FLIGHT DEVELOPMENT OF A GRAVITY-AND-SATELLITE DATA-AIDED INERTIAL NAVIGATION SYSTEM

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Abstract

Key words: inertial navigation, satellite navigation, gravimetry, Kalman filter.

Basic features of constructing a gravity-and-satellite data-aided inertial navigation system (GSINS) are considered. The implementation of the GSINS relies on the integrated use of digital databases on anomalies both of the Earth's gravitational field and of inertial and satellite measurements. As a kernel, the inertial navigation system SINS-500NS based on fiber-optic gyros is included as a component of the GSINS. A technology intended for flight development of the GSINS is described. The studies conducted have corroborated the fact that it is expedient to use digital databases on anomalies of the gravity acceleration in GSINS algorithms.

Analysis of a Gravity-and-Satellite Data-Aided Inertial Navigation System as the Object of Flight Development

At present, the problem of improving the accuracy characteristics of autonomous navigation systems still remains topical. One solution of this problem involves integration of inertial (INS) and geographic information systems which provide navigation by the Earth′s physical fields [1-4]. In [5], present-day approaches to the integration of strapdown INSs (SINSs) and geographic information systems which function over a stretch of terrain were considered.

However, for small terrain gradients along the path of motion, such integration may turn out to be ineffective. In this case, in addition to the aforesaid, it is apparently advisable to use information about the parameters of other Earth′s physical fields, in particular, information about anomalies of the gravity acceleration (GRACC) with respect to the computed one.

Computed values of the GRACC g [6, 7] are determined in the SINS as functions of the following present geographical coordinates: the latitude φ, the longitude λ, and the altitude H of flight above the Earth ellipsoid, i.e.,

$$g = 9.780318\,(1 + 0.0053024 \sin^2 \varphi - 0.59\bullet 10^{-5} \sin^2 2\varphi). \quad (1)$$

Figures 1 and 2 present the plan and profile of the studied flight path of the *ROKO AERO NG-4* airplane (see Fig. 5), where $\Delta\varphi_R = [\varphi(t) - \varphi(t_0)]R$; $\Delta\lambda_R = [\lambda(t) - \lambda(t_0)]R\cos\varphi$; $R = a\,(1 - 0.5e^2 \sin^2 \varphi)$; $a = 6378245\,m$; $e^2 = 0.0066934$. Shown in Fig. 3 is the dynamics of variation of the vertical component Δg of the GRACC anomaly along the path presented, which was obtained from the database [6]. The interpolation of GRACC values between interpolation points was performed with the use of cubic splines. It is seen from Fig. 3 that variations in GRACC anomalies along the path of motion can also be insignificant, and this makes the application of correlation extreme methods of navigation difficult.

At the same time, to improve SINS accuracy characteristics, use can be made of the current values $\Delta\overline{g}$ of GRACC anomalies [6] when solving the basic equation of inertial navigation [7], i.e.,

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$$\dot{\overline{V}} = C^T \overline{a} - 2\overline{\Omega} \times \dot{\overline{V}} - \overline{\omega} \times \overline{V} + \overline{g} + \Delta\overline{g} \ , \tag{2}$$

where $\overline{V}$ is the vector of relative velocity of SINS motion, which is given by its components along the axes of the navigation moving frame (MF); $\overline{a}$ is the vector of output signals of accelerometers; $\overline{g} = \overline{g}_{GR} - \overline{\Omega} \times (\overline{\Omega} \times \overline{R})$ is the vector of GRACC computed values; $\overline{g}_{GR}$ is the vector of gravitational acceleration; $\overline{\Omega}$ is the vector of angular velocity of Earth rotation; $\overline{R}$ is the SINS position vector; C is the direction cosine matrix that characterizes the angular position of the SINS-fixed frame with respect to the geographical moving frame (MF); (×) is the operator of vector product.

