UDC 629.78.051.062.2

Siberian Journal of Science and Technology. 2017, Vol. 18, No. 4, P. 876–881

THE ALGORITHM FOR ESTIMATING ANGULAR RATE OF SPACECRAFT IN SURVIVABILITY MODE

S. V. Latyntsev*, S. V. Meus, A. V. Ovchinnikov

JSC "Academician M. F. Reshetnev" Information Satellite Systems"
52, Lenina Str., Zheleznogorsk, Krasnoyarsk region, 662972, Russian Federation
*E-mail: lat.sv@mail.ru

The paper discusses the issue of ensuring survivability of Spacecraft (SC) in its long-term autonomous operation in space conditions for cases of critical failure of rate sensors. We presented an autonomous control loop in survivability mode in the form of a functional circuit and a mathematical model of control loop. On the spacecraft engineered by JSC ISS – Reshetnev, failures of an angular-rate sensor took place; these failures reduced a redundancy level and unfailing performance of SC; the failure of a standby angular rate sensor will lead to impossibility to use this mode. We came up with a solution to a problem of potential failures of angular rate sensors for spacecraft in operation in orbit using additional control logic; this solution is the purpose of our work. We developed a mathematical model of control without using an angular rate sensor. We described the model in details and it included estimating the angular rate according to previously generated control actions, calculation of control actions and filtration of evaluation registration according to measuring of a solar sensor. We showed the purpose of each newly introduced block that gives such advantages as improving the noise immunity of control loop to measurement errors, providing search rotation in the case of failure of all rate sensors. Improved control algorithm was synthesized. Having improved the basic algorithm, we carried out ground and flight tests. We performed mathematical modeling in the environment called GNU Octave.

Hybrid modeling was performed on rotary tables equipped with functional models of units and a functional model of onboard control subsystem. We conducted flight tests on real geostationary SC flying in orbit. For each test, we provided description of initial conditions and presented graphs of measurement of angular rate. We carried out all the tests successfully, and the algorithm is applied on the SC engineered by JSC "ISS – Reshetnev Company".

Keywords: pointing and attitude control system, spacecraft, angular rate, testing of pointing and attitude control system.

Сибирский журнал науки и технологий. 2017. Т. 18, № 4. С. 876–881

АЛГОРИТМ ОЦЕНКИ УГЛОВОЙ СКОРОСТИ КОСМИЧЕСКОГО АППАРАТА В РЕЖИМЕ ЖИВУЧЕСТИ

С. В. Латынцев*, С. В. Меус, А. В. Овчинников

АО «Информационные спутниковые системы» имени академика М. Ф. Решетнёва»
Российская Федерация, 662972, г. Железногорск Красноярского края, ул. Ленина, 52
*E-mail: lat.sv@mail.ru

Рассмотрен вопрос обеспечения живучести космического аппарата (КА) при его длительной автономной эксплуатации в условиях космического пространства для случаев критических отказов датчиков угловой скорости. Описан автономный контур управления в режиме живучести в виде функциональной схемы работы и математической модели управления. Приведен минимально необходимый приборный состав датчиковой аппаратуры ориентации для реализации режима, а именно, солнечный датчик и датчик угловой скорости. На КА разработки АО «ИСС» имели место отказы датчика угловой скорости, снизившие степень резервирования и надежность КА, выход из строя резервного датчика угловой скорости приведет к невозможности использования данного режима. Предложено одно из решений проблемы возможного отказа датчиков угловой скорости для уже летающих КА на орбите путем разработки дополнительного алгоритма управления, что и является целью статьи. Разработана математическая модель управления без использования показаний датчика угловой скорости. Эта модель подробно описана и включает в себя оценку угловой скорости по ранее выданным управляющим воздействиям, расчет управляющих воздействий и фильтрацию показаний оценки по измерениям солнечного датчика. Показано назначение каждого из вновь введенных блоков, которые дают такие преимущества, как повышение помехозащищённости контура к ошибкам измерений, обеспечение поискового вращения КА в случае отказа всех датчиков угловой скорости. Синтезирован улучшенный алгоритм управления. После доработки основного алгоритма были проведены наземные и летные испытания. Математическое моделирование производилось в среде GNU Octave. Полунатурное моделирование проводилось на поворотных *столах с установленными на них технологическими приборами ориентации и при использовании технологического вычислительного комплекса. Летные испытания проводились на реальном геостационарном КА, летающем на орбите. По каждому виду испытаний приведено описание начальных условий для тестов, приведены графики измерения угловой скорости. Все проведенные испытания окончились успешно, и данный алгоритм применяется на КА разработки АО «ИСС».*

Ключевые слова: система ориентации и стабилизации, космический аппарат, угловая скорость, испытания системы ориентации и стабилизации.

