IN-FLIGHT DEVELOPMENT OF SINS-500NS SATELLITE INERTIAL NAVIGATION SYSTEM AT HIGH LATITUDES

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***Abstract*—Basic features of implementing the modes of operation of a strapdown inertial navigation system (SINS) under polar conditions are considered. The above-mentioned SINS based on fiber-optic gyros has been the subject of our studies. Approaches to the improvement of the accuracy characteristics of such SINS are proposed, which are based on the use of geophysical invariants and on the integrated processing of appropriate observations. The results of field development of the SINS presented in this paper are shown and analyzed.**

Keywords—inertial navigation system, initial alignment, high latitudes, satellite navigation system, Kalman filter

I. INTRODUCTION

At present, the problem of improving the accuracy characteristics of strapdown inertial navigation systems (SINS) operating at high latitudes still remains topical. This is connected with the following features of SINS operation under such conditions: lack of geodetically equipped sites; the necessity of carrying out autonomous initial alignment when horizontal components of the Earth angular velocity vector are small in magnitude; degeneracy of traditional equations of navigation; significant vibrations of the construction of a mobile object, e.g., of a helicopter. Therefore, under such conditions, the initial alignment performed only by gyrocompassing method may prove to be ineffective. Traditional approaches to the solution of the above problem involve selection of coordinate systems [1, 2] and also the use of information [3] which is external with respect to the SINS.

The purpose of this paper is to improve SINS accuracy characteristics at high latitudes on the basis of new approaches to the reckoning of motion parameters, and using the invariants and external information.

The attainment of the formulated purpose relies on the use of combined procedures for the SINS initial alignment (IA) and SINS additional alignment, which are based on a combination of the potentialities of the methods of gyrocompassing, vector matching, and optimal estimation.

II. THE SINS-500NS INERTIAL SATELLITE NAVIGATION SYSTEM AS THE SUBJECT OF STUDIES

In this paper, the subject of the studies is an upgraded version of the SINS-500NS inertial satellite navigation system (see Fig.1) developed by the NaukaSoft Experimental Laboratory, Ltd. (Moscow). The inertial measurement unit (IMU) of the above SINS-500NS [4] system is based on fiber-optic gyros (FOG) developed by Optolink RPC (Zelenograd). The frequency of data updating and recording on a flash memory built in the system is 1 kHz for the IMU, and 1 Hz for the satellite navigation system (SNS) and other external observations. The technological solutions considered in this paper have been implemented in Linux real-time operating system which supports modular architecture of the SINS construction. The presence of built-in flash memory has made it possible to obtain and analyze the recorded data with due regard to actual operating conditions. Furthermore, this has enabled the math-based software (MBS) to be updated and studied on a set of paths and the algorithms synthesized.

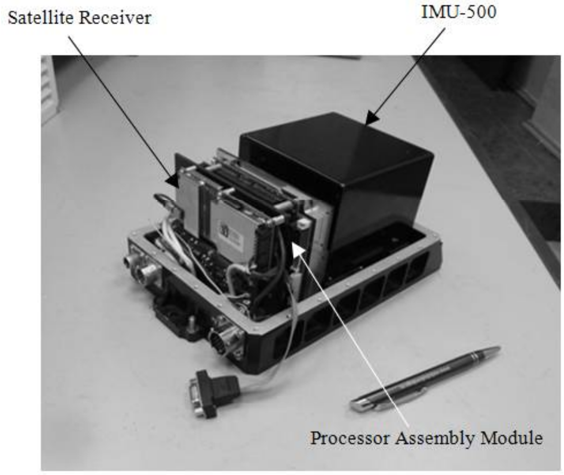

Fig. 1. SINS-500NS strapdown inertial satellite navigation system

The following modes of SINS operation, which take into account reducing observability of the SINS azimuth error with increasing position latitude, have been implemented and studied.

