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DAMPED MICROMECHANICAL HYROVERTICAL

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Abstract—*The article considers the methods for vertical gyro construction on rough microelectromechanical elements, such as: angular velocity sensors and accelerometers. It is proposed to improve the accuracy of the microelectromechanical vertical gyro by combining it with a satellite navigation system. The solutions proposed in the article make it possible to improve the accuracy of the integrated vertical gyro based on micromechanical technologies, by the means of complex data processing that uses a compensation scheme with the latest dynamic filter, which practically does not distort the errors of the strapdown inertial microelectromechanical vertical gyro, and thus obtain an estimate of the ground speed as close to the true speed as possible. Based on the obtained estimate, it is proposed to construct a scheme of the vertical gyro speed correction (damping scheme), which would significantly improve the accuracy of estimation of the angular orientation's parameters.*

Index Terms—Integration; compensation scheme; speed correction; strapdown inertial navigation system; vertical error.

I. INTRODUCTION

While analyzing the primary information sensors of existing attitude and heading reference system and strapdown inertial navigation systems (SINS), it can be noted that they belong to the class of precision sensors, and therefore quite expensive, in addition, they are not suitable for modern microsatellites, microprobes, micro rovers and miniature unmanned aerial vehicles (UAVs) due to their weight and size parameters.

Therefore, nowadays, apart from precision accelerometers and angular velocity sensors in SINS, there is an increasing use of rather rough but microminiature primary information sensors, which are manufactured using micro-electromechanical systems (MEM) technologies that are close to the technologies of large integrated microcircuits. They get mass-produced and cost as much as other microcircuits – a few or tens of dollars.

However, the main disadvantage of microminiature information systems, to which the inertial MEM vertical gyro can be referred, is low accuracy. That is why the currently formed practice of creating such information systems is based on their integration with more accurate, but less informative systems.

As studies show, the most perspective system for integration with SINS is a satellite navigation system (SNS). Their joint use allows, on the one hand, to limit the growth of SINS errors, and, on the other hand, to reduce the noise component of SNS errors, increase the rate of information delivery to onboard consumers, and significantly increase the level of noise immunity. Therefore, when constructing a rough MEM-vertical gyro, it is proposed to integrate it with the SNS.

When solving the problem of complex information processing in integrated information systems, the leading role is undoubtedly given to Kalman filtering. Nevertheless, the use of the Kalman filter encounters certain difficulties in its practical implementation on board of an aircraft. However, in addition to optimal state vector estimation algorithms, there are now other integration methods, in particular, the method of mutual compensation, which has proven itself in practice.

The main advantage of Kalman filtering is that with equipment integration its output restores the estimates of the entire state vector, including the angular coordinates, i.e. it improves the accuracy of the angular orientation.

However, in our opinion, even when applying the compensation scheme in conjunction with velocity correction schemes, there is a possibility to improve the estimation accuracy of angular orientation parameters of the primary MEM-vertical gyro.

II. PROBLEM STATEMENT

Due to the fact that the vertical in SINS is modeled by accelerometer signals through integral correction with further tuning to the Schuler frequency, the presence of instrumental and methodological errors causes undamped oscillations with Schuler period in its structure (thus ensuring the system is invariant to the action of horizontal linear accelerations). These oscillations create errors in attitude, speed and coordinates readings. Thus, SINS is an oscillatory system that needs damping. However, development of autonomous SINS damping methods without involvement of other sources of information leads to the loss of SINS invariance with respect to linear accelerations influencing the object.

The most common methods of SINS damping are those based on integration with other sensors of non-inertial nature. The effective methods are those that eliminate or reduce Schuler period oscillations in SINS by adjusting it from SNS receivers.

The block diagram of integration of SNS and strapdown inertial MEM-vertical gyro (SIMVG), which implements the compensation method together with the correction scheme, is displayed in Fig. 1.

