TECHNOLOGY AND RESULTS OF TESTS OF THE STRAP-DOWN STAR-INERTIAL UNIT FOR CONTROL SYSTEMS OF SPACECRAFTS*

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Abstract

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The description of design principles of the Strap-down Star-Inertial Unit (SSIU), created in RPE "Hartron-Arkos" on the basis of the fiber-optical gyroscopes (FOG) and star tracker (ST), is given. The methodology of working out of the mathematical model of the temperature drift of FOG, the studying of its sensitivity to the influence of an external magnetic field, the concept of ground tests of ST, technology and the basic results of tests of the SSIU, are presented.

Introduction

The continuous growth of quality requirements of modern control systems of moving objects, in particular, rockets-vehicles and spacecrafts, forces developers of devices to improve their technical characteristics on an ongoing basis. The accuracy of devices is important characteristics. Now devices whose functioning is based on different physical principles are used. At the same time, the forthcoming of new type command devices demands enhancement of their test technology and methodology of definition of technical characteristics, working out of mathematical models [1, 2].

In the present report the description the description of design principles of the Strap-down Star-Inertial Unit, created in RPE "Hartron-Arkos" on the basis of the fiber-optical gyroscopes of type OIUS 501 (Research-Production Company «Optolink», Zelenograd) and star tracker (State Enterprise «Arsenal», Kiev with RPE «Hartron-Arkos»), is presented. SSIU is allotted to determine the projections of the vector of absolute angular velocity of the spacecraft on the axis of the instrument coordinate system (ICS), as well as to determine the quaternion orientation of this coordinate system in inertial space. SSIU consists of an inertial unit (IU), electronic unit (EU), and star tracker.

The aim of the work

The major principle of functioning SSIU is inertial orientation with an astrocorrection [3]. The angular velocity and orientation quaternion of the SSIU ICS are calculated by using the four FOGs. The star tracker SSIU consists of three optical heads. The working configuration ST depends on required accuracy of attitude and can be the follows: minimum - one optical head, average - two optical heads or maximum - three optical heads.

The facade of uncapped SSIU (without ST) is shown in Fig. 1.

The problem was posed: to achieve greater accuracy of the device by research of influence of the main components of the errors of FOG and their further suppression. The investigations were carried out on experimental data of the tests. The purposes of the tests were the following:

- developing a methodology, software and debugging of hardware of the workplace for FOG testing;
- determination of systematic drift of the FOG's zero signal, depending on temperature;
- determination of influence of an external magnetic field on the FOG's indications;
- development of the mathematical model of FOG measurement and its verification for adequacy;
- working off the methodology of ground tests of ST.

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Building the mathematical model of the temperature drift of the FOG

As is known, the temperature is one of the essential factors, which affect the accuracy of the FOG [2, 4]. So the first problem in improving the accuracy of the FOG was part of the problem of determining the displacement of the zero FOG signal as a function of temperature, i.e. building a mathematical model of the temperature drift of the FOG.

The tests to determine the dependence of sensor characteristics of the FOG from temperature were spent in climatic chamber MS-71 (the temperature range was from -80ºC to +105ºC, size – 400×400×400 mm). The zero sensor signal of the FOG at different temperatures in a range of working temperatures of the sensor +10ºC … +30ºC was measured. The obtained values were approximated by a method of the least squares for polynomial model in the space of centered and normalized dimensionless factors Z_k=$Z_k(t)$ (k=1, 2) by using a model of the following structure:

$$\begin{aligned} Y = K_{00} + K_{10}Z_1 + K_{01}Z_2 + K_{11}Z_1Z_2 + K_{20}Z_1^2 + {} \\ K_{02}Z_2^2 + K_{12}Z_1Z_2^2 + K_{21}Z_1^2Z_2 + K_{30}Z_1^3 + K_{03}Z_2^3 \end{aligned}, \qquad (1)$$

where Kij (i, j=0, 1, 2, 3) – the required coefficients (parameters) of the model;