Coarse initial alignment of the SINS-500NS system is performed by the gyrocompassing method, using the signals from inertial sensors — gyros and accelerometers. This mode has the following specific features of implementation: primary processing of sensor signals is carried out with the use of combined digital filtering [5]; the sensor signals are protected against outliers by combined goodness-of-fit tests [6].

Adaptive tuning of the parameters of a digital filter in the frequency domain allows one to take into account spectral characteristics of vehicle vibrations. In this paper, such a vehicle is a helicopter.

Fine initial alignment of the SINS-500NS system is performed with the use of geophysical invariants and the Kalman filter. The invariants are physical quantities the values of which are known a priori and do not change in time and space. Such invariants are the angular rate of the Earth rotation and immobility of the SINS base during the initial alignment. A specific feature of this mode is associated with the implementation of “pseudoreckoning” of attitude and navigation parameters by sensor signals when the system base is immobile. Taking into account the necessity of using the SINS at high latitudes, such reckoning was implemented on the basis of a quaternion modification of the all-latitude reckoning algorithm [2]:

$$\dot{\bar q}_0 = \Pi_0 \bar q_0;\ \dot{\bar p}_1 = \Pi_1 \bar p_1, \qquad (1)$$

where $\bar q_0 = \{q_0, q_1, q_2, q_3\}$ is a quaternion which characterizes the angular position of the IMU frame $oxyz$ relative to the inertial frame $OX_IY_IZ_I$; $\bar p_1 = \{p_0, p_1, p_2, p_3\}$ is a quaternion which characterizes the angular position of the wander-azimuth reference navigation trihedron $o\xi\eta\zeta$ relative to the geocentric frame $OX_EY_EZ_E$;

$$\Pi_0 = \begin{bmatrix} 0 & -\dot\Theta_x & -\dot\Theta_y & -\dot\Theta_z \\ \dot\Theta_x & \cdots & \cdots & \cdots \\ \dot\Theta_y & \vdots & \tilde\Pi_0 & \\ \dot\Theta_z & \vdots & & \end{bmatrix};$$

$$\Pi_1 = \begin{bmatrix} 0 & -\omega_\xi & -\omega_\eta & -\omega_\zeta \\ \omega_\xi & \cdots & \cdots & \cdots \\ \omega_\eta & \vdots & \tilde\Pi_1 & \\ \omega_\zeta & \vdots & & \end{bmatrix};$$

$$\tilde\Pi_0 = \begin{bmatrix} 0 & \dot\Theta_z & -\dot\Theta_y \\ -\dot\Theta_z & 0 & \dot\Theta_x \\ \dot\Theta_y & -\dot\Theta_x & 0 \end{bmatrix};\ \tilde\Pi_1 = \begin{bmatrix} 0 & \omega_\zeta & -\omega_\eta \\ -\omega_\zeta & 0 & \omega_\xi \\ \omega_\eta & -\omega_\xi & 0 \end{bmatrix};$$

$\dot{\bar\Theta} = [\dot\Theta_x \quad \dot\Theta_y \quad \dot\Theta_z]^T$ is the vector of FOG output signals; $\bar\omega = [\omega_\xi \quad \omega_\eta \quad \omega_\zeta]^T$ is the vector of angular velocities of rotation of the reference trihedron $o\xi\eta\zeta$ in the geodetic frame [2]. Moreover, when reckoning the coordinates for the wander-azimuth trihedron, $\omega_\zeta = 0$. Components of the vector $\bar\omega$ are determined from the orthogonal components V_ξ, V_η, V_ζ of the relative-velocity vector $\bar V$, which are taken from the solution of the following basic equation of inertial navigation [2]:

$$\dot{\bar V} = C_3^{T}\bar a + \bar g - 2\bar\Omega\times\bar V - \bar\omega\times\bar V - \bar\Omega\times(\bar\Omega\times\bar R), \qquad (2)$$