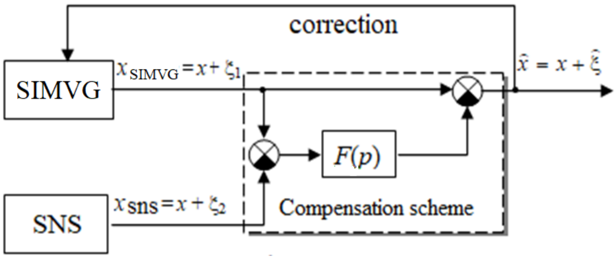

Fig. 1. Block diagram of SNS and strapdown inertial MEM-vertical gyro integration

The algorithm for complex information processing, which uses the compensation method, has a rather simple form compared to the optimal Kalman filtering:

$$\hat{x} = x_{\text{SIMVG}} - F(p)\left(x_{\text{SIMVG}} - x_{\text{SNS}}\right),$$

where $F(p)$ is the dynamic filter of the compensation scheme; $x_{\text{SIMVG}}, x_{\text{SNS}}$ are navigation parameters received from SINS and SNS (strapdown vertical gyros are built according to SINS algorithms and are able to generate, besides the angular orientation parameters, navigation parameters, and ground speed components, in particular); $\hat{x}$ is the evaluation of this navigation parameter.

If the filter $F(p)$ is selected so that it passes interference ξ_1 with minimal distortion and suppresses interference ξ_2, then the error of the complex system will be minimal, i.e. the error decreases according to the difference in the spectral characteristics of interferences ξ_1 and ξ_2. If the difference in frequency characteristics of interference is significant, the output of filter $F(p)$ (see Fig. 1) will fully reconstruct interference ξ_1, that is the SIMVG error, and at the compensation scheme output the estimation of the navigation parameter will match the measured parameter x as closely as possible.

The task can be defined as follows: using the latest dynamic filter in the compensation scheme, which practically does not distort the SIMHV errors, to obtain estimate of the ground speed as close to the true speed as possible. Based on the reproduced estimate, to form SIMVG velocity correction scheme (damping scheme), which would significantly improve the accuracy of estimation of the angular orientation parameters obtained from the primary inertial MEM-vertical gyro.

III. PROBLEM SOLUTION

In contrast to Kalman filtering, the inertial-satellite navigation systems integration based on the compensation scheme is more fast-acting, and most importantly, non-critical to non-stationary random processes, likedrifts of real SINS primary information sensors, and in addition,it can be quite easily implemented in on-board CPUs. Results of studies of compensation schemes [4] with a first-order dynamic filter in the form of an aperiodic link $F(p) = 1/(Tp+1)$ show that the estimate of initial parameters is incomparably smaller than the error of the SINS itself. However, compared to the SNS error, there is a change in the compensation scheme error over time. The maximum is reached at half the Schuler period time.In this case, the error is approximately twice the error of the reference system (SNS). This is explained by the fact that the SINS error, caused by the angular velocity sensor error, apart from the component that changes with the Schuler period, has a component that increases in proportion to time. The first-order low-pass filter, on the other hand, is effective only for constant, time-invariant errors. However, a more complex third-order filter such as:

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

no longer passes though not only the constant component of the SINS error, but also errors that change according to the laws of the first and second orders. It also provides good filtering properties of the integration scheme and fairly high accuracy characteristics of current coordinates estimates, not worse than the optimal Kalman filtering scheme [1]. It is these estimates that are used in damping schemes of inertial MEM-vertical gyro.

A simple one-component inertial MEM-vertical gyro scheme was used to conduct studies of velocity correction schemes. The inertial attitude and heading reference system is constructed using algorithms similar to those of SINS, therefore, when obtaining simplified algorithms for a single-component inertial vertical, the well-known SINS algorithms [2] were used. The three-component SINS algorithms were simplified and reduced to measuring only the pitch angle and the northern component of the ground speed, assuming the heading of the aircraft was equal to zero. Simplified kinematic equations of the one-component inertial vertical are as follows:

$$\dot{V}_N = a_N\,,\ \ a_N = a_y \sin\vartheta - a_x \cos\vartheta,$$

$$\dot{\vartheta} = \omega_{y_\Sigma} = \omega_{z_\text{A}} - \omega_{z_{NHE}}\,,\ \omega_{z_{NHE}} = -\frac{V_N}{R_\text{E}} = -\dot{B},$$

where V_N is the true northern component the aircraft’s ground speed; a_N is the projection of aircraft’s apparent acceleration, measured by accelerometers (signals a_x, a_y), on to the ON axis of navigation trihedron; ϑ is the pitch angle; ω_{z_A} is the angular velocity of the aircraft rotation in pitch; B is the geographic latitude; R_E is the Earth radius.