Introduction. Spacecraft (SC) operation in orbit is connected to such an important concept as permanent performing of an object function. In the early going, the quality management system of SC is meant to provide SC runnability in case of equipment failure [1; 2]. For their part, the failures can be classified as: a) failures not having a considerable effect on performing an object function of SC and b) failures capable of leading to a temporary time gap in the operation of SC for the purpose intended [3]. The time gap can appear due to loss of orientation. For SC, engaged in communication session, in the areas of lack of communication, disorientation and electric battery discharge can cause disastrous effects, e.g. loss of spacecraft.

Survivability mode. To provide survivability of spacecraft during its continuous autonomous operation in conditions of outer space, JSC "ISS – Reshetnev" use autonomous control loop of vehicle orientation – survivability mode [4–6]. According to a patent, the idea of the mode involves automatic unfolding of a solar panel into a fixed position relative to a main body of spacecraft to make solar panels as enlightened by the Sun as possible. Consequently, spacecraft maintains positive power balance and it is saved. The flow chart of an autonomous control loop in survivability mode is shown in the fig. 1.

The operation algorithm consists of three blocks:

1) defining the angle of orientation of SC ($\Psi = [\psi\ \varphi\ \theta]$, ′), which is performed using a solar sensor (SS) [7]. In that mode, we used solar sensors that identify the sun position by means of two angles (φ and θ);

2) defining the angular rate of SC ($\Omega = [\omega_x\ \omega_y\ \omega_z]$, ′/s) it is performed using an angular-rate sensor or using the algorithm of angular rate calculation [8];

3) calculation and generation of control actions on SC [9].

The unit of evaluation and generation of control actions on SC exerts control by the laws [10]:

$$M = -K^a\Psi - K^D\Omega = \begin{bmatrix} -K_x^a\psi - K_x^d\omega_x \\ -K_y^a\varphi - K_y^d\omega_y \\ -K_z^a\theta - K_z^d\omega_z \end{bmatrix}, \qquad (1)$$

$$\tau = J / M \cdot \Delta t, \qquad (2)$$

where $K^a = [\,K_x^a\ \ K_y^a\ \ K_z^a\,]$ is the coefficient of amplification, N·m·s/′; $K^d = [\,K_x^d\ \ K_y^d\ \ K_z^d\,]$ – damping coefficient, N·m·s^2/′; M – required control moment, N·m; τ – total time of generation of control signal, s; Δt – control period, s; J – momentum of inertia of SC, kg·m^2.

Using of orientation sensors (solar sensors and angular rate sensors), on-board digital computer system and jet orientation engines supports the survivability mode. Partial or complete failure of an angular rate sensor can cause a problem. Partial failure of an angular rate sensor occurred on the geostationary SC engineered by JSC "ISS – Reshetnev". Complete failure of an angular rate sensor would lead to disability of using survivability mode. An appropriate solution can be the algorithm of calculating angular rate on available orienting point – a star or the Sun, which is offered in [8]. However, using of these ways does not give the opportunity to provide search speed without orienting point in sight of a solar sensor.

We offered the solution in the form of a control algorithm taking into account failures of an angular rate sensor via one or more control channels with additional protection from short time false indications.

