UDC 625.735.(043.2)

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Double-deck estimation of flight-navigation parameters in inertial-satellite navigation systems for unmanned aerial vehicles

The possibility of using the compensation's schemes in inertial-satellite systems for estimating not only the observed components of the state vector but also the parameters of the angular orientation with simultaneous flight's calibration of the block of inertial sensors is considered.

In solving the problem of data fusion in inertial- satellite navigation systems (ISNS) is the most attractive, of course, Kalman filtering (KF). When applying KF at the filter output, the estimates for the entire state vector are restored, including the systematic components of the errors of the sensors, which makes it possible to perform their flight calibration. However, the use of KF meets certain difficulties in its implementation on board the aircraft. In particular, this divergence phenomenon that occurs when working with unknown stochastic signal at the input of the filter, which is typical for strapdown inertial navigation systems (SINS).

Currently in modern airborne complexes in addition to algorithms for optimal estimation of the state vector (KF algorithms), use of other methods of processing information homogeneous, well proven itself in practice. In particular, this method of mutual compensation (MC). In [1] the filter of MC scheme is proposed, which provides the data fusion of observed navigational components of the state vector, with quality comparable to optimal KF. But when complexing the SINS and the satellite navigation system (SNS) on the basis of the MC method, the angular orientation parameters are not estimated.

The first level estimates the flight parameters - angular orientation parameters, obtained using readings of rather crude micromechanical accelerometers (MMA) and angular velocity sensors (MMAVS).

Using the MMA block as an inclinometer, it's may be use the algorithms of the BINS prelaunch exhibition to determine the angles of the UAV tilt, in particular, the angles of roll and pitch. But the MMA signal even in static mode has a considerable noise component. And given that on a moving object, in addition to the gravity, there are also act other forces caused by accelerations, rotations, shakes, etc., it becomes clear that measure the parameters of angular orientation in flight with the help of accelerometers is a very problematic task.

In the working algorithm of SINS parameters of the angular orientation of the object are determined as integral of output signal of MMAVS. Unlike the accelerometer's method the method of obtaining information on the angles of a roll and pitch by integration the signal of AVS causes a rapidly increasing measurement error due to the presence of a standing error in the MMAVS.

Analysis of output signals ("raw" value of acceleration and integrated value of angular velocity), for one of the axes of the fixed MPU-6050 chip (the MPU-6050 combines a module of inertial MEMS sensors – a three-axis accelerometer and a three-axis gyroscope – on a single silicon crystal) certify the peculiarities of errors in obtaining information about the angular orientation from the MEMS-sensors. On the other hand, the analysis of the output signals of the block MPU-6050 shows that the errors of measuring the parameters of angular orientation with the help of MMA and MMAVS lie in different frequency range. Therefore, the method of compensation is ideally suited for solving the problem of data fusion of two gauges.

The block diagram of the first level of estimation that implements the compensation method for data fusion the gyrovertical (GV) based on the MMAVS and the accelerometric vertical (AV) based on the MMA is presented in Fig. 1.

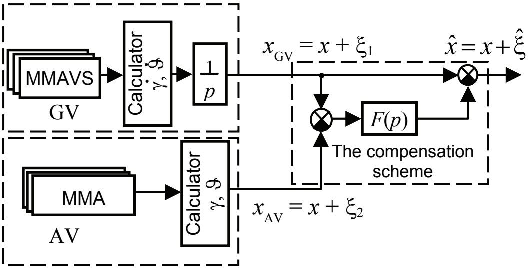

Fig. 1. The first level of estimation

The algorithm for integrated information processing which using the compensation method has a fairly simple view:

$$\hat{x} = x_{GV} - F(p)(x_{GV} - x_{AV})$$

where F(p) is the dynamic filter of the compensation scheme; x_{GV}, x_{AV} are angular orientation parameters are derived from GV i AV ; $\hat{x}$ is the estimate of in question parameter of angular orientation.

If you select the filter $F(p)$ such that it misses the systems error ξ_1 with the minimum distortion and silences the noise ξ_2, then the error in the integrated system will be minimal, that is, the error will be reduced depending on the difference in the spectral characteristics of the errors ξ_1 and ξ_2. With a significant difference in the frequency characteristics of the errors at the output of the filter $F(p)$ (see Fig. 1), will be reproduced completely the error ξ_1, that is, the error of the GV, and at the output of the compensation scheme, the estimate of the parameter will coincide as exactly as possible with the measurable parameter x .