A scheme of a single-component inertial MEM-vertical gyro with velocity correction is displayes in Fig. 2.

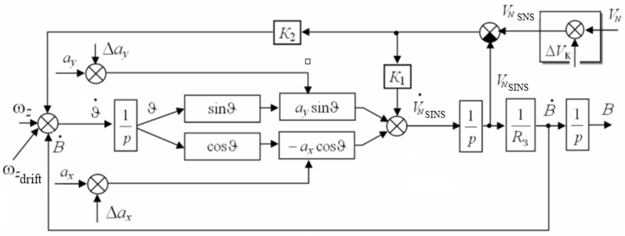

Fig. 2. Block diagram of the SNS and the strapdown inertial MEM gyro-vertical integration

In contrast to implementation of a damping scheme in a platform based SNS, in SINS the additional circuit K_1 is introduced not into the accelerometer output signal line, but into acceleration line reduced to the geographic accompanying basis.

Signals Δa_x, Δa_y and ω_{z_drift} represent the most significant sources of MEM-vertical errors. The one-component vertical gyro is a negative feedback circuit, and the presence of two integrating links in the loop indicates the structural instability of such a circuit. When such a circuit is exposed to disturbances in the form, for example, of errors Δa_x, Δa_y or ω_{z_drift}, it causes undamped oscillations with natural frequency $\sqrt{g(R)^{-1}}$. Structural analysis of the circuit shows that the presence of a constant accelerometer error Δa_x, Δa_y,, will cause an error in the reproduction of the vertical (pitch angle ϑ), while in the presence of a constant drift of the angular velocity sensor ω_{z_drift}, the vertical is reconstructed without a constant error, but there is a periodic error. Typical graphs of changes in vertical reconstruction errors in the presence of a constant accelerometer error and angular velocity sensor drift are shown in Fig. 3.

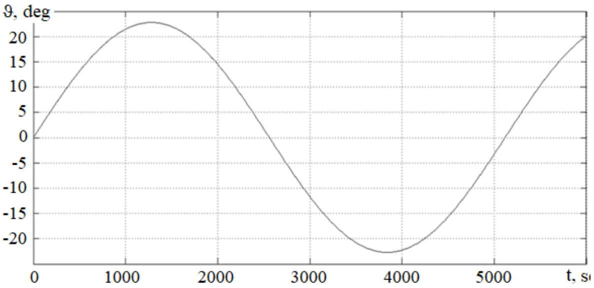

Fig. 3. Typical graphs of vertical reconstruction errors

Let us carry out an analysis of the corrected vertical gyro circuit. Let us define the error of speed determination as

$$\Delta V_{N_\text{SINS}} = V_{N_\text{SINS}} - V_N,$$

where $\Delta\dot{V}_{N_\text{SINS}} = \dot{V}_{N_\text{SINS}} - \dot{V}_N$, here V_{N_SINS} is the northern component of ground speed measured by SINS; V_N is the true northern component of the aircraft ground speed.

Making the assumption about the aircraft’s horizontal flight, we will assume that while flying around the spherical Earth the angular velocity ω_z will equal to:

$$\omega_z = -V_N / R_\text{E}\ .$$

Then, writing down the equation for the left adder of the block diagram, we get the error of the pitch angle changing:

$$\Delta\dot{\vartheta} = \omega_{z\,\text{drift}} + \frac{1}{R_\text{E}}\Delta V_{N_\text{SINS}} - K_2\left(\Delta V_\text{K} - \Delta V_{N_\text{SINS}}\right).$$

In horizontal flight, the aircraft’s acceleration changes only in the horizontal plane, i.e. accelerometers, taking into account their own errors, produce such data $a_x = \dot{V}_N + \Delta a_x$, $a_y = g + \Delta a_y$ (where g – gravity acceleration). Assuming that for small angles $\sin\Delta\vartheta = \Delta\vartheta$, and $\cos\Delta\vartheta = 1$, we write the equation for the right adder of the block diagram

$$\dot{V}_{N_{\text{SINS}}} = \dot{V}_N + \Delta a_x - g\Delta\vartheta + K_1\left(\Delta V_{\text{K}} - \Delta V_{N_{\text{SINS}}}\right).$$