To define angular rate, we introduced an additional block, which calculates evaluation of angular rate according to the following formula:

$$\hat{\Omega}_i = \Omega_{i-1}^{op} + \Omega_{i-1}^{or.eng}, \qquad (3)$$

where $\hat{\Omega}_i$ is the calculating values of angular rate at present, ′/s; Ω_{i-1}^{op} – control rate at a previous step, ′/s; $\Omega_{i-1}^{or.eng}$ – calculated value change of angular rate of SC according to generated control action speed at a previous step, ′/s. In survivability mode, ignition of an orientation engine provides control input according to the formula:

$$\Omega_{i-1}^{or.eng} = \tau_{i-1} \cdot p \cdot l / J, \qquad (4)$$

where τ_{i-1} is the time of orientation engine ignition, s; p – rated thrust of an orientation engine, H; l – the arm of an orientation engine action, m; J – momentum of inertia of SC, kg·m^2.

Using of computer model of orientation engine ignition allows calculating the angular rate of SC that provides the system with parameters for controllability. The inaccuracy of angular rate depends on the accuracy of computer model of an orientation engine, as well as on initial value of angular rate. Nevertheless, using of estimation of angular rate by generated action allows providing search rotation of SC in the case of failure of all angular rate sensors that measure angular rate of SC in direction of search rotation.

Using a filter of angular rate of SC helps solve the task of protection from false indicated readings of ratemeter (levelling of impact) and compensation of inaccuracy of defining angular rate by the impact:

$$\hat{\Omega}_i^{op} = \hat{\Omega}_i + k\left(\Omega_i^{meas} - \hat{\Omega}_i\right), \qquad (5)$$

where $\hat{\Omega}_i^{op}$ is control angular rate at present step, ′/s; Ω_i^{meas} – measured angular rate, ′/s; k – filter gain. The filter gain defines the convergence rate of rate estimation to measured rate, and it is chosen in the range from 0 to 1.

In fig. 2 we presented The flow chart of improved autonomous control loop in survivability mode.

