Compensation Gyrocompass Based on MEMS

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Abstract. The study of an astatic compensating gyrocompass, built on the basis of a modulation micromechanical gyroscope (MMG) of a hybrid type, has been carried out. A kinematic diagram is given and the principle of operation of the device has describing. The device uses the modulation principle based on obtaining information about the angular motion of the rotor and creating control torques in a rotating coordinate system, which makes it possible to exclude such a significant disadvantage of MMG as "zero offset". A feature of the gyrocompass under consideration is the use of two channels for controlling the rotor of the MMG, namely: a channel for the formation of a guiding moment, striving to combine its main axis with the direction of the true meridian and a channel for compensating this guiding moment. A linearized mathematical model has building, on the base of which an effective algorithm for the operation of a compensatory astatic gyrocompass is proposed. The device under consideration can be used to determine the true azimuth of the longitudinal axis of a mobile ground object, it has a higher measurement speed compared to devices built on three-degree "heavy" gyroscopes, and has good resistance to external influences (vibrations, shocks, etc.).

1. Introduction

In orientation systems, instruments built on three-degree "heavy" gyroscopes on an elastic and magnetic suspension, have found wide application. However, their main disadvantages are low noise immunity to disturbances of the base (vibration, shocks, shocks, etc.) and long duration of measurements. In addition, they have significant dimensions and a high level of energy consumption, in connection with which, in the development of orientation devices, microelectromechanical systems (MEMS), namely micromechanical gyroscopes (MMG), are increasingly used [1-8]. The proposed work continues a series of our papers [9-13], devoted to the use of microelectromechanical systems in solving problems of orientation of moving objects. Below is the kinematic diagram of the astatic compensating gyrocompass based on a three-degree hybrid MMG has been developed [14]. The considered device is using to determine the true azimuth of the longitudinal axis of a mobile ground object. Digital modeling of the MMG motion has carried out using the structural method [15] and the Maple high-level environment. An algorithm for the operation of the device and technical solutions has proposed, which make it possible significantly improve the dynamics of the operation of the device.

2. The kinematic diagram and mathematical model of the gyrocompass

Figure 1 shows that a coordinate system $O\xi\eta\zeta$ is rigidly connected to a moving object, the axis $O\zeta$ of which is its longitudinal axis. A coordinate system $OXYZ$ is associated with the body of a gyrocompass, fixed on an object, and a coordinate system $oxyz$ is associated with its rotor.
The kinematic circuit includes a drive motor MMG 1, rigidly connected to the body of the device 2. On the rotating shaft 3 of the drive motor, a gyro rotor 4 is fixed, made using the technology of solid-state microelectromechanical systems, it is connected to the drive motor shaft by a "spiral" elastic suspension 5 [3].

![Diagram of an astatic compensation gyrocompass](image)

**Figure 1.** Kinematic diagram of an astatic compensation gyrocompass based on a three-degree modulation MMG.

The information about the angular motion of the MMG rotor is reading out by the angle sensor 6. In order to create the control torques applied to the gyroscope rotor, the moment sensor 7 is used. The device uses the modulation principle of picking up information about the angular motion of the rotor, as well as the application of control torques to it in a rotating coordinate system, which makes it possible to exclude such a disadvantage of MMG as "zero shift". To separate information along the corresponding axes of the gyroscope sensitivity, demodulators and a sine-cosine rotating transformer (SCRT) 8 are used.

A feature of the gyrocompass under consideration is the use of two channels for controlling the rotor of the MMG, namely: a channel for the formation of a guiding moment, striving to combine its main axis with the direction of the true meridian and a channel for compensating this guiding moment. The channel for the formation of the guiding moment $M_{tx}$ consists of an angle sensor 6, a demodulator $D_M$, an amplifier with gain $K$, sine-cosine rotating transformer (SCRT), and torque sensor 7. The channel that creates a compensation moment $M_{cx}$ includes a sensor angle 6, demodulator $DM_y$, amplifier with gain $K_c$, SCRT, also torque sensor 7.