After the transformation of this system, we obtain a system of equations, which describe the SINS errors in operational form

$$\begin{aligned} p\Delta\vartheta(p) - \left(\frac{1}{R} + K_2\right)\Delta V_{N_{\text{SINS}}}(p) \\ = \omega_{z_{\text{drift}}}(p) - K_2\Delta V_{\text{K}}(p), \\ g\Delta\vartheta(p) + \left(K_1 + p\right)\Delta V_{N_{\text{SINS}}}(p) \\ = \Delta a_x(p) + K_1\Delta V_{\text{K}}(p). \end{aligned}$$

The characteristic determinant of this system can be written as

$$A(p) = p^2 + K_1 p + g\left(\frac{1}{R} + K_2\right).$$

Analyzing the characteristic equation, it can be noted that the introduction of a correction circuit with a gain K_2 reduces the period of natural oscillations of the system, and the introduction of a correction circuit with a gain K_1 provides damping of oscillations in the system.

To confirm the possibility of an inertial-satellite vertical gyro construction, a strapdown vertical gyro prototype was created. It was based on GPS navigator receiver (GPS-Module-BR355) and flight sensors of low accuracy that were a part of the automatic control systems (angular velocity sensor (DUSM), and two overload sensors (BDLU-3)). The prototype was integrated with the LabView mathematical programming environment. In order to simulate changes in orientation angles, strapdown sensor units were mounted on a rotary stand (Fig. 4), which allowed to change the angular position of the sensor unit with an accuracy of 0.01°.

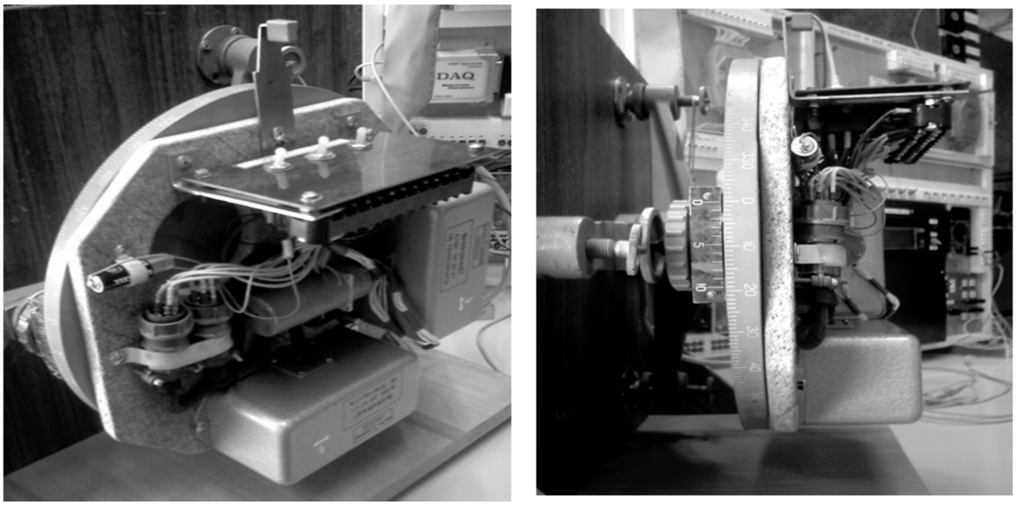

Fig. 4. Prototype of strapdown vertical gyro based on GPS navigation receiver (GPS-Module-BR355) and rough flight sensors

Prototype tests have proved the overall possibility of constructing a damped inertial-satellite vertical gyro. The accuracy of the inertial-satellite vertical gyro was tested with the use of mathematical modeling, as well as by testing its prototype.

A graph of the vertical reproduction errors variations with the use of a speed correction circuit, resulting from mathematical modeling of the considered one-component inertial MEM vertical gyro scheme, is shown in Fig. 5.

The prototype experiments evaluated the accuracy of orientation angles measurements with and without correction from the satellite navigation system. A graph of the vertical reproduction error variations in the presence of a constant accelerometer error and the drift of the angular velocity sensor in the presence of correction from the SNS is shown in Fig. 6.

