THE SPACECRAFT ANGULAR VELOCITY ESTIMATION IN THE ORBITAL STABILIZATION MODE BY THE RESULTS OF THE LOCAL VERTICAL SENSOR MEASUREMENTS*

N.E. Zubov[1,2], **E.A. Mikrin**[1,2], **A.S. Oleynik**[1,3],
V.N. Ryabchenko[1,2], **D.E. Efanov**[1]

[1]OAO Korolev Rocket and Space Corporation Energiya,
Korolev, Moscow region, Russian Federation
e-mail: Nikolay.Zubov@rsce.ru

[2]Bauman Moscow State Technical University, Moscow, Russian Federation
e-mail: nezubov@bmstu.ru

[3]Moscow Institute of Physics and Technology (State University),
Dolgoprudnyy, Moscovskaya oblast, Russian Federation

Implementation of the orbital orientation mode is based on the use of sensor equipment, measuring the spacecraft position angles relative to the coordinates system and the angular velocity of spacecraft rotation relative to inertial space. In case the latter fails the orbital stabilization implementation is impossible. Consequently, it is required to make on-board estimation algorithms for a angular velocity vector in real-time by the results of measurements using an angular position sensor. The exact pole placement method was used to obtain the analytic solution of the estimation algorithm synthesis for angular velocity of the spacecraft rotation in the orbital stabilization mode by the results of local vertical sensor measuring. The mathematical simulation results are presented and the possibility of the developed algorithm implementation is assessed in real-time. The simulation results confirm high efficiency of the algorithm operation.

Keywords**:** spacecraft, exact pole placement method, local vertical sensor, angular velocity, estimation algorithm.

Introduction. The problem of building up and stabilizing orbital navigation mode [1–3] is one of the most common in spacecraft (SC) flights practice regardless of their target mission. As a rule, implementation of the above mentioned mode is based on the use of sensor equipment measuring SC position angles relative to the reference coordinate system and SC angular rotation velocity with respect to inertial space. In case the latter fails the implementation of orbital stabilization is impossible, thus, it is essential to build on-board estimation algorithms for angular velocity vector by the results of angular position sensor measurements in real time. The characteristic feature of many SC is the usage of a local vertical builder (IKV) [4] as a measurement device of angular roll position, which measures only two angles (angles of roll and pitch). The present article is devoted to the analytical synthesis of SC angular velocity estimation algorithm in the orbital stabilization mode by the results of local vertical

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sensor measurements. The basis for the algorithm synthesis is the method of the exact pole placement [2].

The method of the exact pole placement for solving observation problems. Let's look at a linear multidimensional dynamic system, set in a state space by the equations of the type [4].

$$\mathfrak{D}\mathbf{x} = A\mathbf{x} + B\mathbf{u}; \quad \mathbf{y} = C\mathbf{x}, \tag{1}$$

Where $\mathbf{x} \in \mathbb{R}^n$ is vector of state; $\mathbf{u} \in \mathbb{R}^r$ is input vector; $\mathbf{y} \in \mathbb{R}^m$ is output vector; $\mathbb{R}$ is the set of real numbers; $\mathfrak{D}$ is the symbol designating either the differentiating operator $\mathfrak{D}\mathbf{x}(t) = \dot{\mathbf{x}}(t)$, or the shift operator $\mathfrak{D}\mathbf{x}(t) = \mathbf{x}(t+1)$.

Let a pair of matrices (A, C) be fully observed, i.e. Kalman condition is fulfilled

$$\operatorname{rank}\begin{pmatrix} C \\ CA \\ \vdots \\ CA^{n-m} \end{pmatrix} = n,$$

then it is possible to build the observer to estimate the state vector of $\mathbf{x}$ object according to $\mathbf{u}$ input and $\mathbf{y}$ output vectors. If the observer forms the estimation of the total $\mathbf{x}$ vector, then we speak about full rank observer, if only some part of this vector is estimated, the observer is called reduced.

