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IMPROVING AN ANALYTICAL GYROSCOPE AZIMUTH MODE TO COMPENSATE FOR THE BALLISTIC DEVIATION OF A MARINE GYROCOMPASS

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One of the main errors of the gyrocompass is ballistic deviance, which occurs when maneuvering a vessel. This is an important aspect related to solving the issue of navigational safety, which is the object of this research. As part of the study, it is proposed to improve the regime of analytical gyroscope azimuth to compensate for the ballistic deviance of marine gyrocompass, which is the subject of current scientific research.

When using the classic technique for reducing ballistic deviance (physical switching of the device to the mode of gyroscope azimuth), under certain conditions the gyrocompass after the maneuver may not return to the meridian and lose its performance. At the same time, classical algorithmic compensation by calculating ballistic deviance requires information from external devices, such as a lag and/or a GPS receiver (Global Positioning System). To compensate for ballistic deviance, this work has improved the mode of analytical gyroscope azimuth, designed to enhance the accuracy of the marine gyrocompass on the maneuver, by using a third-order filter accelerometer for filtration. This makes it possible to compensate for ballistic deviance and reduce intercardinal deviance during pitching. The current paper proposes a procedure for calculating the switching time between gyrocompass modes, which makes it possible to obtain the predefined value of ballistic deviance. As a result, the improved technique to reduce deviance demonstrates an accuracy comparable to the classical one. When using this technique, the loss by gyrocompass of the properties of selectivity relative to the meridian (indication of the course) is excluded because the device does not switch to a gyroscope azimuth mode.

The proposed observation device can be used on standard gyrocompasses without the need for reconfiguration and achieve the desired value of the residual error of deviance compensation (according to calculations, up to 0.3°)

Keywords: gyrocompass, gyroscope azimuth, analytical gyroscope azimuth regime, ballistic deviance, analytical compensation of errors

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1. Introduction

One of the main sources of errors of adjusted gyrocompass (AGC) is ballistic deviance, which occurs when the vessel moves evenly or when performing a maneuver due to the impact of acceleration on the horizon indicator. The consequence is the error in measuring the course, which adversely affects the safety of navigation. According to the requirements of SOLAS (International Convention for the Safety of Life at Sea), gyrocompass must be installed on all ships with a tonnage of more than 500 tons. As a result, in order to ensure the safety of navigation, it is necessary to devise and apply techniques to improve the accuracy of AGC. In particular, compensating for its errors in such a way as to guarantee the performance of the device under any conditions of navigation and vessel maneuvering. Thus, it is a relevant theoretical and practical task to develop such techniques to compensate for gyrocompass errors.

2. Literature review and problem statement

To compensate for ballistic deviance in modern gyrocompasses with a sensitive gyroscopic element of high accuracy, automatic switching of the device from a gyrocompass mode to a gyroscope azimuth mode is carried out [1, 2]. That is, disconnecting the azimuthal channel of the device from the signal of the horizon indicator. The disadvantage of this technique is that the device under a given mode does not have the properties of selectivity either relative to the meridian plane or in relation to any other azimuthal direction. Therefore, without taking additional measures, under certain conditions gyrocompass may never return to the meridian [3], and, due to the drift of the gyroscope over time, the course determining error will increase in proportion to time.

Paper [4] states that improving the accuracy of modern AGCs is limited to several factors. Given the high cost of gyroscopes needed to create gyrocompass with increased accuracy, manufacturers are forced to return to pendulum gyrocompasses (Anschutz "Standart-XXII") or design so-called GPS compasses. The disadvantage of the former is the low, compared to AGC, accuracy and long time of arrival in the meridian, the latter – the fact that they do not provide for the continuity of navigation parameters (satellites are not always available). There are no ways to reduce the errors of AGC in the cited paper.

Work [5] investigates gyrocompass with indirect control for ground-based moving objects based on a dynamically tuned gyroscope (DTG). The cited study provides a general model of errors of such gyrocompass, as well as a scheme of hardware compensation for systematic gyrocompass errors caused by the drift of DTG. The author did not analyze other errors and develop ways to compensate for them.

Paper [6] compared the errors of the classical gyrocompass, gyrocompass on fiber-optic gyroscopes, and satellite compass. Fourier analysis was used to analyze errors and spectra of device errors were determined; recommendations were compiled to reduce low-frequency distortions of the ship's course, including those stern-introduced. The cited paper does not provide an analysis of the dynamic errors of the gyrocompass, including ballistic deviance.

Article [7] proposes a new scheme of the dynamic gyrocompass on laser gyroscopes and analyzes the main errors of such a device: the influence of the gyroscope's natural noises, slow drift, and the magnetic component of drift. However, no analysis of dynamic errors of gyrocompass and methods of their compensation is given.

Study [8] considers the functioning of a free-platform gyrocompass on fiber-optic gyroscopes, including switching between modes of operation during the maneuvering of a vessel. However, the authors' proposed change in damping coefficients depending on the acceleration of the vessel is unsuitable for use in the classical AGC.

A similar procedure of switching between gyrocompass modes is described in [9]; the classification of the states of the system "compass – vessel" based on wavelets is used. That requires considerable computing power of control electronics and increases the cost of the device.