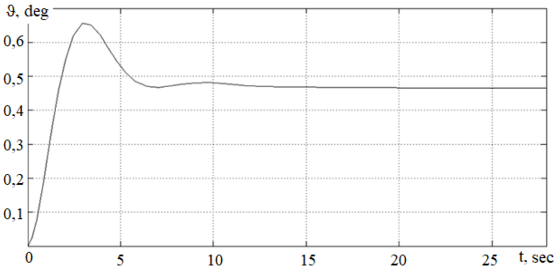

Fig. 5. A graph of the vertical reproduction errors variations with the use of a speed correction circuit, resulting from mathematical modeling

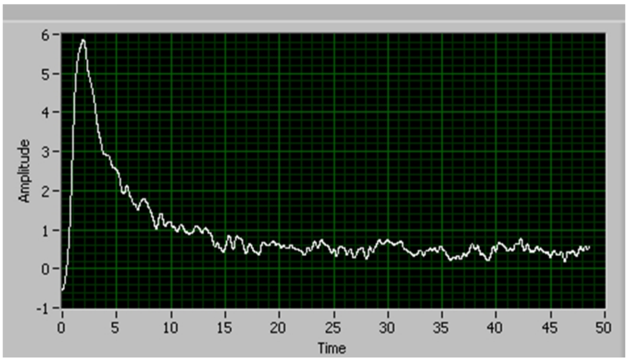

Fig. 6. A graph of the vertical reproduction errors variations with the use of a speed correction circuit, resulting from experiments with prototype

The constant vertical reproduction error $\Delta\vartheta$ depends on a pitch angle ϑ and on the deterministic components of accelerometer errors Δa_x, Δa_y, and is described by

$$\Delta\vartheta = \arcsin\frac{\Delta a_y \sin\vartheta - \Delta a_x \cos\vartheta}{g}.$$

The vertical reproduction error for the ADXL 150 micromechanical accelerometer from Analog Devices, with a zero shift error of 0.01 g, equals to 0.5°. This meets the requirements of existing precision vertical gyros.

IV. CONCLUSIONS

The solutions proposed in the article make it possible to improve the accuracy of an integrated vertical gyro, which is based on micromechanical technologies, through the latest integrated information processing and velocity correction, and which can be implemented quite easily on board of an aircraft.

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М. К. Філяшкін, О. І. Смірнов. Демпфована мікромеханічна гіровертикаль

Розглянуто способи побудови гировертикалей на грубих мікроелектромеханічних елементах: датчиках кутової швидкості та акселерометрах. Підвищити точність мікроелектромеханічної гіровертикалі пропонується шляхом її комплексування із супутниковою навігаційною системою. Запропоновані в статті рішення дозволяють підвищити точність роботи інтегрованої гіровертикалі, побудованої на основі мікромеханічних технологій, шляхом комплексної обробки інформації, що використовує схему компенсації з новітнім динамічним фільтром, що практично не спотворює похибки безплатформної інерційної мікроелектромеханічної гіровертикалі, і отримати оцінку дорожньої швидкості і максимально оцінити шляхову швидкість. За відтвореною оцінкою пропонується сформувати схему швидкісної корекції гіровертикалі (схему демпфування), яка істотно поліпшила точність оцінювання параметрів кутової орієнтації.

Ключові слова: комплексування; схема компенсації; швидкісна корекція; безплатформна інерціальна навігаційна система; похибка вертикалі.

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М. К. Филяшкин, О. И. Смирнов. Демпфированная микромеханическая гировертикаль

Рассмотрены способы построения гировертикалей на грубых микроэлектромеханических элементах: датчиках угловой скорости и акселерометрах. Повысить точность микроэлектромеханической гировертикали предлагается путем ее комплексирования со спутниковой навигационной системой. Предложенные в статье решения позволяют повысить точность работы интегрированной гировертикали, построенной на основе микромеханических технологий, путем комплексной обработки информации, использующей схему компенсации с новейшим динамическим фильтром практически не искажающим погрешности безплатформенной инерциальной микроэлектромеханической гировертикали, и получить оценку путевой скорости максимально приближенную к истинной. По воспроизведенной оценке предлагается сформировать схему скоростной коррекции гировертикали (схему демпфирования), которая бы существенным образом улучшила точность оценивания параметров угловой ориентации.

Ключевые слова: комплексирование; схема компенсации; скоростная коррекция; бесплатформенная инерциальная навигационная система; погрешность вертикали.

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