In the work for the compensation scheme, a filter of the form was proposed:

$$F(p) = \frac{3Tp + 1}{(Tp + 1)(Tp + 1)(Tp + 1)} . \tag{1}$$

Unlike the classical aperiodic filter, the transfer function of the low frequencies of such a filter has the form:

$$[1 - F(p)] \approx \frac{T^3 p^3}{T^3 p^3 + 3T^2 p^2 + 3Tp + 1} .$$

Such a filter, providing an astaticism of third order, no longer passes not only the constant component of the GV error, but also the errors that vary according to the laws of the first and second order.

The high-frequency filter $F(p)=\dfrac{3Tp+1}{(Tp+1)(Tp+1)(Tp+1)}$ due to the presence of forcing link ($3Tp + 1$) slightly amplifies the high-frequency component of the AV error, but this is successfully compensated by a triple increase in its filtering properties.

Research of the of the first level of estimation that implements the compensation method with various dynamic filter configurations were carried out by means of mathematical modeling in the Delphi environment. Researches have shown (see Fig. 2) that the proposed third-order filter provides good filtering properties of the complexing circuitry. The filter also provides sufficiently high accuracy characteristics of the estimation of the angular orientation parameters, not even worse than the scheme of optimal Kalman filtration.

The analysis of GV errors (see Fig. 2) shows that they are continuously increasing, so it is expedient to carry out periodic or continuous flight's calibration of MMAVS and correction of GV on the information about the estimated values of the parameters of angular orientation. Estimated values of angular velocity can be obtained from simplified equations [2]:

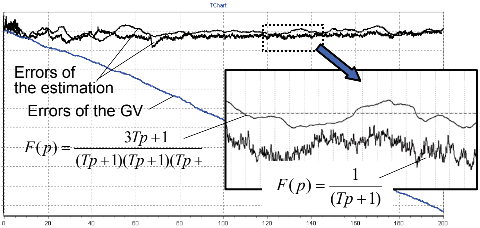

Fig. 2. Research's results of the first level of estimation

$$\hat{\omega}_x \approx \dot{\hat{\gamma}};\quad \hat{\omega}_z \approx \dot{\hat{\vartheta}}\cos\hat{\gamma},$$

where $\hat{\gamma}$, $\hat{\vartheta}$ are estimated values of the roll and pitch; $\dot{\hat{\gamma}}$, $\dot{\hat{\vartheta}}$ are the rate of change of the angular orientation parameters, which is formed by the ordinary differentiation. Here it is taken into account that under certain fixed values of the angular velocity of the turn ψ the compensation scheme is disconnect.

Research's results of the level of estimation of the flight's parameters with simultaneous flight's calibration and correction of the block of inertial sensors are show in Fig. 3. Here, using estimated values of angular velocity and the angular velocity values arriving from MMAVS, the current values of zero drift values of the

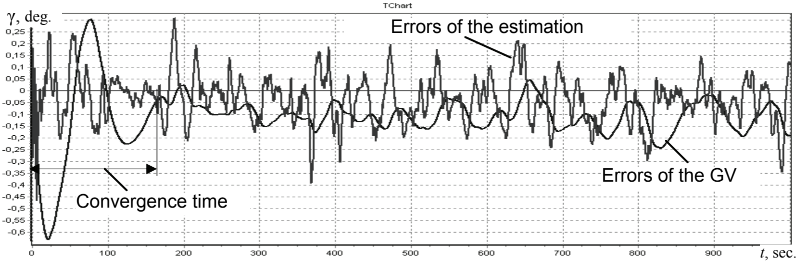

Fig. 3. Research's results of the level of estimation of the flight's parameters with simultaneous flight's calibration and correction of the block of inertial sensors

sensor on the corresponding axes are calculated, which are used for the calibration in the flight of the MMAVS. And for the implementation of the correction of the GV, the difference between the current values of the angular orientation parameters and their estimates is used.

In algorithms of the second level of estimation with the help of information from the SNS, the estimation of the errors of the algorithms of the calculus in the SINS of the coordinates and the flight speed with the subsequent correction of the SINS information is carried out. Such scheme is well known and called invariant integration scheme. Using this scheme the problem to estimate the errors of a subsystem taking into account errors of another is solved.

Here, as for the first level of estimation, the method of mutual compensation is used. As a dynamic filter of the compensation scheme in the coordinate and flight channels, it is proposed to use second-order Butterworth filters, and the compensation of the inertia of the Butterworth filters in the channel of coordinates realize using a signal $\Delta\hat{V}$ from the channel of velocity estimation (see Fig. 3) and in the channel of velocity using a signal $\Delta\hat{a}$ from the channel of horizontal acceleration. Estimate of the horizontal component of acceleration is obtained by data fusion SINS and derivative of velocity signal supplied from the SNS. When differentiating of radio signals of SNS use the usual procedures of filtering for signals corrupted by noise.

In Fig. 4 shows the structure of the dynamic filter F_1 (p) of the MC circuit in the coordinate field. A similar structure has the $F(p)$ filter in the speed channel. In the acceleration channel, the previously proposed filter (1) is used.