Let us consider the peculiarity of measuring the angle $\theta$ between the main axis of the gyroscope $Oz$ and the plane of the true meridian, which is associating with the value $I_{ts}$ of the compensation current flowing through the winding of the torque sensor. Figure 1 shows the position of the gyroscope axes relative to the plane of the true meridian. Before starting the measurements, the gyrocompass body is leveling, while the main gyroscope axis $Oz$ and the Ox axis will be parallel to the plane of the local horizon, and the Oy axis will coincide with the vertical of the place. At the stage of preliminary orientation of the main body, the value of the angle $\theta$ is chosen not large (the value should not exceed), therefore, $\sin \theta \approx \theta$ for small angles. From Fig. 1 it follows that the projection of the horizontal component $\omega_g$ of the Earth's rotation onto the axis of the gyrocompass body is

$$\Phi'_X = \Omega_e \cos \phi \sin \theta \approx \Omega_e \theta \cos \phi = \omega_g \theta,$$  

(1)
\( \Omega_E \) – the angular velocity of the Earth’s rotation, \( \phi \) is the latitude of the place.

As a result, of rotation of the plane of the local horizon with an angular velocity \( \Phi' X \) due to the apparent departure of the gyroscope, the angle of inclination of its main axis will change by the angle \( \theta_x \), which determines by the expression

\[
\theta_x = \Phi' X t = \omega_y \theta t .
\]  

(2)

The angle \( \theta_x \) measures by the gyroscope angle sensor 6, converting into an amplitude-modulated signal, is serving to the body through the information pickup and conversion system, demodulating by \( U_{dx} \), then through a circuit consisting of a power amplifier with gain \( K_m \), SCRT, serving to the rotating part, to the input torque sensor 7. The torque sensor 7 creates a guiding moment \( M_{tsx} \) around the axis, equal to

\[
M_{tsx} = K \omega_y \theta t , \quad K = k_1 K_m K_{ts} .
\]  

(3)

\( k_1 \) – the transmission coefficient of the system for removing and converting information of the modulation MMG, \( K_m \) is the gain of the power amplifier, \( K_{ts} \) is the transmission coefficient of the torque sensor.

Due to the property of precession under the action of the guiding moment \( M_{tsx} \), the main axis of the gyroscope \( O_x \) tends to rotate around the axis in the direction of alignment with the true meridian. However, in the astatic compensation gyrocompass, the gyroscope’s tendency to rotate around the axis by the angle \( \theta_y \) is compensating by the moment created by the torque sensor 7 about the axis. The circuit for creating a compensation torque includes an angle sensor 6, which measures the angle of rotation of the gyroscope rotor \( \theta_y \) and converts it into an amplitude-modulated signal. It includes also a system for retrieving and converting information, a demodulator, at the output of which the signal \( U_{dy} \) is generating, an isodromic link, power amplifier with gain \( k_c \), SCRT and torque sensor 7. The latter creates a compensation torque

\[
M_{cx} = K_1 I_{ts} , \quad K_1 = k_1 K_{ts} K_c ,
\]  

(4)

\( K_{ts}, K_c \) – the transmission coefficients of the isodromic link, the torque sensor and the amplification factor of the power amplifier, respectively, \( I_{ts} \) is the current flowing through the control winding of the torque sensor.

In a state of equilibrium, \( M_{tsx} = M_{cx} \), then, based on expressions (3) and (4), we get

\[
I_{cx} = k \theta t ,
\]  

(5)

\( k = \frac{K \omega_y}{k_1} \) = const.

Differentiating expression (5), we get

\[
\frac{dI_{cx}}{dt} \approx \frac{\Delta I_{cx}}{\Delta t} = k \theta .
\]  

(6)

From expression (6), it follows that if we measure the value of the increment of the current \( \Delta I_{cx} \) flowing through the control winding of the torque sensor for a fixed period \( \Delta t = t_f \), then the value of the angle \( \theta \) will determined by the expression

\[
\theta = \frac{\Delta I_{cx}}{k} / t_f .
\]  

(7)

Expression (7) shows that by measuring the rate of rise of the current of the control winding of the torque \( \Delta I_{cx} / t_f \), and then scaling it by a factor of \( 1 / k \), as a result, of measurements, the value of the angle \( \theta \) can obtained.
To ensure the operability of the gyrocompass in conditions when $\theta > \theta_{max} = 5^0$, it is necessary to install it on a horizontal platform with a drive turning it around the local vertical in the direction of decreasing the angle $\theta$ according to the generated signal corresponding to the condition $\Delta l_{cx} \geq l_{max}$. This operating mode of the gyrocompass corresponds to its self-orientation in the direction of the true meridian. The transition to the previously considered mode of measuring the angle of misalignment $\theta$ is carried out after the condition $\theta < \theta_{max}$ is satisfied.