Full rank observer is defined by the equation:

$$\mathfrak{D}\hat{\mathbf{x}} = (A - LC)\,\hat{\mathbf{x}} + L\mathbf{y} + B\mathbf{u}$$

here $\hat{\mathbf{x}} \in \mathbb{R}^n$ is the observer condition representing the estimation sought for; L is the matrix of the observer feedback.

To solve the observer synthesis problem (the L matrix definition) it is possible to apply any method of modal control. Similar to the work [5], let's use the method used in works [2, 6]. Let's introduce a multilevel decomposition of the system (1) given by a pair of matrices (A, C):

a zero (starting) level

$$A_0 = A^{\mathrm{T}}, \quad B_0 = C^{\mathrm{T}}; \tag{2}$$

k^{th} *level* $\left(k = \overline{1, J},\ J = \operatorname{ceil}\left(\dfrac{n}{m} - 1\right)\right)$

$$A_k = B_{k-1}^{\perp} A_{k-1} B_{k-1}^{\perp -}, \quad B_k = B_{k-1}^{\perp} A_{k-1} B_{k-1}.$$

here $B_i^{\perp}$ is annihilator (zero divisor) of the matrix B_i, $B_i^{\perp} B_i = 0$; $B_i^{\perp -}$ is 2-semireversible matrix for B_i, i.e. the matrix satisfying the regularity conditions

$$B_i^{\perp} B_i^{\perp -} B_i^{\perp} = B_i^{\perp}, \ B_i^{\perp -} B_i^{\perp} B_i^{\perp -} = B_i^{\perp -}.$$

In compliance with the work [5] the sought for matrix $L = L_0 \in \mathbb{R}^{m\times n}$ is calculated by recursive formulas

$$L_J = B_J^+ A_J - \Phi_J B_J^+;$$

$$L_k = B_k^- A_k - \Phi_k B_k^-;\;\; B_k^- = L_{k+1} B_k^\perp + B_k^+,\;\; k = \overline{0, J-1},$$

and provides the exact set pole placement. This is actually so, as all elements of the set of eigenvalues $\mathrm{eig}\,(A - LC)$ correspond to eigenvalues of a set of stable matrices Φ_i, of the size $m \times m$, $i = \overline{0, J}$. Here $B_0^+, \ldots, B_J^+$ are pseudo reverse matrices of Moor – Penrose. Thus, for the synthesis of the observer of a full rank order considered hereit is necessary:

1) to conduct a linear approximation for further using the observer synthesis algorithm for linear systems [7];

2) to use the following synthesis algorithm for full rank state observer:

— set the matrices

$$A_0 = A^{\mathrm{T}};\;\; B_0 = C^{\mathrm{T}}$$

— calculate

$$J = \mathrm{ceil}\left(\frac{n}{m}\right) - 1;$$

— set the matrices $\Phi = \Phi_0, \Phi_1, \ldots, \Phi_J$ so that the desired spectre of the state observer comprises

$$\bigcup_{i=1}^{J+1} \mathrm{eig}\,(\Phi_{i-1})\,;$$

— define the ortogonal annihilator $B_{k-1}^\perp$ and then matrices

$$A_k = B_{k-1}^\perp A_{k-1} B_{k-1}^{\perp\mathrm{T}};$$
$$B_k = B_{k-1}^\perp A_{k-1} B_{k-1},\;\; k = \overline{1, J};$$

— consecutively calculate the matrices

$$\begin{aligned} L_J^{\mathrm{T}} &= \Phi_J B_J^+ - B_J^+ A_J; \\ B_k^- &= B_k^+ - L_{k+1}^{\mathrm{T}} B_k^\perp; \\ L_k^{\mathrm{T}} &= \Phi_k B_k^- - B_k^- A_k,\;\; k = \overline{J-1, 0}. \end{aligned} \qquad (3)$$

The SC angular velocity estimation by the local vertical sensor results. The SC movement as a solid body around the centre of mass is described by a system of the Euler dynamic equations:

$$\begin{aligned} J_x\frac{d\omega_x}{dt}+(J_z-J_y)\omega_y\omega_z&=M_x;\\ J_y\frac{d\omega_y}{dt}+(J_x-J_z)\omega_x\omega_z&=M_y;\\ J_z\frac{d\omega_z}{dt}+(J_y-J_x)\omega_x\omega_y&=M_z, \end{aligned}\tag{4}$$

where J_x, J_y, J_z are the main moments of SC inertion; $\omega_x, \omega_y, \omega_z$ are the projectors of SC angular velocity at the axis of coordinate systems, rigidly connected to the craft; M_x, M_y, M_z are external forces moments.