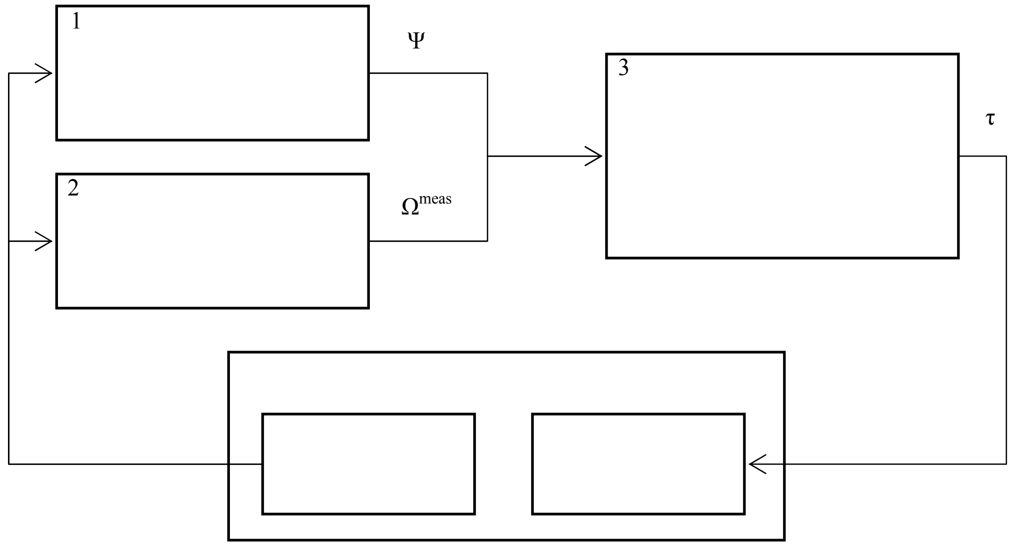


Fig. 1. Flow chart of an autonomous control loop in survivability mode

Рис. 1. Функциональная схема автономного контура управления в режиме живучести

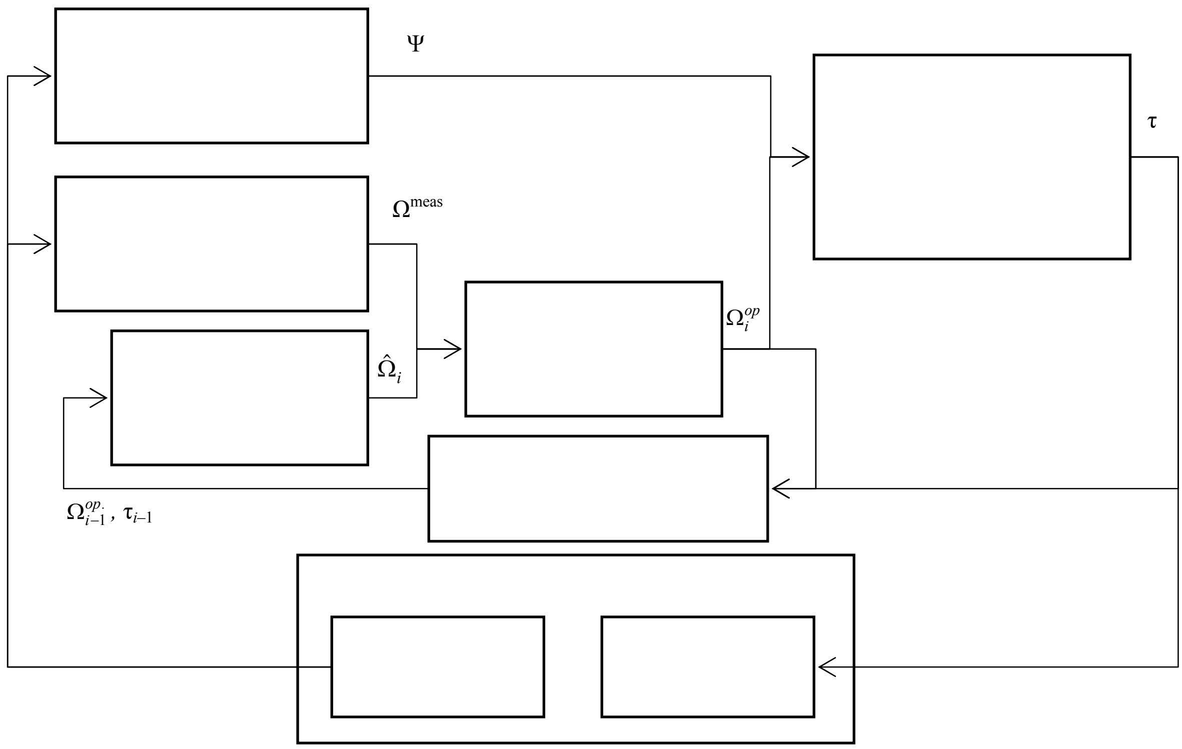


Fig. 2. Flow chart of improved autonomous control loop in survivability mode

Рис. 2. Функциональная схема усовершенствованного автономного контура управления в режиме живучести

