the deviation of the sighting axis from the direction to the geometric center of the MS, the relative distance D MS, rate of change of relative distance $\dot{D}$, a sign of the presence of MS in the field of view of the device.

When studying in detail the influence of device characteristics on the quality of transient processes and maneuvering trajectories, additional characteristics are introduced (field of view, frequency of information generation, etc.) [11–15].

Mathematical models of executive bodies that provide the issuance of control actions for performing maintenance and rendezvous operations at all stages of spacecraft operation require more detailed study than sensitive elements, namely:

– the model of the electromechanical actuator (EMA) generates control torque along the channels of yaw, roll and pitch of the spacecraft from electromagnetic actuators, and, depending on the various configurations of the flywheel control motors and their installation, as well as their characteristics, the picture of transition processes changes significantly;

–the model of the unit jet engine correction (UJEC) generates the output of control acceleration (thrust). When modeling, it is necessary to consider the characteristics of both xenon and hydrazine engines. An important point when developing a thruster model is to take into account the operating principle of the engine, since it imposes significant restrictions on the development of rendezvous algorithms (it is necessary to take into account the frequency of thrust generation, its characteristics and magnitude, an important parameter is also the specific impulse of the engine, which affects the assessment of fuel costs when performing a maneuver);

–the UJEO model generates control torque along the yaw, roll and pitch channels of the spacecraft. By analogy with the UJEC, it is necessary to take into account all the same characteristics;

–the model of the solar battery drive device (SBDD) forms the rotation speed of the solar battery drive. This model can be simplified and limited by the output, speed and rotation angle of solar panels.

The specified list of mathematical models makes it possible to fully simulate orbital assembly processes and conduct a study of MS control algorithms in order to formulate requirements for the MS control system.

Conclusion

At the current stage of work on developing an approach to modeling the operations of orbital assembly of MS with RS in geostationary orbit, the following results were obtained:

– the stages of the orbital functioning of the MS were determined and the analysis of the orbital assembly of the MS with RS was performed as a stage of the orbital functioning of the MS;

– a list of necessary mathematical models for modeling the operations of orbital assembly of MS with RS has been determined;

– a mathematical apparatus that makes it possible to simulate the operations of orbital assembly of MS with RS is described.

The results obtained allow us to move on to the next task - modeling the operations of the orbital assembly of MS with RS.

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