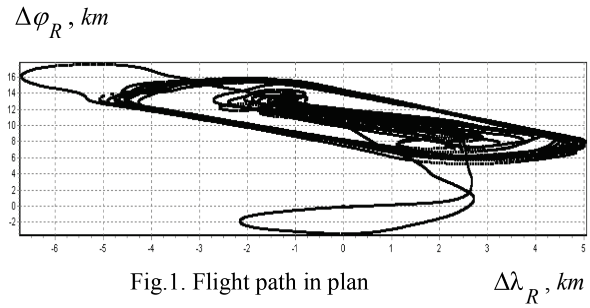

Fig.1. Flight path in plan

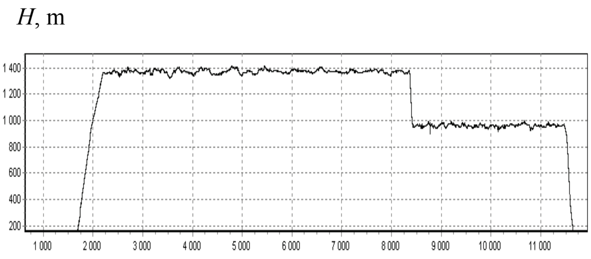

Fig. 2. Flight path profile

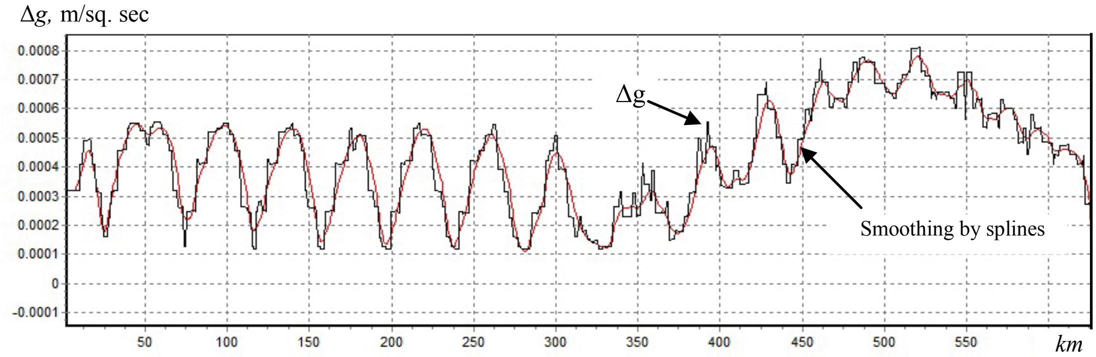

Fig. 3. Dynamics of variation of GRACC anomalies against the distance

The implementation of the proposed approach to the construction of an aircraft (Acft) navigation system is based on the inclusion, in the SINS math-based architecture, of a memory module that contains data about the digital chart of the GRACC anomalies (DCGAA) in the flight path. In this case, the values of GRACC anomalies are read out of the memory module as a function of the present geodetic coordinates. Moreover, the present coordinates can be determined both continuously, by the use of the SINS, and discretely, by a satellite navigation system (SNS). Thus, it is apparently possible to construct a closed gravity-and-satellite data-aided inertial navigation system (GSINS). In such a system, the inertial-and-satellite mode can be considered as a standby mode that is connected with the dynamic calibration and periodic updating of the SINS.

A block diagram of the GSINS is depicted in Fig. 4, where the following notation is introduced: Y_{SNS} is the vector of navigation parameters that are determined by the SNS; Z is the vector of inertial-and-satellite observations [8] of navigation parameters; $\hat{x}$ is the estimate of the vector x of SINS errors; EKF is an extended Kalman filter.

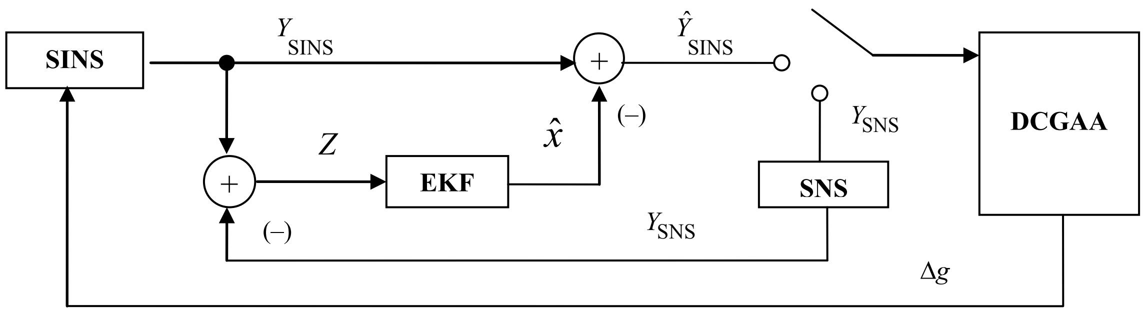

Fig. 4. Block diagram of a gravity-and-satellite data-aided inertial navigation system