To describe SC movement in the reference coordinates system it is necessary to know kinematic correlations demonstrating the dependence of angular velocity projections $\omega_x, \omega_y, \omega_z$ on the position of a connected coordinate system relative to the reference one. This dependence is set up with the help of three Euler angles: roll angle γ; yaw angle ψ; pitch angle ϑ.

For craft orientation in the orbital coordinates system:

$$\begin{aligned} \omega_x&=\dot\gamma+(\Omega-\dot\vartheta)\sin\psi;\\ \omega_y&=\dot\psi\cos\gamma-(\Omega-\dot\vartheta)\sin\gamma\cos\psi;\\ \omega_z&=-(\Omega-\dot\vartheta)\cos\gamma\cos\psi-\dot\psi\sin\gamma. \end{aligned}\tag{5}$$

We differentiate the kinematic equations (5):

$$\begin{aligned} \dot\omega_x&=\ddot\gamma+(\dot\Omega-\ddot\vartheta)\sin\psi+(\Omega-\dot\vartheta)\dot\psi\cos\psi;\\ \dot\omega_y&=\ddot\psi\cos\gamma-\dot\psi\dot\gamma\sin\gamma-(\dot\Omega-\ddot\vartheta)\sin\gamma\cos\psi-\\ &\qquad-(\Omega-\dot\vartheta)(\dot\gamma\cos\gamma\cos\psi-\dot\psi\sin\gamma\sin\psi);\\ \dot\omega_z&=-(\dot\Omega-\ddot\vartheta)\cos\gamma\cos\psi+(\Omega-\dot\vartheta)(\dot\gamma\sin\gamma\cos\psi+\\ &\qquad+\dot\psi\cos\gamma\sin\psi)-\ddot\psi\sin\gamma-\dot\psi\dot\gamma\cos\gamma. \end{aligned}\tag{6}$$

After the linear approximation the systems (5) and (6) will gain the following appearance

$$\omega_x=\dot\gamma+\Omega\psi;\;\;\omega_y=\dot\psi-\Omega\gamma;\;\;\omega_z=\dot\vartheta-\Omega;\tag{7}$$

$$\dot\omega_x=\ddot\gamma+\Omega\dot\psi;\;\;\dot\omega_y=\ddot\psi-\Omega\dot\gamma;\;\;\dot\omega_z=\ddot\vartheta.\tag{8}$$

Inserting (7) and (8) into (4) we obtain:

$$\begin{aligned} &J_x\ddot\gamma+\Omega^2(J_z-J_y)\gamma+\Omega(J_x+J_y-J_z)\dot\psi=M_x;\\ &J_y\ddot\psi+\Omega^2(J_z-J_x)\psi-\Omega(J_x+J_y-J_z)\dot\gamma=M_y;\\ &J_z\ddot\vartheta=M_z. \end{aligned}\tag{9}$$

The pitch channel is autonomous, it can be regarded independently of the other two channels movement. The roll and yaw channels are closely connected. This is explained by the presence of angular velocity of the orbital coordinate system in the orbit plane, which leads to the appearance of gyroscopic cross connections:

$$\begin{aligned} &J_x \frac{d\omega_x}{dt} + (J_z - J_y)\Omega\omega_y = M_x; \\ &J_y \frac{d\omega_y}{dt} + (J_z - J_x)\Omega\omega_x = M_y; \\ &J_z \frac{d\omega_z}{dt} = M_z. \end{aligned} \tag{10}$$