$$Z_k(t) = \frac{X_k(t) - X_{kr}}{X_{k\max} - X_{kr}}, \qquad (k=1, 2)$$

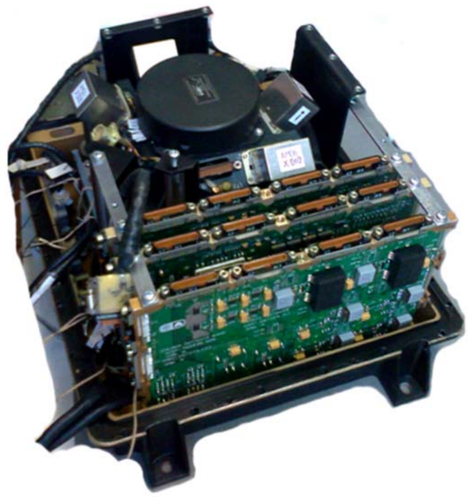

Fig. 1. The facade of uncapped SSIU

where $X_k(t)$ – the current value of k-th factor; X_{kr} – the average (working) value of k-th factor (the basic level of a factor);X_{kmax} – the maximum value of k-th factor.

It was taken as the first factor (temperature T): X_{1r}=20°C, X_{1max}=30°C; and as the second factor (a temperature gradient G) – X_{2r}=0°C/min, X_{2max}=0,25°C/min.

The coefficients $K_{00}, K_{10}, K_{01}, K_{03}$ in the model (1) were chosen after checking the statistical significance of the calculated coefficients K_{ij}, and after assessing the adequacy and accuracy of the model to determine the angular velocity and angular position. The mathematical model of the temperature drift of FOG was created on the basis of the accepted model and knowledge of etalon measurements (a projection of the angular velocity of the Earth on the axis of sensitivity of the FOG at latitude of Kharkov).

The errors in angular velocity estimations δω without indemnification of temperature drift (1) and with indemnification (2) are shown in Fig. 2, the errors in angular position estimations δγ without indemnification (1) and with indemnification (2) in two run by duration on 700 min everyone are shown in Fig. 3. These two runs were combined in one run by duration of 1400 min.