According to Fig. 4, in the GSINS, inertial reckoning of Acft motion parameters is performed having regard both to the current values Δg of GRACC anomalies [6] and to the dynamic calibrations of SINS sensors, which were obtained by processing the vector Z of observations. On the other hand, if we compensate for the estimates of biases of SINS accelerometers and if we use the SINS vertical channel, it is apparently possible to determine the GRACC anomalies from the solution of the inverse problem of inertial navigation.

The purpose of this paper is to study the possibilities for the raising of SINS accuracy characteristics on a basis of the use of data about the GRACC anomalies and compensation for the estimates of sensor drifts, which are determined from inertial-and-satellite observations in the process of dynamic calibration.

Analysis of the Results of Studies

For conducting the flight experiment, the SINS-500NS system [8], based on fiber-optic gyros (see Fig. 6) was upgraded for GSINS functions.

Fig. 5. ROKO AERO NG-4 airplane (Czechia)

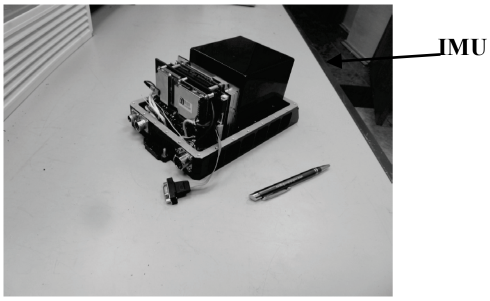

Fig. 6. SINS-500NS system

The following cyclogram of GSINS operation has been implemented: coarse initial alignment (t = 0÷100s); fine initial alignment (100 < t <600s); inertial-and-satellite navigational mode (600 < t < 2000s), which provides SINS additional alignment and estimation of residual drifts of sensors, such as gyros and accelerometers; the mode of autonomous gravity data-aided inertial navigation (t >2000 s), together with compensation for the residual drifts of sensors. The frequency of data updating and data recording is 1 kHz for sensors, and for the SNS, such a frequency is ≤ 1Hz. Some of the results of experiments are presented in the following figures: in Figs. 1, 2, flight path parameters are shown; in Fig. 7, the variation of the component of the vector of path velocity along the o*E* axis of the moving frame *oENH* of the geodetic coordinate system is depicted; in Fig. 8, the angle of true heading; in Fig. 9, estimation of the *ox* FOG residual drift is presented; in Fig. 10, estimation of the *ox* accelerometer bias is given.