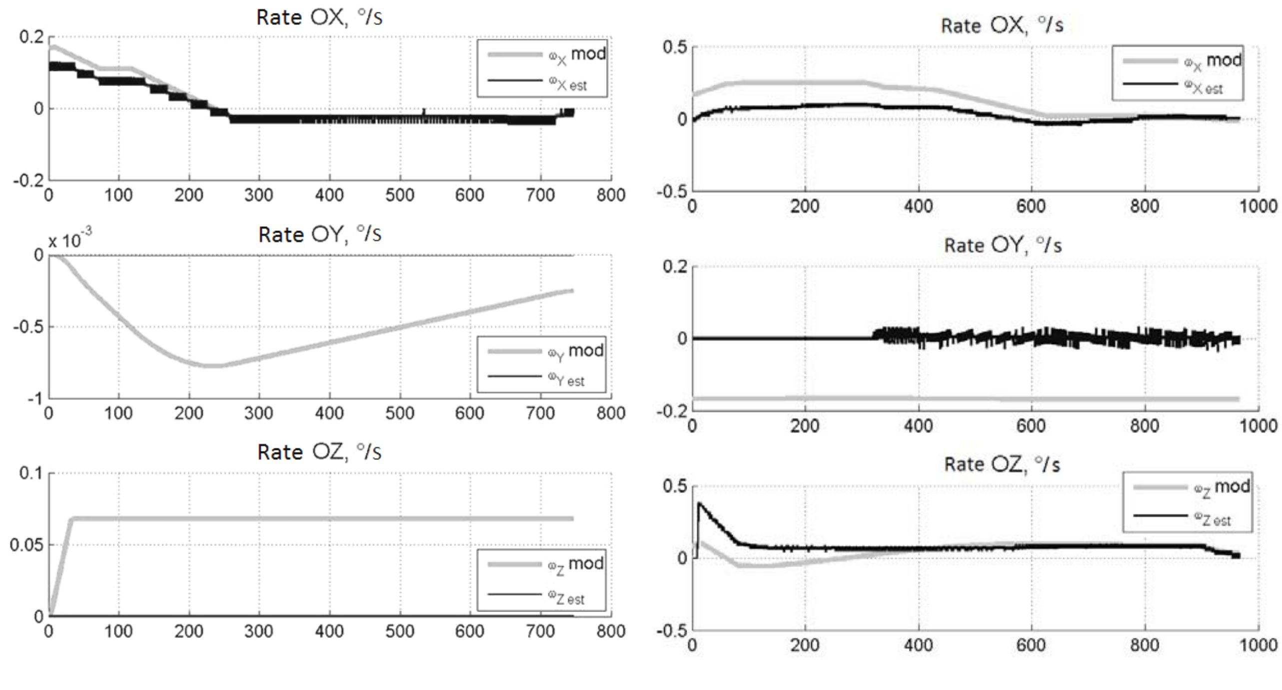
Tests. For algorithm qualification, we used mathematical modeling in mathematical computation environment Octave GNU and in simulation ground-based debugging complex of onboard radioelectronics [11]. The mathematical model consisted of the following blocks: kinematic and dynamic model of SC [12]; device model; control system model [13]; model of orientation engine [14].

We simulated situations when at starting moment of time, angular rate in onboard software and model angular rate differed significantly (from –15 to 15 ′/s) for different failures of angular rate sensors (8 failure combinations). We carried out more than 1000 test variations. Fig. 3 shows the results of two tests for two cases: *a* – failure of an angular rate sensor via channel *X*, *b* – failure of an angular rate sensor via all available channels. In the fig. 3 we labelled model angular rate of SC – $\omega_x$mod and angular rate estimation – $\omega_{x\ est}$.

Readings comparison of model angular rate and angular rate estimation shows ability to make required control actions via all control channels. We should focus on the situation of complete failure of an angular rate sensor and, consequently, lack of information about angular rate of SC. In this variant of failure, the algorithm of angular rate estimation solves the task of defining angular rate. Angular rate decrease via roll channel is impossible in some modes; one of these situations is shown in fig. 3, *b*. Its analysis shows that angular rate via pitch channels and yaw channels are calculated with some inaccuracy that decreases over time. The initial rate via roll channel (unknown to the algorithm) is not decelerated but it does not get lower. The fact that orientation is performed by a roll axis to the Sun does not give a possibility to measure angular rate via a roll channel using this orienting point. As high reliability and maximum possible development of the algorithm are required, we performed additional checking on an "iron bird", which consisted of real technological devices of a solar sensor and an angular rate sensor installed on rotary tables. You can see the description of an "iron bird" and methods of testing in the sources [14; 15]. We presented the graphs of angular rate changing while "iron bird" testing in fig. 4.

We can describe the results of the ground processing as effective: the algorithm successfully passed all the tests in all variants for all possible combinations of failures of an angular-rate sensor at different stages of processing.

The final test of the algorithm was live testing carried out on real SC, i. e. we prepared the programme to take spacecraft off into survivability mode with the simulation of angular-rate sensor failures. We carried out the four tests successfully. The logic of survivability mode with the improved algorithm effectively dealt with the orientation of SC on the Sun in the context of simulated failures of an angular rate sensor. Graphs of angular rate changing at verification tests in situ are shown in fig. 5.



a *b*

Fig. 3. Results of ground-based modeling tests with (*a*) failure of an angular rate sensor via channel *X*; failure of an angular rate sensor via all available channels (*b*)

Рис. 3. Результаты испытаний при наземном моделировании при отказе только ДУС по каналу *X* (*а*), и отказе ДУС по всем каналам управления (*б*)