It should noting that before measuring $\theta$, it is necessary to form the initial conditions, i.e. form the value of the moment $M_{t_{cx}}$, with the help of which the compensation of the "latitudinal error" associated with the presence of the vertical component of the Earth's rotation $\omega_y = \Omega_E \sin \varphi$ is carried out. Such compensation is carried out by the formation of an appropriate amount of current flowing through the control winding of the torque sensor.

The linearized mathematical model of a three-degree modulation MMG, describing its motion in a rotating coordinate system under conditions of rotation of the base at a constant speed, has the form

$$\begin{align*}
A\theta_x''(t) + \mu \theta_x'(t) + (k + (C - B)\Omega^2 + 2(C - B)\Omega \Phi_x')\theta_x(t) - \Omega (A + B - C) \theta_x(t) = (C + A - B)\Omega \Phi_x' \sin \Omega t - \Phi_x' \cos \Omega t, \\
B\theta_y''(t) + \mu \theta_x'(t) + (k + (C - A)\Omega^2 + 2(C - A)\Omega \Phi_x')\theta_y(t) + \Omega (A + B - C) \theta_x(t) = (C - A + B)\Omega \Phi_y' \cos \Omega t + \Phi_y' \sin \Omega t,
\end{align*}$$

where $\mu$ is the coefficient of viscous friction in the material of the suspension and friction of the rotor against the environment, $k$ is the rigidity of the suspension, $A, B, C$ are the equatorial and polar moments of inertia of the rotor, respectively, $\Omega$ is the angular velocity of rotation of the rotor, $\Phi_x' = \omega_y \sin \theta$, $\Phi_y' = \omega_y$, $\Phi_x' = \omega_y \cos \theta$.

### 3. Results and conclusions

We represent the system of equations (8) in the complex form

$$\begin{align*}
J \theta'_{xy}(t) + (\mu + j\Omega(A + B - C)) \theta'_{xy}(t) + \\
+ \left( k + (C - J)\Omega^2 + K_1 \right) \theta_{xy}(t) + J_1 \theta''_{xy}(t) + (J_1 \Omega^2 + K_2) \theta''_{xy}(t) = j\Omega \Phi_{xy}' e^{-j\Omega t} - 2jJ_1 \Omega \Phi_{xy}' e^{j\Omega t},
\end{align*}$$

$$J = \frac{A + B}{2}, \quad J_1 = (A - B)/2, \quad K_1 = (2C - A - B)\Omega \Phi_x', \quad K_2 = (A - B)\Omega \Phi_x', \quad \theta_{xy} = \theta_x + j\theta_y - \text{angular displacement of the rotor}, \quad \Phi_{xy} = \Phi_x + j\Phi_y - \text{angular displacement of the base of the device, the sign \((*)\) corresponds to the complex conjugate value.}

The definition of the form of the transfer functions of the device will carried out on the base of the method of complex coordinates and complex transfer functions used for two-dimensional systems with modulation, identical channels and antisymmetric cross-feedback, which class includes modulation MMG.

Using the methodology given in the work [15], the expressions of the transfer functions of the tuned gyroscope in the frame coordinate system along the main and cross channels at the "zero frequency" will have the form

$$W_0(p) = -k_1 K_{go} \frac{T_{n1}p^2 + 2\xi_{n1}T_{n1}p + 1}{(T_{g}p + 1)(T_{n1}p^2 + 2\xi_{n1}T_{n1}p + 1)},$$

$$W_n(p) = -k_1 K_{gn} \frac{T_{n2}p + 1}{(T_{g}p + 1)(T_{n2}p^2 + 2\xi_{n2}T_{n2}p + 1)}.$$

The right-hand sides of the obtained expressions depend on the transmission coefficient of the gyroscope angle sensor, on the transmission coefficient of the demodulators and on the frequencies of nutation and precessional oscillations of the MMG in the coordinate system associated with the device case.
In accordance with the mathematical model (9), a structural diagram of the astatic compensation gyrocompass has developed, shown in Fig. 2.