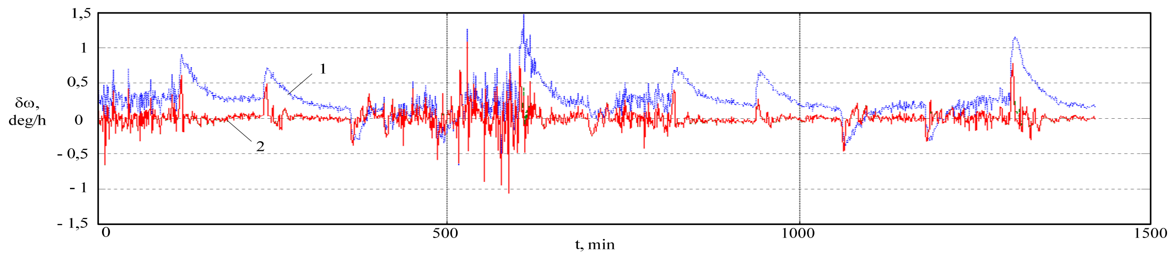

Fig. 2. The graphs of angular velocity estimation errors

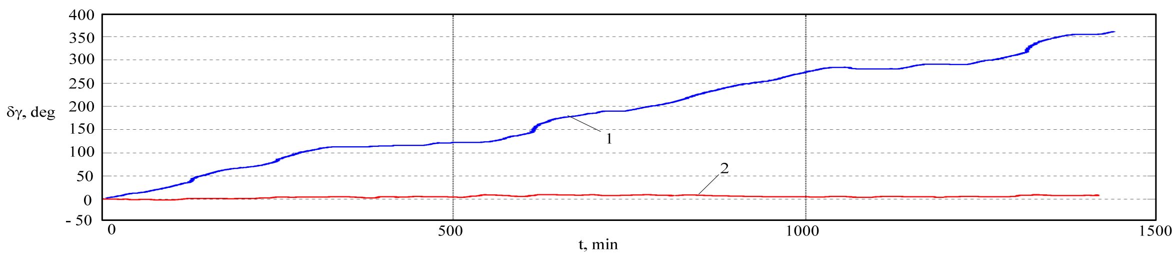

Fig. 3. The graphs of angular position estimation errors

The research of the influence of an external magnetic field

Determination of the influence of an external magnetic field on the testimony of the FOG were performed by using the original method, based on different of the FOG's magnetic sensitivity (channels X and Y), within the inertial unit, and were manifested at different orientations of the inertial unit in the Earth's magnetic field. Changing the orientation of the rotation was carried IU around a vertical axis with a resolution in the azimuthal angle ψ_i (i=1-25) at 15°. The measurements FOG were spent in 25 fixed positions IU at angle ψ_i changing from 0° to 360°.

The model of average measurements of the FOGX and FOGY was represented in the form of [5]:

$$\Omega_{Xi} = \Omega_{\varphi} \cdot \cos(\psi_i + \Delta\psi_0) + \delta\hat{\Omega}_X + A_c \cdot \cos(\psi_i + \Delta\psi_0) + A_s \sin(\psi_i + \Delta\psi_0), \tag{2}$$

$$\Omega_{Yi} = \Omega_{\varphi} \cdot \sin(\psi_i + \Delta\psi_0) + \delta\hat{\Omega}_Y + C_c \cdot \cos(\psi_i + \Delta\psi_0) + C_s \cdot \sin(\psi_i + \Delta\psi_0), \tag{3}$$

where

$$A_c = \mu_{XX} \cdot B_N - \mu_{XY} \cdot B_E;\ A_s = \mu_{XX} \cdot B_E + \mu_{XY} \cdot B_N;\ \delta\hat{\Omega}_X = \delta\Omega_X + \mu_{XZ} \cdot B_H;$$

$$C_c = -\mu_{YY} \cdot B_E + \mu_{YX} \cdot B_N;\ C_s = \mu_{YY} \cdot B_N + \mu_{YX} \cdot B_E;\ \delta\hat{\Omega}_Y = \delta\Omega_Y + \mu_{YZ} \cdot B_H;$$

$\Omega_{\varphi} = \Omega_E \cdot \cos\varphi_0$ – the projection of the Earth rotation angular velocity (Ω_E=15,04°/h) on the axis of the inclined-rotary device (IRD), directed on the North at a latitude of Kharkov (φ_0=50,05° n.l.); ψ_i (i=1-25) – the azimuthal angle of the sensitivity axis of the FOGX; $\Delta\psi_0$ – the error of the initial trim of IU; $\delta\Omega_X$, $\delta\Omega_Y$ – the constant systematic drift of the FOGX, FOGY; B_N, B_E, B_H – the projections of a magnetic induction vector on the northern, eastern and the vertical axes of the local geographical coordinates system respectively;

μ_{jX}, μ_{jY}, μ_{jZ} $(j = x, y)$ – the coefficients of FOGJ's magnetic sensitivity (J=X, Y) to projections of a magnetic induction vector on own sensitivity axis and perpendicular to it.

As a result of data tests processing on the basis of the method of least squares the plot approximating functions $f_j(\psi)$ (j=x, y) for FOGX and FOGY measurements errors were built. It is possible to present them in the following way (the error $\Delta\psi_0$ is small):

$$f_x(\psi) = \delta\hat{\Omega}_x + S_x \sin(\psi + \Delta\varphi_x),\quad f_y(\psi) = \delta\hat{\Omega}_y + S_y \cos(\psi + \Delta\varphi_y), \tag{4}$$

where $\delta\hat{\Omega}_j$ (j=x, y) – the estimation of constant systematic drift of the zero signal of the FOGJ; S_j (j=x, y) – the amplitude of the periodic component of the measurement error of the FOGJ; ψ – the azimuth angle of the FOGX; $\Delta\varphi_j$ (j=x, y) – the phase of the periodic component of the measurement error of the FOGJ.