where $\bar a = [a_x \quad a_y \quad a_z]^T$ is the vector of output signals of accelerometers; $\bar g = [g_\xi \quad g_\eta \quad g_\zeta]^T$ is the vector of gravitational acceleration; $\bar\Omega = [\Omega_\xi \quad \Omega_\eta \quad \Omega_\zeta]^T$ is the vector of angular velocity of the Earth rotation; $\Omega = \|\bar\Omega\|_2^2$; $\bar R = [0 \quad 0 \quad R]^T$ is the IMU position vector; $(\times)$ is the operator of vector product; C_3 is the directional cosine matrix (DCM) which characterizes the angular position of the IMU-fixed frame relative to the reference frame $o\xi\eta\zeta$. In addition, from the elements of the above-mentioned quaternions one can find the angles ψ, ϑ, γ of the IMU angular positon relative to the moving trihedron *oENH* of the geodetic frame, along with the geodetic latitude φ, geodetic longitude λ, and the azimuth A of the trihedron $o\xi\eta\zeta$ relative to the reference point *oENH*:

$$\varphi = arctg[(p_0^2 + p_3^2 - 0.5)/\sqrt{(p_0^2 + p_3^2)(p_1^2 + p_2^2)}];$$
$$\lambda = arctg[(p_2p_3 - p_0p_1)/(p_1p_3 + p_0p_2)];$$
$$A = arctg[(p_0p_2 - p_1p_3)/(p_2p_3 + p_0p_1)].$$

Observations of the invariants have the following form:

$$z_{\Theta(i)} = C_{0(i)}^T \int_{t_{i-1}}^{t_i} \dot{\bar\Theta}(\tau)d\tau - [0 \vdots 0 \vdots \Omega\Delta t_i]^T; \qquad (3)$$

$$z_{C(i)} = [\varphi_i\lambda_ih_i]_{\mathrm{SINS}}^T - [\varphi_i\lambda_ih_i]_{\mathrm{PIA}}^T; \qquad (4)$$

$$z_{V(i)} = [V_\xi V_\eta V_\zeta]_{\mathrm{SINS}(i)}^T, \qquad (5)$$

where PIA stands for the position of the initial alignment; φ_i, λ_i are the geodetic latitude and longitude of the SINS position; $\Delta t_i = t_i - t_{i-1}$ is an observation interval; C_0 is the directional cosine matrix which characterizes the angular position of the IMU-fixed frame relative to the inertial frame.

The vector of the SINS errors comprises 18 parameters, namely: errors in the reckoning of components of the relative-velocity vector; errors in the reckoning of elements both of navigation and attitude quaternions; angular drifts of FOGs; biases of accelerometers, and error in the reckoning of elevation relative to the Earth ellipsoid. In order to increase the timeliness of the SINS errors estimation, observation of the following increments of velocity has also been considered:

$$Z_{\Delta V(i)} = [V_\xi V_\eta V_\zeta]^{\mathrm{T}}_{\mathrm{SINS}(i)} - [V_\xi V_\eta V_\zeta]^{\mathrm{T}}_{\mathrm{SINS}(i-1)}. \qquad (6)$$

The mode of autonomous additional alignment of the SINS-500NS system provides for the refinement of IMU angular position and sensor drifts on a mobile base. For this purpose use is traditionally made of sensors of information that is external (SEI) with respect to the SINS. We propose to use invariants as external information. Such invariants can be formed by updating the observation (3) for the mobile base, namely:

$$z_{\Theta(i)} = \int_{t_{i-1}}^{t_i} \{C^T_{0(i)} \dot{\overline{\Theta}}(\tau)d\tau - C^T_{1(i)}[\overline{\omega}_i(\tau) + \dot{\overline{\delta}}_i(\tau)]\}d\tau -$$

$$-[0 \vdots 0 \vdots \Omega\Delta t_i]^{\mathrm{T}}, \qquad (7)$$

where C_1 is the DCM which characterizes the angular position of the reference trihedron $o\xi\eta\zeta$ relative to the inertial frame; $\dot{\overline{\delta}} = [\dot{\delta}_\xi \dot{\delta}_\eta \dot{\delta}_\zeta]^{\mathrm{T}}$ is the vector of angular velocity of IMU rotation relative to the reference trihedron, i.e.,

