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Algorithms for Complexing an Inertial Navigation System with Angular Acceleration Sensors

Abstract

In this paper the problem of increasing the accuracy of inertial navigation system of an aircraft in the absence of high-precision additional information sensors, such as GPS, has been studied. It is proposed to install angular acceleration sensors on the gyro-stabilized platform of the inertial navigation system. The use of signals from the angular acceleration sensors made it possible to generate correction signals for the inertial navigation system. Correction algorithms have been developed in the structure of the inertial navigation system and in its output signal. The effectiveness of the developed algorithms has been demonstrated using semi-natural simulation with the Ts060K inertial navigation system.

Keywords: *aircraft, inertial navigation system, angular acceleration sensor, correction, error compensation algorithms, semi-natural simulation*

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Алгоритмы комплексования инерциальной навигационной системы с датчиками угловых ускорений

Исследована задача повышения точности платформенной инерциальной навигационной системы летательного аппарата в условиях отсутствия высокоточных дополнительных датчиков информации, например GPS. Предложено установить на гиросtabilизированную платформу инерциальной навигационной системы датчики угловых ускорений. Использование сигналов с датчиков угловых ускорений позволило сформировать сигналы коррекции для инерциальной навигационной системы. Разработаны алгоритмы коррекции в структуре инерциальной навигационной системы и в ее выходном сигнале. Эффективность разработанных алгоритмов продемонстрирована с помощью полунатурного моделирования с инерциальной навигационной системой Ц060К.

Ключевые слова: *летательный аппарат, инерциальная навигационная система, датчик угловых ускорений, коррекция, алгоритмы компенсации ошибок, полунатурное моделирование*

Introduction

Aircraft control is carried out on the basis of information about its location, speed, acceleration and orientation angles. This information is obtained from various measuring systems. Aircraft measuring systems are based on various physical principles [1, 2], one of the most common types of aircraft measuring systems are gyroscopic systems [1, 3]. Gyroscopic systems, in particular gyro-stabilized platforms (GSPs), make it possible to materialize the accompanying trihedron of coordinate system in which the parameters of orientation and navigation of the aircraft are determined. For example, an inertial navigation system (INS) consists of a GPS and accelerometers installed on it [4, 5]. With the help of the GPS, the given orientation of accelerometers along the axes of accompanying trihedron of selected coordinate system is determined. INS tuned to the Schuler period is invariant to horizontal accelerations, but its errors increase with time, which is due to gyroscope drift, zero offset and accelerometer drift, as well as other perturbing factors. INS with high-precision gyroscopes and accelerometers has higher accuracy, however cost more. When the applied INS on aircraft with elements of low accuracy, the accuracy of INS can be significantly improved by attracting additional information from various sensors and systems.

Currently, for the correction of aircraft measuring complex, it is usually proposed to use classical estimation algorithms. As a rule, this is the Kalman filter and its various adaptive modifications [6–8]. However, these filters can not allow correction of aircraft measuring complex when the signal from an external source is temporarily absent. Over time, the GSP deviation angles increase and the parameter readings of INS become unreliable [1, 9], and a significant increase in the accuracy characteristics of INS can be achieved with the corrective devices [10, 11].

The reference coordinate system is implemented by GSP. However, the GSP deviates from the given position due to gyroscope drift, zero offset and accelerometer drift, and errors of the first integrator. A significant increase in the angles of deviation of GSP leads to the drift of GSP, in this case, moments of residual imbalance around the precession axes of gyroscopes, anisoelectricity of the GSP, and gyroscopes during oscillation and vibration of the base all will lead to the drift of GSP. Considering that errors of the autonomous INS increase with time, in order to obtain reliable information about the orientation of aircraft, it is necessary to

compensate for deviations of GPS from the given position.

The most common INS correction scheme involves the application of Global Positioning System (GPS) [12, 13], while, GPS signals are subject to active and passive interference, therefore, it is not possible to receive reliable navigation information from GPS.

In the absence of GPS signals, other sensors can be considered and applied to correct INS, for example, angular acceleration sensors (AAS). The use of AAS for integration with INS can significantly improve the accuracy of navigation information and information about the orientation of aircraft with low-cost INS elements. For that, algorithms for INS complex with AAS need to be developed. The paper proposes two algorithms for complexing. The first correction algorithm in the INS structure, and the second algorithm can help to carry out a correction in the INS output signal.