Using systems (8)–(10) for the connected channels, we obtain:

$$\begin{pmatrix} \dot\gamma \\ \dot\omega_x \\ \dot\psi \\ \dot\omega_y \end{pmatrix} = \begin{pmatrix} 0 & 1 & -\Omega & 0 \\ 0 & 0 & 0 & -\dfrac{J_z - J_y}{J_x}\Omega \\ \Omega & 0 & 0 & 1 \\ 0 & -\dfrac{J_z - J_x}{J_y}\Omega & 0 & 0 \end{pmatrix} \times$$

$$\times \begin{pmatrix} \gamma \\ \omega_x \\ \psi \\ \omega_y \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ \dfrac{1}{J_x} & 0 \\ 0 & 0 \\ 0 & \dfrac{1}{J_y} \end{pmatrix} \begin{pmatrix} M_x \\ M_y \end{pmatrix};$$

$$A = \begin{pmatrix} 0 & 1 & -\Omega & 0 \\ 0 & 0 & 0 & -\dfrac{J_z - J_y}{J_x}\Omega \\ \Omega & 0 & 0 & 1 \\ 0 & -\dfrac{J_z - J_x}{J_y}\Omega & 0 & 0 \end{pmatrix}; \quad B = \begin{pmatrix} 0 & 0 \\ \dfrac{1}{J_x} & 0 \\ 0 & 0 \\ 0 & \dfrac{1}{J_y} \end{pmatrix}; \tag{11}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}. \tag{12}$$

In accordance with (2) and on the basis of (11) and (12) for the zero level of a discrete system with h tract let's put

$$A_0 = A^{\mathrm{T}} = \begin{pmatrix} 1 & 0 & a_{31}h & 0 \\ h & 1 & 0 & a_{42}h \\ a_{31}h & 0 & 1 & 0 \\ 0 & a_{24}h & h & 1 \end{pmatrix}; \tag{13}$$

$$B_0 = C^{\mathrm{T}} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \tag{14}$$

In this case the state vector dimension is $n_x = 4$, of a vector of the observed variables is $m_y = 1$ and the number of decomposition levels additional to the zero one:

$$J = \mathrm{ceil}\left(\frac{n_x}{m_y}\right) - 1 = 4 - 1 = 3.$$

According to the multilevel decomposition introduced above, matrices A_k, B_k, $k = \overline{1, J}$, have the following appearance

level 1

$$B_0^{\perp} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}; \tag{15}$$

$$B_0^{+} = \begin{pmatrix} 1 & 0 & 0 & 0 \end{pmatrix}; \tag{16}$$

$$A_1 = B_0^{\perp} A_0 B_0^{\perp \mathrm{T}} = \begin{pmatrix} 1 & 0 & a_{42}h \\ 0 & 1 & 0 \\ a_{24}h & h & 1 \end{pmatrix}; \tag{17}$$

$$B_1 = B_0^{\perp} A_0 B_0 = \begin{pmatrix} h \\ a_{13}h \\ 0 \end{pmatrix}; \tag{18}$$

level 2

$$B_1^{\perp} = \begin{pmatrix} -a_{13} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}; \tag{19}$$

$$B_1^{+} = \begin{pmatrix} \dfrac{h}{a_{13}^2 h^2 + h^2} & \dfrac{a_{13}h}{a_{13}^2 h^2 + h^2} & 0 \end{pmatrix}; \tag{20}$$

$$A_2 = B_1^{\perp} A_1 B_1^{\perp \mathrm{T}} = \begin{pmatrix} a_{13}^2 + 1 & -a_{13}a_{42}h \\ h - a_{13}a_{24}h & 1 \end{pmatrix}; \tag{21}$$

$$B_2 = B_1^{\perp} A_1 B_1 = \begin{pmatrix} 0 \\ a_{13}h^2 + a_{24}h^2 \end{pmatrix}; \tag{22}$$

level 3

$$B_2^{\perp} = \begin{pmatrix} 1 & 0 \end{pmatrix}; \tag{23}$$

$$B_2^{+} = \begin{pmatrix} 0 & \dfrac{1}{a_{13}h^2 + a_{24}h^2} \end{pmatrix}; \tag{24}$$

$$A_3 = B_2^{\perp} A_2 B_2^{\perp\mathrm{T}} = \left(a_{13}^2 + 1\right); \tag{25}$$

$$B_3 = B_2^{\perp} A_2 B_2 = \left(-a_{13}a_{42}h\left(a_{13}h^2 + a_{24}h^2\right)\right). \tag{26}$$