![Figure 2. Block diagram of the astatic compensation gyrocompass.](image)

A feature of the above scheme is the presence of cross-links between the channels, as well as the channel for creating the compensation moment $M_{cx}$ along the previously considered circuit. The output signal corresponding to the value of the current $I_{ts}$ flowing through the control winding of the torque sensor is determined by the value of the angular deviation of the main axis of the gyroscope rotor from the direction of the true meridian $\theta$. Using the given block diagram (Fig. 2), we obtain dynamic characteristics connecting the current through the control winding of the torque sensor $I_{ts}$ with the gyroscopic moments $M_{gy}, M_{gy}$.

Let us define an expression connecting the value of the current through the control winding of the torque sensor $I_{ts}$ with the gyroscopic moment $M_{gy} = -H\omega_{g}sin\theta$

$$\Phi_{1}(p) = \frac{I_{ts}(p)}{M_{gy}(p)} = \frac{K_{p}\omega_{g}N^{2}(Tp + 1)(T_{ts}p + 1)}{NT\omega_{nutk}(T_{ts}p^{4} + p^{3})TH\omega_{nutk} + K_{c}K_{ts}N\omega_{g}(T^{2}p^{2} + p + D)}, \quad (10)$$

$$K_{p} = K_{m}K_{c}, \quad H = C\Omega \quad \text{gyroscopic momentum}.$$

Taking into account that in the range of operating frequencies, in the characteristic equation the term $T_{ts}p^{4}$ is negligible, compared to other terms of the polynomial, we will neglect it. Then the characteristic equation of the closed-loop system can be written as

$$D(p) = HT\omega_{nutk}(TH\omega_{nutk}p^{3} + NK_{c}K_{ts}\omega_{g}(T^{2}p^{2} + p + D)). \quad (11)$$

Comparison of the values of the roots of the full and truncated characteristic polynomial for specific parameters of the modulation MMG showed the presence of rapidly damping oscillations that actually do not affect the dynamics of the device.

Thus, the determination of the true azimuth of the longitudinal axis of the ground object $A_{ob}$ consists of two stages. The first is precision measurement of the angle $\theta_{pr}$ between the gyroscope axis, previously deployed in the direction of the true meridian, and the longitudinal axis of the object being oriented. The second – measurement of the angular misalignment $\theta$ between the main axis of the gyroscope and true meridian, i.e. $A_{ob} = 360^{0} - (\theta_{pr} + \theta)$.

In this case, the operation algorithm of the gyrocompass will be as follows. The projection $\Phi'_{X} = \omega_{g}sin\theta$ creates an apparent departure of the main axis of the gyroscope around the axis relative to its
base at a constant speed and with a linearly increasing angle of rotation. The guiding moment will change in the same way. $M_{\text{SSX}}$, respectively, are the current of the control winding of the torque sensor $I_{\text{ts}}$ and the compensation torque $M_{\text{cx}}$, and the rate of rise $I_{\text{ts}}$ will determined by the value of the angle $\theta$. By measuring the magnitude of the increment $\Delta I_{\text{ts}}$ for a fixed time interval $t_f$ with subsequent scaling, the value of the angle $\theta$ is determined.

It should noting that for the implementation of the considered algorithm of the device operation, it is necessary to ensure the linear nature of the change in the current $I_{\text{ts}}$ on a fixed time interval, which determines the accuracy of the measurements.

If there is no possibility of preliminary orientation of rotation axis of MMG in the true meridian direction with an accuracy $\theta_{pr} > 5^\circ$, then device is installing on a platform. Then a rough orientation of the axis of rotation of the rotor is carrying out with sequential measurement of the angle, until its value satisfies earlier the specified value. In this case, the compass time is increasing by the value of the time interval spent on rough orientation of the axis of rotation of the MMG rotor and is determined by the speed of the reference system.

4. References

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