The efficiency of the developed algorithms for complexing has been validated through semi-natural simulation. Two series of experiments are conducted with a serial INS Ts060K: the first series — INS is installed on a fixed base, and the second ones — INS is installed on the stand and the mode of the oscillating base is set. Results of the experiment are presented in this paper, the accuracy of INS with AAS is compared with an autonomous INS, an INS with correction in the output signal using an adaptive Kalman filter [6–8] and an INS with correction in the structure using a controller [14, 15]. When correcting the INS with Kalman filter and the controller, GPS signals are used, this correction is often applied and allows to get the highest possible accuracy. When there are no GPS signals, it is suggested to use AAS. The possibilities of the developed algorithms are shown in comparison with INS without correction and INS and GPS with the most effective correction.

This paper organizes as following structure. The first section is devoted to the development of an algorithm for integrating INS with AAS and a correction algorithm in the INS structure is formed. In the second section, a method for correcting the output signal of INS is proposed. The third section contains information about a semi-natural experiment that proves the effectiveness of the developed algorithms. The conclusions contain a brief summary of the work.

Prospects for further research are related to the study of proposed algorithms under the conditions of a flight experiment, as well as a more detailed study of the processes of accumulation of INS errors using nonlinear INS error equations

Algorithm for complexing INS with AAS during correction in the structure of INS

Improving the stabilization accuracy of GSP used in the INS is achieved by introducing a significant number of corrections to the readings of system elements during the prelaunch preparation of INS. The introduction of corrections is associated with the accuracy of their calculation and implementation, in addition, with the scarce time consumption. In this regard, there is a need to find other methods to improve the accuracy of GSP. One of such methods can be the use of angular acceleration sensors (AAS) as such external information sensors in the INS correction scheme. The installation of three AAS devices with orthogonal measuring axes on the GSP allows obtaining information about the angular movements of GSP, which can be implemented to correct the position of platform in space.

In this scheme, correction will be carried out by applying signals, the signals are generated according to the readings of AAS both to the corresponding torque sensors of GPS gyroscopes, and to the output information of INS. Therefore, It is possible to correct the signals of accelerometers installed on the GSP or their integrals with time.

The possibility of correcting INS of GSP by introducing information from AAS is considered. Installing three AAS with orthogonal measuring axes on the GSP allows to obtain information about the deviations of GSP from the initial position in inertial space. Signals received from AAS in the formation of corrective signals are delivered to the corresponding torque sensors of gyroscopes, and will lead to the precession of GSP in the direction of reducing stabilization errors. Here we consider such possibilities on the example of a simplified equation of AAS motion and the precessional motion of one GSP channel:

$$k_m \theta = J_m \ddot{\alpha} M_m; \quad H \dot{\alpha} = M_\delta + M_k, \quad (1)$$

where α — angle of deviation of GSP from the initial position in inertial space; θ — angle of deviation of the sensitive mass of AAS relative to the GSP; H is the own kinetic momentum of GSP gyroscope; k_m — rigidity of electric spring of AAS; M_δ — external perturbing moment around the gyroscope precession axis; M_k — corrective moment around the gyroscope precession axis; J_m — inertial moment of the sensitive mass of AAS relative to the suspension axis; M_m — external perturbing moment around suspension axis of the sensitive mass of AAS.

The correction signals are generated from information of ASS, and they are transferred to the torque sensor of GSP gyroscope: $M_k = M_k(\theta)$. Then expressions (1) can be written in the following form:

$$\left. \begin{aligned} \dot{\alpha} &= \frac{M_k(\theta)}{H} + \frac{M_\delta}{H} \\ \theta &= -\frac{J_m}{k_m} \ddot{\alpha} + \frac{M_m}{k_m} \end{aligned} \right\} \quad (2)$$

suppose

$$M_k(\theta) = k_2 \iint \theta(dt)^2. \quad (3)$$

Substitute eq. (3) in the second equation of system (2), and then into the first equation of system (2), we have

$$\dot{\alpha} + \frac{J_m k_2}{H k_m} \alpha = \frac{M_\delta}{H} + \frac{k_2}{H k_m} \iint M_m(dt)^2.$$

For the case in conditions

$$M_p^* = \text{const}; \quad M_m^* = \text{const}; \quad \alpha(0) = \alpha_0.$$

The solution of equations has the following form:

$$\begin{aligned} \alpha(t) &= -\frac{H k_m M_m^*}{J_m^2 k_2} t + \frac{M_m^2}{2 J_m} t^2 + \\ &+ \left(\frac{k_m M_\delta^*}{J_m k_2} + \frac{H^2 k_m^2}{J_m^3 k_2^2} \right) \left(1 - e^{-\frac{J_m k_2 t}{k_m}} \right) + \alpha_0 e^{-\frac{J_m k_2 t}{k_m}}. \end{aligned}$$

Thus, when GSP is corrected in eq. (3), the perturbing moments around gyroscope precession axes no longer lead to an increase in GSP stabilization errors, but the systematic errors of AAS still have a significant effect on the stabilization accuracy. In this situation, when the systematic errors of AAS are small or practically absent, which is possible with an appropriate choice of the coefficient k_2 , a significant increase in the accuracy of GSP stabilization compared to an uncorrected system can be obtained, and for this, an inequality should be satisfied as

$$k_2 \gg \frac{k_m M_\delta^*}{J_m}.$$

The possibilities of GSP correction based on information from AAS to improve accuracy of GSP stabilization are largely related to the accuracy of AAS. High-precision AAS will reduce GSP stabilization errors caused by the systematic drift of gyroscopes. Also, it follows from this that the GSP corrected by AAS signals in the form (3) does not require the installation of precision gyroscopes on it.