On the basis of formulae (3) and (13)–(26) it is possible to find the observer matrix $L0$. In their general form formulae for the matrix L_0 component look very bulky. Therefore, it was decided not to present these expressions. To provide the fastest convergence with the usage of the solution obtained in the paper, it is necessary in (3) to assume own values equal to zero: $\Phi_0 = \Phi_1 = \Phi_2 = \Phi_3$. Then the observer matrix L_0 in accordance with (3) will gain the following appearance:

$$L_0^{\mathrm{T}} = \begin{pmatrix} l_1 & l_2 & l_3 & l_4 \end{pmatrix}, \tag{27}$$

where

$$\begin{gathered}
l_1 = -a_{13}^2 - 4;\\
l_2 = -\frac{a_{24}(6a_{13}^2+4a_{13}^4+a_{13}^6+a_{24}a_{42}h^2-a_{42}a_{13}^3h^2+a_{24}a_{42}a_{13}^2h^2+a_{24}a_{42}a_{13}^4h^2+3)}{h(a_{13}^2+1)(a_{13}+a_{24})}-\\
-\frac{3a_{13}^2+3a_{13}^4+a_{13}^6+3a_{24}a_{42}h^2-a_{42}a_{13}^3h^2+4a_{24}a_{42}a_{13}^2h^2+2a_{24}a_{42}a_{13}^4h^2+1}{a_{42}h^3(a_{13}^2+1)(a_{13}+a_{24})};\\
l_3 = \frac{a_{13}^6-a_{42}a_{13}^5h^2+a_{24}a_{42}a_{13}^4h^2+3a_{13}^4-5a_{42}a_{13}^3h^2+3a_{13}^2-3a_{42}a_{13}h^2+1}{a_{13}a_{42}h^3(a_{13}^2+1)(a_{13}+a_{24})}-\\
-\frac{a_{13}^6+a_{24}a_{42}a_{13}^4h^2+4a_{13}^4-a_{42}a_{13}^3h^2+a_{24}a_{42}a_{13}^2h^2+6a_{13}^2+a_{24}a_{42}h^2+3}{h(a_{13}^2+1)(a_{13}+a_{24})}-a_{31}h;\\
l_4 = -\frac{2a_{13}^6+3a_{24}a_{42}a_{13}^4h^2+7a_{13}^4-2a_{42}a_{13}^3h^2+5a_{24}a_{42}a_{13}^2h^2+9a_{13}^2+4a_{24}a_{42}h^2+4}{h^2(a_{13}^2+1)(a_{13}+a_{24})}.
\end{gathered} \tag{28}$$

Thus, with the help of the above method it is quite easy to get the matrix for the pitch channel and it will look as follows:

$$L_\vartheta^{\mathrm{T}} = \begin{pmatrix} l_1^\vartheta & l_1^\vartheta \end{pmatrix}. \tag{29}$$

Here $l_1^\vartheta = -2,\ l_2^\vartheta = -1/h$.

The analysis of the expressions (28), which, in accordance with (27) and (29), represent the analytical algorithm of the observer synthesis shows that its realization is based on the fulfillment of such elementary operations as addition, multiplication and division. This fact allows stating the possibility of doing the algorithm in real time with the help of the onboard computer.

The results of simulation. Let's do mathematical simulation. Let the main moments of SC inertia kg/m^2 have the following values: $J_x = 77521$;

$J_y = 274021$; $J_z = 238845$, and with the usage of a set of units (SI) the initial values of SC state vector are equal $\begin{pmatrix} \gamma & \omega_x & \psi & \omega_y \end{pmatrix}^{\mathrm{T}} = \begin{pmatrix} 0{,}1 & 0{,}005 & -0{,}1 & 0{,}002 \end{pmatrix}^{\mathrm{T}}$; $\begin{pmatrix} \vartheta & \omega_z \end{pmatrix}^{\mathrm{T}} = \begin{pmatrix} 0{,}1 & 0{,}003 \end{pmatrix}^{\mathrm{T}}$. As an initial approximation of estimation values for the angular velocity vector let's choose the beginning of coordinates: $\begin{pmatrix} \hat{\omega}_{x0} & \hat{\omega}_{y0} \end{pmatrix}^{\mathrm{T}} = (\ 0,0 \quad 0,0\ )^{\mathrm{T}}$; $\hat{\omega}_{z0} = 0{,}0$.