$$\dot{\delta}_\xi = \dot{\vartheta}\cos\psi_g - \dot{\gamma}\sin\psi_g \cos\vartheta ; \qquad (8)$$

$$\dot{\delta}_\eta = \dot{\vartheta}\sin\psi_g + \dot{\gamma}\cos\psi_g \cos\vartheta ; \qquad (9)$$

$$\dot{\delta}_\zeta = \dot{\psi}_g + \dot{\gamma}\sin\vartheta . \qquad (10)$$

The attitude angles ψ_r, ϑ, γ are determined from the matrix elements $C_3 = C_0 C_2^T C_1^T$, and their derivatives are determined from the solution of the following equations:

$$\dot{C}_3 = \dot{C}_0 C_2^T C_1^T + C_0 \dot{C}_2^T C_1^T + C_0 C_2^T \dot{C}_1^T ; \qquad (11)$$

$$\dot{C}_0 = \widetilde{\Pi}_0 C_0 ; \; \dot{C}_1(t) = \widetilde{\Pi}_1 C_1, \qquad (12)$$

$$C_2 = \begin{bmatrix} \cos\Omega t & \sin\Omega t & 0 \\ -\sin\Omega t & \cos\Omega t & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad \vartheta = \mathrm{arctg}\frac{C_{3(23)}}{\sqrt{C^2_{3(13)} + C^2_{3(33)}}} ;$$

$$\gamma = \mathrm{arctg}[-\frac{C_{3(13)}}{C_{3(33)}}]; \; \psi_g = \mathrm{arctg}\left[-\frac{C_{3(21)}}{C_{3(22)}}\right],$$

where *t* is the time of SINS functioning; C_0 and C_1 are the DCM determined from the elements of the quaternions $\overline{q}_0$ and $\overline{p}_1$, and their derivatives determined from Eqs. (12); $C_{3(ij)}$ are the elements of the DCM C_3.

In the SINS-500NS system, the navigation problem is solved in the inertial and inertial satellite modes. In both of these modes, the Eqs. (1), (2), and (7) are solved; in addition, in the inertial satellite mode the following observations are formed and processed using the Kalman filter:

$$Z_{C(i)} = [\varphi_i \lambda_i h_i]^{\mathrm{T}}_{\mathrm{SINS}} - [\varphi_i \lambda_i h_i]^{\mathrm{T}}_{\mathrm{SNS}} ;$$

$$Z_{V(i)} = C_4^T [V_\xi V_\eta V_\zeta]^{\mathrm{T}}_{\mathrm{SINS}(i)} - [V_E V_N V_H]^{\mathrm{T}}_{\mathrm{SNS}(i)},$$

where $C_4 = C_2$ when the substitution $\Omega\Delta t = A$ is made.

III. ANALYSIS OF THE RESULTS OF IN-FLIGHT DEVELOPMENT OF SINS-500NS SYSTEM

In-flight experiments were conducted onboard a helicopter beyond the polar circle ($\varphi > 69^0$). The results of comparative analysis were obtained on the basis of motion parameters reckoning from the recorded IMU signals and from data coming from the SNS [4]. The cyclogram of the system operation is as follows: coarse (CIA); fine IA (FIA); navigation mode (*t* > 860 s). Figs. 2, 3 show the following circular position errors of the SINS-500NS system in the inertial mode: in Fig. 2, only after coarse IA; in Fig. 3, after fine IA, additional alignment, and compensation for the estimates of sensor drifts, where

$$\Delta S = \sqrt{\delta^2_\varphi + \delta^2_\lambda} ; \delta_\lambda = (\lambda_{\mathrm{SINS}} - \lambda_{\mathrm{SNS}})R\cos\varphi_{\mathrm{SNS}} ;$$

$\delta_\varphi = (\varphi_{\mathrm{SINS}} - \varphi_{\mathrm{SNS}})R$; *R* is the SINS position vector.