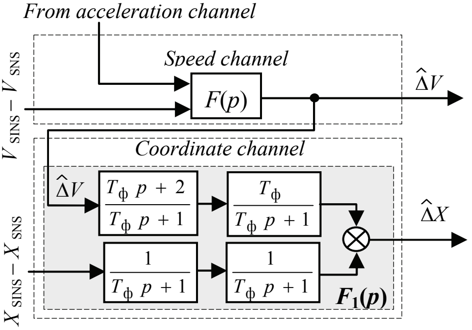

Fig. 4. The structure of the dynamic filter of the MC circuit in the second level of estimation

For the comparative analysis of errors of assessment procedures for evaluating the coordinates and flight speed errors in work, limited to filtration algorithms only in the longitudinal channel, an optimal Kalman filter (FC) was synthesized. When the optimum FC is synthesized the error model of calculating flight parameters can be represented as:

$$\Delta\dot{X} = \Delta V_x;\;\; \Delta\dot{V}_x = \Delta a_x;\;\; \Delta\dot{a}_x = \xi_x$$

where ΔX, ΔV_x, Δa_x – errors of SINS in coordinate and its derivatives, respectively; ξ_x – accelerometer noise given as white noise with intensity S_{ax}.

Observation model will be written as:

$$Z_1 = X_{\text{INS}} - X_{\text{SNS}} = \Delta X + \varsigma_x; Z_2 = V_{\text{INS}} - V_{\text{SNS}} = \Delta V + \varsigma_v;$$

$$X_{\text{INS}} = X^{\text{tr}} + \Delta X;\;\; V_{\text{INS}} = V^{\text{tr}} + \Delta V; X_{\text{SNS}} = X^{\text{tr}} + \varsigma_x;\;\; V_{\text{SNS}} = V^{\text{tr}} + \varsigma_v.$$

The solution of given problem is the continuous reduced Kalman filter:

$$\Delta\dot{\hat{X}} = \Delta\hat{V} + K_{\text{ф}1}(Z_1 - \Delta\hat{X});$$

$$\Delta\dot{\hat{V}} = \Delta\hat{a} + K_{\text{ф}2}(Z_2 - \Delta\hat{V});$$

$$\Delta\dot{\hat{a}} = K_{\text{ф}3}(Z_1 - \Delta\hat{X});$$

Here: X_{INS}, V_{INS} – coordinate and velocity measured by SINS; X_{SNS}, V_{SNS} – coordinate and velocity obtained from SNS receiver; X^{tr} – true value of coordinate; ΔX, ΔV – errors of SINS which are considered as systematic errors caused by gyroscope drifts and inaccuracy of accelerometers; ς_x, ς_v – white's noise components of SNS receiver; $K_{\text{ф}i}$, $i = \overline{1,3}$ – coefficients of filtering, which can be obtained as constants from steady-state Riccati equations.

The simulation results which show errors estimation of coordinate and velocity on an enlarged scale for the different variants of integration shows in Fig. 5.

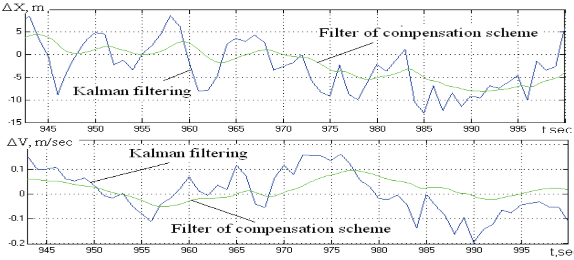

Fig. 5. Research's results of the level of estimation of the flight's parameters with simultaneous flight's calibration and correction of the block of inertial sensors

The comparative analysis of the simulation results shows that, by the accuracy of the error estimate of the coordinate and velocity, the proposed compensation scheme with the dynamic filter F2 (p), which is based on the second-order Baterworth filter, is not inferior to the scheme of optimal Kalman filtration, but even exceeds the quality of filtration of the noise components of the SNS.

Conclusions. The two-level estimation of the flight-navigational parameters proposed for the ISNS, which using a mutual compensation scheme with different variants of dynamic filters at each level, is not inferior to the optimal Kalman filtering on the accuracy characteristics of the of data fusion and even surpasses it in filtering the noise components of the SNS. Fight's calibration of the block of inertial sensors with simultaneous correction of MMAVS significantly increases the autonomous operation time of the navigation system of an unmanned aerial vehicle.

References

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2. M.K. Filyashkin, M.P. Mukhina "Gyro-accelerometric method of determination of angular orientation parameters" Systems of control, navigation and communications, no. 2 (30), 2014. pp. 56 -62.