The simulation results are given in Figure 1, which presents the change of non-correction components of angular velocity vector ($\tilde{\omega}_x = \omega_x - \hat{\omega}_x$, $\tilde{\omega}_y = \omega_y - \hat{\omega}_y$, $\tilde{\omega}_z = \omega_z - \hat{\omega}_z$) in accordance with the iteration index.

The range of non-connection changes (part *a* and *b* of the figure) is quite large and correspondingly it is difficult to estimate the convergence accuracy of SC angular rotation velocity vector using the given dependencies, that is why starting from the fourth tact of iteration process, the simulation results are presented in Table 1.

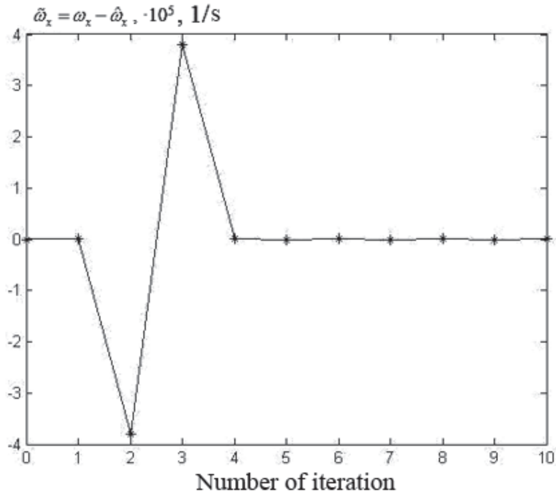
Table 1

Results of simulation

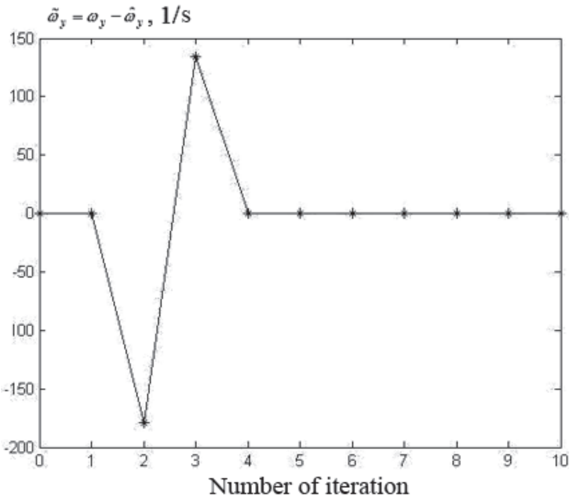
Non-connection component of angular rotation velocity vector, 1/s	Iteration index						
	4	5	6	7	8	9	10
$\hat{\omega}_x$	–0.0110	0.0343	–0.0179	0.0089	0.0050	0.0050	0.0050
$\tilde{\omega}_x = \omega_x - \hat{\omega}_x$	0.0160	–0.0293	0.0229	–0.0039	0.0000	0.0000	0.0000
$\hat{\omega}_y$	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020
$\tilde{\omega}_y = \omega_y - \hat{\omega}_y$	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
$\hat{\omega}_z$	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030
$\tilde{\omega}_z = \omega_z - \hat{\omega}_z$	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

The analysis of the data presented in Figure 1 and Table 1 shows that during eight iterations angular velocity vector agrees with the real value of angular velocity vector of a SC.