As follows from the figures, in the autonomous navigation mode, the SINS alignment and additional alignment from the observations of invariants (3) – (7) decreased the SINS circular error by no less than an order of magnitude.

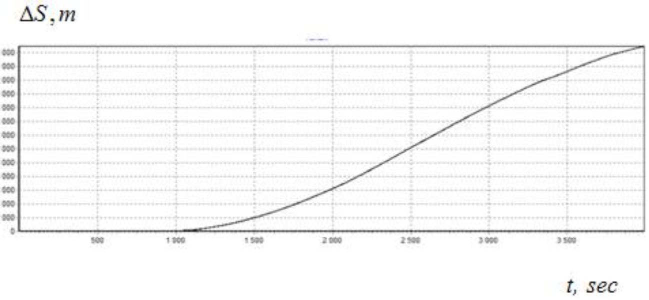

Fig. 2. Circular position error in the inertial mode after CIA ($0 < t_{\mathrm{CIA}} \le 860$ sec)

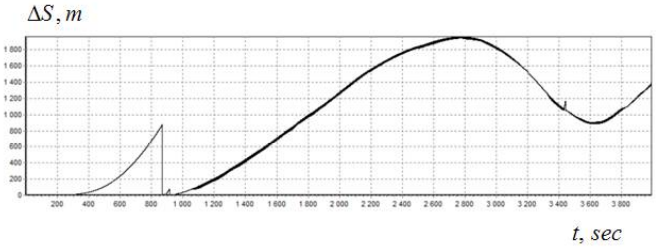

Fig. 3. Circular position error in the inertial mode after FIA ($t_{\text{CIA}} = 0 \div 190$ sec; $190 \text{ sec} < t_{\text{FIA}} \le 860$ sec)

Figs. 4, 5 show the following circular position errors of the SINS-500NS system in the inertial satellite mode: in Fig. 4, in the mode of compensation for all estimated SINS errors; in Fig. 5, in the mode of compensation for estimated residual drifts and estimated biases in sensor signals.

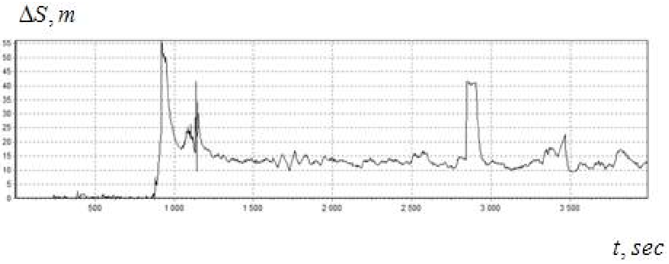

Fig. 4. Position error in the inertial satellite mode after compensation for all estimated SINS errors ($t_{\text{CIA}} = 0 \div 190$ sec; $190 \text{ sec} < t_{\text{FIA}} \le 860$ sec; $t_{\text{SINS + SNS}} > 860$ sec)

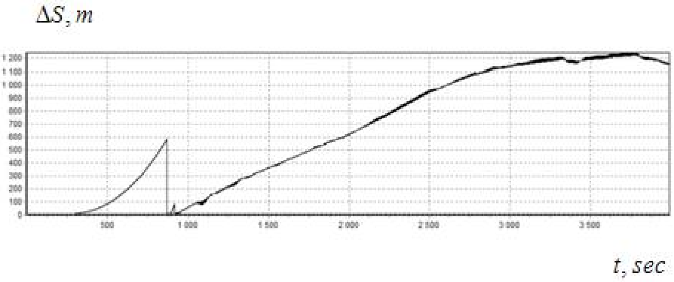

Fig. 5. Position error in the inertial satellite mode after compensation for estimated drifts in sensor signals ($t_{\text{CIA}} = 0 \div 190$ sec; $190 \text{ sec} < t_{\text{FIA}} \le 860$ sec) $t_{\text{SINS + SNS}} > 860$ sec

Some results of sensor drifts estimation are presented in the following figures: in Fig. 6, estimation of the *ox* FOG residual drift is shown; in Fig. 7, estimation of the *ox* accelerometer bias is given.