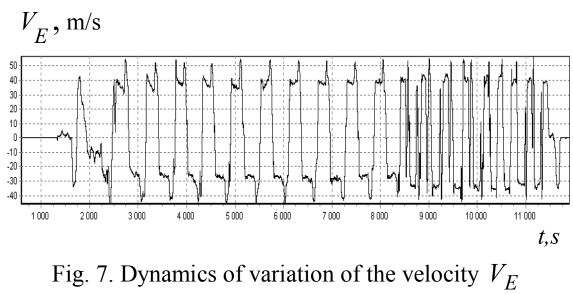

Fig. 7. Dynamics of variation of the velocity V_E

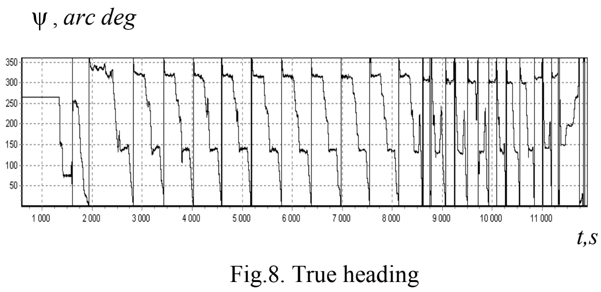

Fig.8. True heading

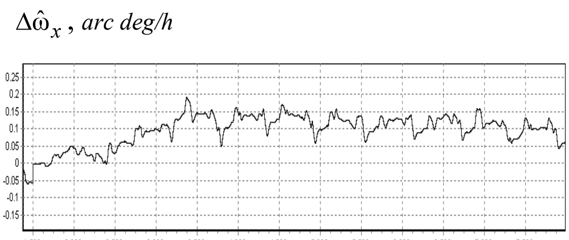

Fig. 9. Estimation of the *ox* FOG residual drift

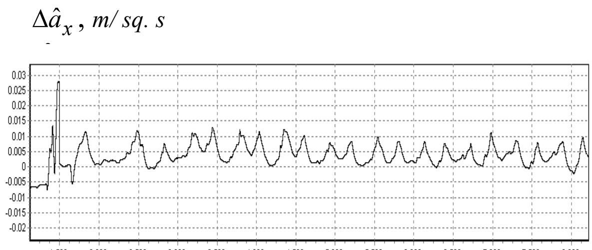

Fig. 10. Estimation of the *ox* accelerometer bias

In Fig. 11 is shown the circular position error ΔS of estimating the Acft position, which corresponds to the reckoning of SINS-500NS motion parameters with no damping of the estimates of sensor residual drifts and also without making corrections for GRACC anomalies in the mode of autonomous navigation, where

$$\Delta S = \sqrt{\delta_{\varphi}^2 + \delta_{\lambda}^2}\,; \qquad \delta_{\varphi} = (\varphi_{\text{SINS}} - \varphi_{\text{SNS}})R\,; \qquad \delta_{\lambda} = (\lambda_{\text{SINS}} - \lambda_{\text{SNS}})R\cos\varphi_{\text{SNS}}\,.$$

Figure 12 shows the circular error ΔS, which conforms to the gravity data-aided inertial reckoning of Acft flight parameters with regard both to the making of corrections for the GRACC anomalies and to the compensation for the estimates of sensor drifts, which were obtained in the process of the fine initial alignment and inertial-and-satellite additional alignment of the SINS-500NS system in flight.

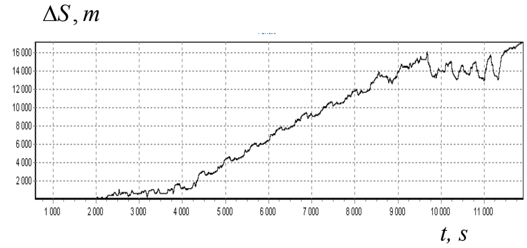

Fig.11. Circular position error with no compensation for the estimates of sensor residual drifts and also without making corrections for GRACC anomalies

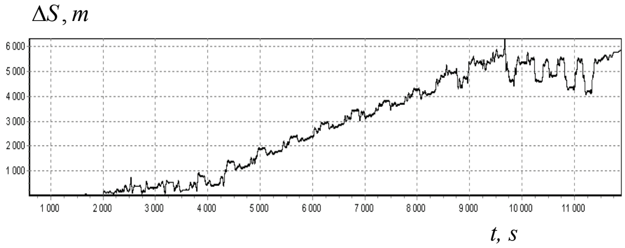

Fig. 12. Circular position error with regard both to the compensation for the estimates of sensor residual drifts and to the making of corrections for GRACC anomalies

One can see that the compensation for the estimates of sensor residual drifts and the making of corrections for the GRACC anomalies have permitted us to reduce the GSINS circular position error in the gravity data-aided inertial mode between the periods of satellite updating by no less than one and a half.

Conclusions

An analysis of the results of GSINS flight development has shown that periodic use of satellite information makes it possible to estimate and to damp the errors of SINS sensors, which remained after factory calibration and the initial alignment. SINS accuracy characteristics can also be improved on a basis of employing, in the math-based software, the following modules: a database on GRACC anomalies; a module for the isolation of and counteraction against faults on the basis of adaptive robust processing of observations [9]. The application of such procedures and such modules has allowed us to maintain the accuracy characteristics of a strapdown gravity-and-satellite data-aided inertial navigation system at a level of one mile per flying hour.

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