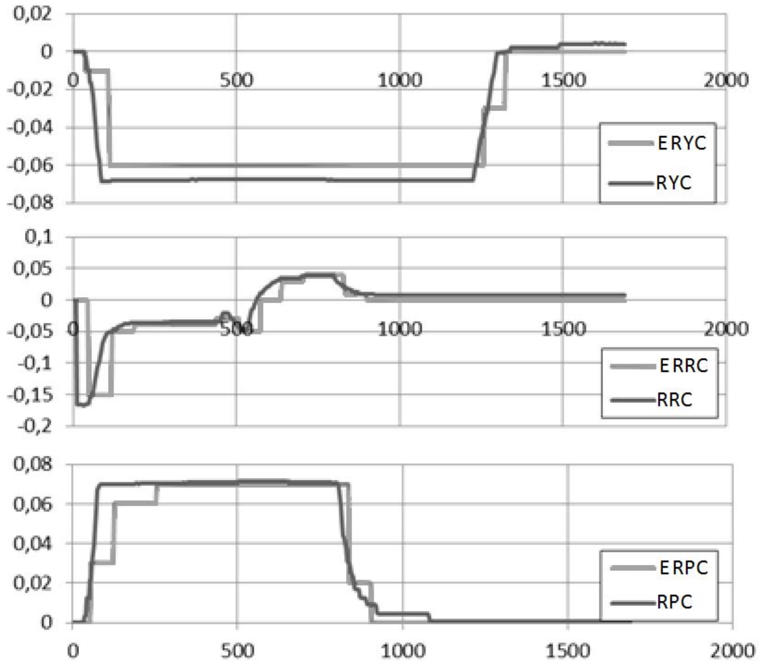


Fig. 4. Graphs of angular rate changing while "iron bird" testing

Рис. 4. Графики изменения угловой скорости при полунатурных испытаниях

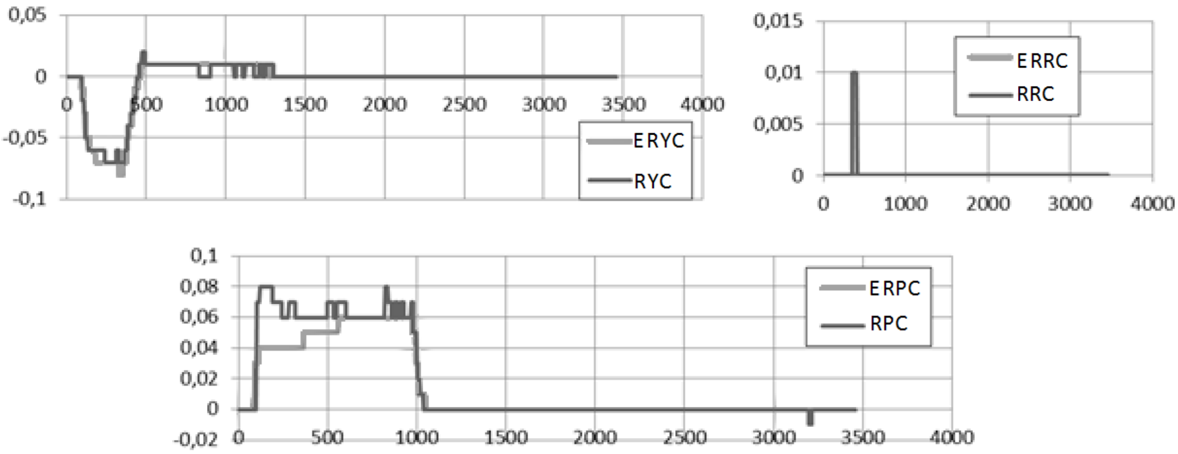


Fig. 5. Graphs of angular rate changing at verification tests in situ

Рис. 5. Графики изменения угловой скорости при натурных испытаниях

Conclusion. As a result of the research performed, the introduced method of algorithm improvement allows counteracting eventual failures of angular-rate sensors and ensuring protection from short time false indications; it was proved by the results of ground processing, "iron bird" tests and flight tests.

The improved algorithm is effectively applied on the geostationary SC developed by the JSC ISS – Reshetnev.