The amplitude S_j and the phase $\Delta\varphi_j$ are nonlinear functions of the FOG's magnetic sensitivity, and the errors of initial trim of IU on azimuth $\Delta\psi_0$ and projections Ω_φ of the Earth rotation angular velocity vector. The equality S_x=–S_y takes place at small magnetic sensitivity of the FOG. Therefore the difference of amplitudes S_j of periodic components of functions $f_x(\psi)$ and $f_y(\psi)$ was taken for measure of the FOG's magnetic sensitivity.

The differences δf_j (j=x, y) of approximating functions for measurements errors were received at high and low magnetic sensitivity (Fig.4). It was provided with additional shielding of IU for FOGX and FOGY.

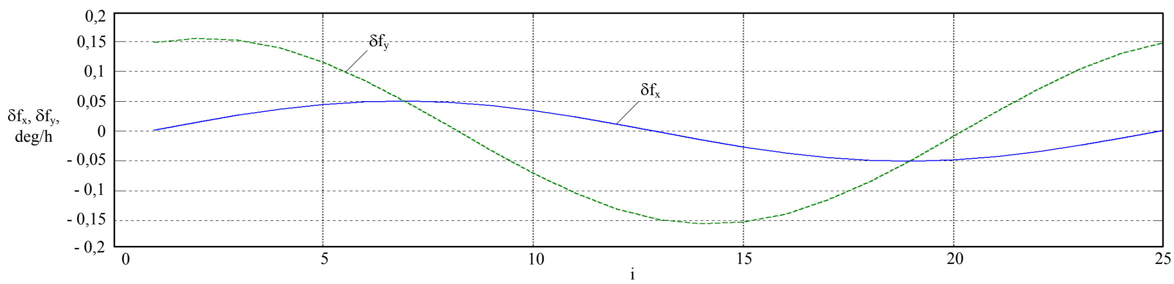

Fig. 4. The graphs of the differences of approximating functions for the measurement errors

The methodology of ground tests of ST

The star tracker of the SSIU is intended for determining of initial orientation definition of inertial unit of the SSIU with its subsequent correction. The each optical head represents the standalone device, whose operating principle is based on registration of a visible star on the CCD-matrix and the subsequent analysis of the received image. The electronics unit performs several tasks on the analysis of input data:

- data acquisition from the CCD-matrix;
- filtering of the received image;
- localization of objects in the image;
- selection of interfering sources and defective pixels.

The following problems are solved in the special processor of the SSIU:

- control of ST as a passive abonent;
- recognition of star images with using of the star catalogue;
- additional selection of interfering sources;
- determining of orientation parameters (quaternion) on the basis of coordinates of the recognized stars from the catalogue and their coordinates fixed on a matrix of the ST.

The concept of star tracker's tests at the physical modeling stand of RPE «Hartron-Arkos» consists in the imitation of star sky by the mask with the apertures that simulate a real site of the star sky. The software for forming of reference orientation quaternion, which corresponds to pictures of the star sky, was developed. The technique of tests consists in comparison of reference orientation quaternion with actual ones, received with the processor of the SSIU at supervision by ST of a simulated site of the star sky.

Conclusion

The mathematical model of dependence of drift of the zero signal of the FOG from temperature and its gradient in the form of the third degree polynomial with constant coefficients was developed. The application of the given model for algorithmic indemnification of temperature drift of the FOG with accuracy of middle class of type OIUS 501, that operates in conditions, similar to test specifications, allowed to reduce regular temperature drift of zero in a run with ±1,0°/h to ±0,05°/h.

The essential influence of an external magnetic field on the FOG's accuracy was revealed. The additional error is about ±0,15°/h. This requires special measures relating to the shielding of the FOG.

The methodology of ground tests of star tracker of SSIU was developed.

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