Correction of ins by ass signals in the output signal of ins

Now we consider correction of the output information of INS accelerometers by the signals of AAS. The output information of INS accelerometers are apparent accelerations, measuring axes of accelerometers are rigidly connected to the GSP. Therefore, in the presence of GSP stabilization errors, accelerometers that measure the apparent accelerations of basic motion not along the axes of accompanying trihedron by the accepted navigation coordinate system, but along the axes rigidly connected to GSP, and which depend on the GSP stabilization errors will be contained in the output information components.

Define that $\dot{v}_\xi, \dot{v}_\eta, \dot{v}_\zeta$ are projections of apparent motion acceleration on the axis of accompanying trihedron, $\dot{v}_x, \dot{v}_y, \dot{v}_z$ are projections of apparent acceleration on the axis of GSP. Taking into account the matrix of direction cosines [16, 17], following dependencies between the indicated projections are obtained:

$$\begin{aligned}\dot{v}_x &= \dot{v}_\xi + \dot{v}_\eta \alpha - \dot{v}_\zeta \mu + \Delta \dot{v}_x, \\ \dot{v}_y &= \dot{v}_\eta - \dot{v}_\xi \alpha + \dot{v}_\zeta \beta + \Delta \dot{v}_y, \\ \dot{v}_z &= \dot{v}_\zeta + \dot{v}_\xi \mu - \dot{v}_\eta \beta + \Delta \dot{v}_z.\end{aligned}\quad (4)$$

Here $\Delta \dot{v}_i$ ($i = x, y, z$) are accelerometer measurement errors. Thus, stabilization errors in GSP lead to errors in determining the projection of apparent acceleration on the axis of accompanying trihedron, and we designate them as

$$\begin{aligned}\delta v_x &= v_\eta \alpha - v_\zeta \mu + \Delta v_x, \\ \delta v_y &= -v_\xi \alpha - v_\zeta \beta + \Delta v_y, \\ \delta v_z &= v_\xi \mu - v_\eta \beta + \Delta v_z.\end{aligned}\quad (5)$$

The task is about at least partially compensate for the errors by eq. (5).

Information from the AAS, and measuring axes of which are collinear to the axes of GSP, will makes it possible to generate compensation signals that are close in magnitude to the errors in eq. (2), and thereby partially compensate them.

If the signal from AAS is formed by analogy with (3) and presented in the following form:

$$\begin{aligned}u_x &= -k_3 \iint \theta_x(dt)^2, \\ u_y &= -k_3 \iint \theta_y(dt)^2, \\ u_z &= -k_3 \iint \theta_z(dt)^2,\end{aligned}\quad (6)$$

where

$$\begin{aligned}\theta_x &= -\frac{J_m}{k_m} \ddot{\beta} + \frac{M_{xm}}{k_m}, \\ \theta_y &= -\frac{J_m}{k_m} \ddot{\mu} + \frac{M_{ym}}{k_m}, \\ \theta_z &= -\frac{J_m}{k_m} \ddot{\alpha} + \frac{M_{zm}}{k_m}.\end{aligned}\quad (7)$$

Coefficient k_3 is chosen as $k_3 = \frac{k_m}{J_m}$.

Taking into account coefficient k_3 , after substituting expressions (7) in (6) and integration, the expressions for signals with AAS can be obtained in following expression:

$$\begin{aligned}u_x &= \beta - \frac{1}{J_m} \iint M_{xm}(dt)^2, \\ u_y &= \mu - \frac{1}{J_m} \iint M_{ym}(dt)^2, \\ u_z &= \alpha - \frac{1}{J_m} \iint M_{zm}(dt)^2.\end{aligned}\quad (8)$$

The constants of integration are considered in the last components.

Using information from accelerometers and AAS located on the GSP, it is possible to generate compensation signals $\delta \dot{v}_{xk}, \delta \dot{v}_{yk}, \delta \dot{v}_{zk}$ according to the following rules:

$$\left. \begin{aligned}\delta \dot{v}_{xk} &= \dot{v}_y u_z - \dot{v}_z u_y \\ \delta \dot{v}_{yk} &= -\dot{v}_x u_z + \dot{v}_z u_x \\ \delta \dot{v}_{zk} &= \dot{v}_x u_y - \dot{v}_y u_x\end{aligned}\right\} \quad (9)$$

The supply of signals in eq. (9) with opposite signs to the output information of INS accelerometers means allow to compensate for the main components of errors.