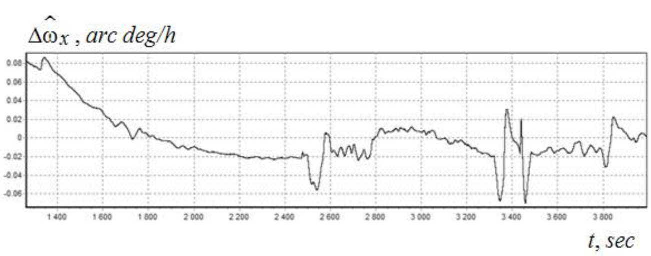

Fig. 6. Estimate of residual drift for the *ox* FOG

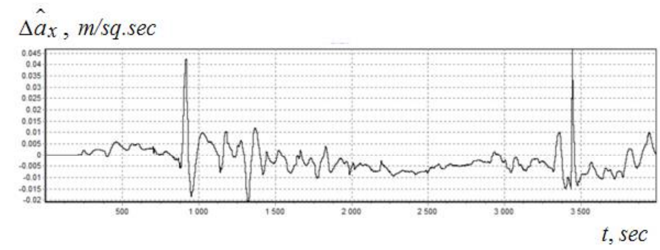

Fig. 7. Estimate of bias for the *ox* accelerometer

IV. CONCLUSION

Improvement of SINS accuracy characteristics at high latitudes can be based on the following upgrades of MBS: the use of quaternion modification of the all-latitude algorithm for coordinates reckoning, as well as its complement [2] on a rectangular grid; SINS initial alignment and additional alignment with the use of invariants; the use of available external information for the sensor drifts estimation and compensation.

REFERENCES

[1] Storozhenko, V.A., Temchenko, M.E., To the Problem of Autonomous Positioning of an Object in Near-Polar Latitudes, Izv. Akad. Nauk SSSR, Mekhanika Tverdogo Tela, 1971, no. 5, pp. 16 – 22.

[2] Babich, O.A., Extension of SINS Algorithms for Solving the Problems of Polar Navigation, Trudy Moskovskogo Instituta Ehlektromekhaniki i Avtomatiki, 2017, no. 19, pp. 18 – 34.

[3] Binder, Ya.I., Blazhnov, B.A., Emelyantsev, G.I., Koshaev, D.A., Staroseltsev, L.P., Stepanov, O.A., Analysis of the Possibility of an Azimuthal Alignment of Borehole Gyro Inclinometers in High Latitudes, Giroskopiya i Navigatsiya, 2013, no. 3, pp. 14 – 23.

[4] Chernodarov, A.V., Patrikeev, A.P., Korkishko, Yu.N., Fedorov, V.A., Perelyaev, S.E., Software Seminatural Development for FOG Inertial Satellite Navigation System SINS-500, Gyroscopy and Navigation, 2010, vol. 1, no 4, pp. 330-340.

[5] Korkishko, Yu.N., Fedorov, V.A., Chernodarov, A.V., Patrikeev, A.P., Perelyaev, S.E., Multilevel Processing of Fiber-Optic-Gyro Signals in Strapdown Inertial Navigation Systems, 15th St. Petersburg International Conference on Integrated Navigation Systems, St: Petersburg, CSRI Electropribor, 2008, pp. 51-53.

[6] Chernodarov, A.V., Kontrol, diagnostika i identifikatsiya aviatsionnykh priborov i izmeritelno-vychislitelnykh kompleksov (Monitoring, Diagnostics, and Identification of Aviation Instruments and Measuring-and-Computing Complexes), Moscow, Nauchtekhizdat, 2017.