However, the algorithm has some drawbacks. One of them is impossibility to define a full vector of angular rate. Another variant of failures may be the failure of a solar sensor. We did not consider it in the paper, but it is rather important. In this case, the appropriate solution to the problem can be orientation in the current from solar panels.

References

1. GOST R 27.001–2009. *Nadezhnost' v tekhnike. Sistema upravleniya nadezhnost'yu. Osnovnye polozheniya* [Reliability in engineering. Reliability management system. Fundamental principles]. Moscow, Standartinform Publ., 2009. 12 p.

2. Chebotarev V. E., Kosenko V. E. *Osnovy proektirovaniya kosmicheskikh apparatov informatsionnogo obespecheniya* [Fundamentals of the design of space vehicles for information support]. 2010, Krasnoyarsk, Sib. gos. aerokosm. un-t Publ., 488 p.

3. Patraev V. E. *Metody obespecheniya i otsenki nadezhnosti apparatov s dlitel'nym srokom aktivnogo sushchestvovaniya. Monografiya* [Methods of providing

and evaluating the reliability of devices with a long life span. Monograph]. 2010, Krasnoyarsk, Sib. gos. aerokosm. un-t Publ., 136 p.

4. Korotkih V. V., Nesterishin M. V., Open'ko S. I., Ovchinnikov A. V., Tentilov Ju. A., Jakimov E. N. *Sposob orientacii iskusstvennogo sputnika Zemli* [Method of orientation of an artificial earth satellite]. Patent RF, No. 2544021, 2015.

5. Open'ko S. I., Andreev A. V., Tjunjagin D. V. et al. [On-Board control system in small spacecraft]. *Aktual'nye voprosy proektirovaniya avtomaticheskikh kosmicheskikh apparatov dlya fundamental'nykh i prikladnykh nauchnykh issledovaniy.* 2015, P. 279–284 (In Russ.).

6. Pichkalev A. V., Grebennikov A. V. The Instrument of measuring angular rate and spatial position of SC for RASO]. *Sovremennye problemy radioelektroniki: sb. nauch. tr.* 2017, P. 303–305 (In Russ.).

7. Fedoseev V. I., Kolosov M. P. *Optiko-elektronnye pribory orientacii I navigacii kosmicheskih aparatov* [Optoelectronic devices of orientation and navigation of spacecraft]. 2007, Moscow, Logos Publ., 248 p.

8. Demchenko A. N., Sokolov M. B., Pozdeev O. V., Sokolov V. N., Kravchuk S. V. *Sposob opredeleniya vektora uglovoy skorosti sobstvennogo vrashcheniya kosmicheskogo apparata vokrug ego tsentra mass* [Method to determine an angular rate vector of self-rotation of spacecraft around its center of gravity]. Patent RF, No. 2396188, 2010.

9. Branec V. N., Sevast'janov N. N., Fedulov R. V. *Lekcii po teorii system orientacii, upravlenija dvizheniem i navigacii* [Lectures on the theory of orientation systems, traffic control and navigation: study guide]. 2013, Tomsk, Tomskiy gosudarstvennyy universitet Publ., 313 p.

10. Kim D. P. *Teoriya avtomaticheskogo upravleniya. V 2 t. T. 1. Lineynye sistemy* [Theory of automatic control. Vol. 1. Linear systems]. 2003, Moscow, Fizmatlit Publ., 288 p.

11. Legan Ju. N. Pichkalev A. V., Prudkov V. V. [Modeling ground debugging complex of on-board radio-electronic equipment]. *Reshetnevskie chteniya.* 2016, P. 339–341 (In Russ.).

12. Raushenbah B. V., Tokar' E. N. *Upravlenie orientatsiey kosmicheskikh apparatov* [Controlling orientation of spacecraft]. Moscow, Nauka Publ., 1974, 600 p.

13. Vasil'ev V. N. *Sistemy orientacii kosmicheskih apparatov* [Systems of orientation of spacecraft]. Moscow, NPP VNIIEM Publ., 2009, 310 p.

14. Sinickij D. E., Murygin A. V. [Simulation of the work of the propulsion system of spacecraft during ground tests]. *Reshetnevskie chteniya : materialy XVII Mezhdunar. nauch. konf.* Krasnoyarsk, 2013, P. 334–335 (In Russ.).