INS correction in the output information has an advantage over correction in the system structure, since it does not affect the GSP dynamics. The integration of INS in AAS could improve the accuracy of obtaining navigation information about the aircraft. The presented method is expedient to apply in conditions when information about the navigation parameters of a dynamic object cannot be received from more accurate sensors, such as GPS.

Results of semi-natural simulation

For the purpose of checking the function performance and quality of the proposed algorithms,

results of semi-natural simulation with a real INS Ts060K are used. In the process of installing INS on the basis of the stand, the accuracy characteristics of system in statics are determined.

Since the system is installed on a fixed base, the position and velocity outputs are correspondingly INS errors. Navigation information is removed from the output and display unit visually after 5 minutes.

At the output of INS, errors in velocity, the deviation angles of GSP from the horizon plane are registered.

Modeling according to the data of a laboratory experiment is carried out using a nonlinear Kal-

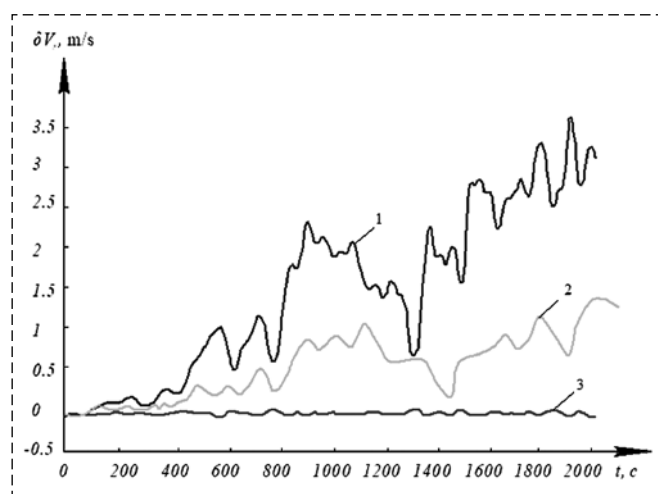


Fig. 1. The simulation result of INS error in offline mode and with correction, where 1 — INS error in determining velocity in autonomous mode (without correction); 2 — INS error in determining velocity after correction using the control algorithm [18–20]; 3 — INS error with correction in the structure from AAS



Fig. 2. Deviation angles of GSP, where 1 — deviation angles of GSP of the real system; 2 — estimations of the GPS deviation angle using adaptive Kalman filter [3]; 3 — deviation angle of GPS with correction from AAS in the output signal

Accuracy of INS correction using AAS in the structure, and a linear adaptive Kalman filter

Complexing system INS + AAS in structure	Correction accuracy on a fixed base 65 %	Correction accuracy on a oscillating base 68 %
INS + AAS in output signal	70 %	60 %
INS + GPS	85 %	72 %

man filter. The simulation results are presented in Fig. 1, 2.

The correction accuracy of INS using AAS, linear adaptive Kalman filter is shown in the Table.

When the INS is corrected by GPS signals with Kalman filter, the measurement sample contained 15 % of anomalous measurements.

Analysis of simulation results

The results of semi-natural modeling have demonstrated high efficiency of the developed complexing algorithms, accuracy of INS correction using GPS and the adaptive Kalman filter is the highest. While when it is not possible to use GPS signals, an autonomous INS is applied. Autonomous INS errors are large and increase over time. Therefore, it is proposed to reduce them by combining INS with AAS, and complexing algorithms have been developed. The effectiveness of the proposed correction algorithms is explained by the fact that in the absence of GPS signals, it is possible to increase the accuracy of navigation determinations of aircraft velocity by an average of 30 %; angle of deviation of the GSP — 45 %. These values are obtained in comparison with the autonomous INS Ts060K.

Conclusion

Simple algorithms for combining INS and AAS have been developed in this paper. These algorithms could carry out INS correction in the absence of high-precision additional navigation systems such as GPS. Algorithms for integrating INS with AAS are proposed, which make it possible to carry out correction in the INS structure and in its output signal. The effectiveness of the proposed algorithms has been verified using a semi-natural experiment with a serial platform INS Ts060K. Based on the results of experiment, it can be concluded that the integration algorithm in the INS structure is more accurate under the conditions of aircraft maneuvering. In the horizontal flight of the aircraft at a

constant velocity, the correction algorithm in INS output signal shows a higher accuracy. For further verification, this conclusion needs to be confirmed under the conditions of a flight experiment.

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