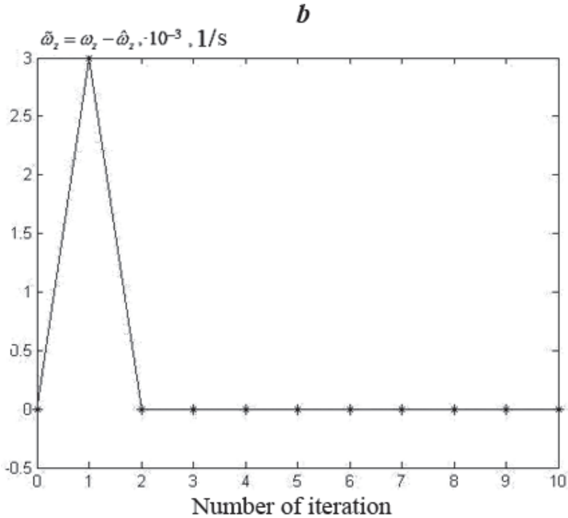
Conclusion. In the present article the exact pole placement method enables the analytical solution of SC angular velocity estimation synthesis in a mode of orbital stabilization by the results of the local vertical sensor measurements. The results of mathematical simulation are presented, confirming the high algorithm efficiency. In accordance with the analysis of computational expenses of the algorithm based on the expression (16) and the number of iterations providing the convergence of the process by the simulation results it may be concluded that its realization is feasible in real time.



a



b



c

Changes of the non-connection component of angular velocity vector in channels of tilt (*a*), yaw (*b*), and pitch (*c*)

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Contributors

Zubov N.E. — D.Sc. (Eng.), Deputy Director for Science, Research and Development Center of OAO Korolev Rocket and Space Corporation "Energiya", Professor of Engineering, Department of Automatic Control Systems, Bauman Moscow State Technical University, author of over 90 publications in the field of problems of spacecraft control.
Bauman Moscow State Technical University, ul. 2-ya Baumanskaya 5, Moscow, 105005 Russian Federation.
OAO Korolev Rocket and Space Corporation "Energiya", ul. Lenina 4a, Korolev, Moscovskaya oblast, 141070 Russian Federation.

Mikrin E.A. — D.Sc. (Eng.), Member of the Russian Academy of Sciences, Head of the Department of Automatic Control Systems, Bauman Moscow State Technical University, First Deputy General Designer, OAO Korolev Rocket and Space Corporation "Energiya", author of over 150 publications in the field of problems of spacecraft control.
Bauman Moscow State Technical University, ul. 2-ya Baumanskaya 5, Moscow, 105005 Russian Federation.
OAO Korolev Rocket and Space Corporation "Energiya", ul. Lenina 4a, Korolev, Moscovskaya oblast, 141070 Russian Federation.

Oleynik A.S. — Ph.D. student, Moscow Institute of Physics and Technology (State University), engineer, OAO Korolev Rocket and Space Corporation “Energiya”, author of four publications in the field of problems of spacecraft control.
Moscow Institute of Physics and Technology (State University), Institutskiy per. 9, Dolgoprudny, Moscovskaya oblast, 141700 Russian Federation.
OAO Korolev Rocket and Space Corporation “Energiya”, ul. Lenina 4a, Korolev, Moscovskaya oblast, 141070 Russian Federation.

Ryabchenko V.N. — D.Sc. (Eng.), Leading Researcher, Research and Development Center, OAO Korolev Rocket and Space Corporation “Energiya”, Professor of Engineering, Department of Automatic Control Systems, Bauman Moscow State Technical University, author of over 200 publications in the field of problems of spacecraft control.
Bauman Moscow State Technical University, ul. 2-ya Baumanskaya 5, Moscow, 105005 Russian Federation.
OAO Korolev Rocket and Space Corporation “Energiya”, ul. Lenina 4a, Korolev, Moscovskaya oblast, 141070 Russian Federation.

Efanov D.E. — Ph.D. student, Research and Development Centre, OAO Korolev Rocket and Space Corporation “Energiya”, author of over 10 publications in the field of problems of spacecraft control.
OAO Korolev Rocket and Space Corporation “Energiya”, ul. Lenina 4a, Korolev, Moscovskaya oblast, 141070 Russian Federation.

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