15. Sinickij D. E., Fedchenko D. A., Murygin A. V. [Use of the method of dynamic in-line simulation for testing the system of orientation and stabilization of spacecraft]. *Aktual'nye problemy aviatsii i kosmonavtiki.* 2012, No. 8, P. 43–44 (In Russ.).

Библиографические ссылки

1. ГОСТ Р 27.001–2009. Надежность в технике. Система управления надежностью. Основные положения. М., 2009. 12 с.

2. Чеботарев В. Е., Косенко В. Е. Основы проектирования космических аппаратов информационного обеспечения : учеб. пособие / Сиб. гос. аэрокосмич. ун-т. Красноярск, 2011. 488 с.

3. Патраев В. Е. Методы обеспечения и оценки надежности аппаратов с длительным сроком активного существования : монография / Сиб. гос. аэрокосмич. ун-т. Красноярск, 2010. 136 с.

4. Пат. 2544021 Российская Федерация, МПК[7] В 64 G 1/24, В 64 G 1/44. Способ ориентации искусственного спутника Земли / Коротких В. В., Нестеришин М. В., Опенько С. И., Овчинников А. В., Тентилов Ю. А., Якимов Е. Н. № 2013108292/11 ; заявл. 25.02.13 ; опубл. 10.03.15, Бюл. № 7. 7 с.

5. Бортовой комплекс управления в малых космических аппаратах / С. И. Опенько [и др.] // Актуальные вопросы проектирования автоматических космических аппаратов для фундаментальных и прикладных научных исследований. 2015. С. 279–284.

6. Пичкалев А. В., Гребенников А. В. Аппаратура измерения угловых скоростей и пространственного положения КА для РАСО // Современные проблемы радиоэлектроники : сб. науч. тр. 2017. С. 303–305.

7. Федосеев В. И., Колосов М. П. Оптико-электронные приборы ориентации и навигации космических апаратов : учеб. пособие. М. : Логос, 2007. 248 с.

8. Пат. 2396188 Российская Федерация, МПК[7] В 64 G 1/28 В 64 G 1/24. Способ определения вектора угловой скорости собственного вращения космического аппарата вокруг его центра масс / Демченко А. Н., Соколов М. Б., Поздеев О. В., Соколов В. Н., Кравчук С. В. № 2009109602/11 ; заявл. 18.03.2009 ; опубл. 10.08.2010, Бюл. № 22. 7 с.

9. Бранец В. Н., Севастьянов Н. Н., Федулов Р. В. Лекции по теории систем ориентации, управления движением и навигации : учеб. пособие. Томск : Томский гос. ун-т, 2013. 313 с.

10. Ким Д. П. Теория автоматического управления. В 2 т. Т. 1. Линейные системы. М. : Физматлит, 2003. 288 с.

11. Леган Ю. Н. Пичкалев А. В., Прудков В. В. Моделирующий наземный отладочный комплекс бортовой радиоэлектронной аппаратуры // Решетневские чтения : материалы XVII Междунар. науч. конф. / под общ. ред. Ю. Ю. Логинова ; Сиб. гос. аэрокосмич. ун-т. Красноярск, 2016. С. 339–341.

12. Раушенбах Б. В., Токарь Е. Н. Управление ориентацией космических аппаратов. М. : Наука, 1974. 600 с.

13. Васильев В. Н. Системы ориентации космических аппаратов. М. : ФГУП «НПП ВНИИЭМ», 2009. 310 с.

14. Синицкий Д. Е., Мурыгин А. В. Имитация работы двигательной установки космического аппарата при наземных испытаниях // Решетневские чтения : материалы XVII Междунар. науч. конф. / под общ. ред. Ю. Ю. Логинова ; Сиб. гос. аэрокосмич. ун-т. Красноярск, 2013. С. 334–335.

15. Синицкий Д. Е., Федченко Д. А., Мурыгин А. В. Использование метода полунатурного динамического моделирования для испытания системы ориентации и стабилизации КА // Актуальные проблемы авиации и космонавтики. 2012. № 8. С. 43–44.