To determine the moment of switching a gyrocompass between the gyrocompass and gyroscope azimuth modes, the value of the acceleration of the vessel is used. To measure this acceleration, it is proposed to use an electromagnetic lag [10] or Doppler lag [11], which makes it possible to determine the speed of the vessel and, accordingly, its acceleration. The disadvantage of that approach is the need to differentiate the speed signal from the lag, which leads to interference.

Techniques for dealing with errors involve reducing the error by changing the structure of the device (the classical mode of gyroscope azimuth) or its parameters (for example, coefficients). The use of modern microprocessor technology makes it possible to solve the issue of compensation of errors by calculating the error value and its algorithmic compensation based on the data from devices available on the ship. Such compensation usually requires the use of a gyro tachometer or other devices to measure the ship's angular velocity on circulation, as well as differentiation of the lag signal (or GPS) to measure the acceleration of the vessel.

There are several ways to use microprocessors to compensate for ballistic deviances in gyrocompass readings [12]. As a rule, a correction for AGC is calculated on the basis of the solution to differential equations of its movement using the acceleration signal of the vessel. The disadvantages, in this case, are the same as in the technique proposed in [10, 11].

It is also possible to determine the speed of movement of the vessel with high accuracy using the receiver of satellite navigation systems (SNS), as proposed in the integrated navigation system [1], built on the basis of AGC. The current value of the acceleration of the vessel is determined using an observation device built on the basis of the optimal Kalman filter. At the same time, it is necessary to have on board the ship the equipment of SNS consumer and a powerful calculator, which would solve the problem of optimal Kalman filtration in real time. This puts forward requirements for equipping the vessel with SNS equipment and increases the cost of the device at the expense of the calculator.

Therefore, in most of the above studies, no analysis of dynamic errors, including ballistic deviance, and ways to compensate for it has been carried out. At the same time, the techniques proposed in [1, 10, 11] to compensate for ballistic deviance require the installation of additional devices on the ship, which increases the cost of a gyrocompass and is not always possible for structural reasons. At the same time, in the gyrocompass, there are internal sources of information about the acceleration of the vessel, for example, the horizon indicator (accelerometer), which can be used instead of differentiating the signals of the lag and SNS about the speed of the vessel.

The task of compensating AGC errors during maneuvering (ballistic deviance) by assessing errors according to the measurement of the output signal of the accelerometer filter (horizon indicator) was not considered in the cited studies. Paper [13] proposes a compensation technique, termed the mode of analytical gyroscope azimuth, but the latter needs to be improved in order to reduce the ballistic deviance of the device. It was also proposed to use the signal filter of the third-order horizon indicator to effectively reduce intercardinal deviance in the case of re-launch of gyrocompass in the sea during pitching. It should be noted that the use of a third-order filter for the output signal of the horizon indicator can be recommended not only for the accelerated guiding mode but also for the regular mode of AGC operation. Owing to that, the AGC error during pitching is significantly reduced, which makes it possible to install the device at a great distance from the center of the pitching, for example, on the bridge of a dry cargo ship or container ship.

3. The aim and objectives of the study

The purpose of this study is to significantly improve the technique reported in paper [13] to reduce the ballistic deviance of the device by using a third-order accelerometer signal filter, which also reduces intercardinal deviance. This will make it possible to improve the accuracy of the gyrocompass on the maneuver and, as a result, the safety of navigation.

To accomplish the aim, the following tasks have been set:

– to synthesize an observation device that will assess the ballistic deviance of AGC based on the output signal of the accelerometer filter with a third-order filter;

– to compare the effectiveness of analytical gyroscope azimuth modes and the switching of AGC to a gyroscope azimuth mode;

– to devise a procedure for determining the switching time between modes in which the ballistic error will correspond to the predefined value;

– to assess the impact of the inaccuracy of parameters of the observation device on the accuracy of assessing the AGC errors.

4. The study materials and methods

The object of our research is maritime navigation safety. The main hypothesis assumes that the use of a third-order accelerometer signal filter and an observation device could improve the accuracy of the gyrocompass on the maneuver by compensating for ballistic deviance and thereby improve the safety of navigation. When considering the dynamics of the movement of gyrocompass and the synthesis of the observation device, linear equations of AGC movement with the accelerated movement of the vessel are taken as a basis.

During our research, methods from classical and modern control theory were used for the synthesis of the observation device and the construction of a mathematical model of the errors of the device. To assess the effectiveness of the analytical gyroscope azimuth mode and the effect of the accuracy of determining the parameters of the observation device on the accuracy of error compensation, we simulated the functioning of the gyrocompass and observation device using the MATLAB software package (USA). It was based on the digital gyrocompass AGC-01, designed at Igor Sikorsky Kyiv Polytechnic Institute (Ukraine) in 2021. That has made it possible to assess the effectiveness of the proposed mode of analytical gyroscope azimuth and the effect of the accuracy of determining the parameters of the observation device on the accuracy of error compensation.

5. Results of improving the analytical gyroscope azimuth mode

5. 1. Synthesis of the observation device

When synthesizing the observation device, we took into consideration that the interference in the output signal of the accelerometer, which has the character of high-frequency noise [14, 15], is largely suppressed by a low-frequency filter. In addition, it was taken into consideration that AGC is a very inertial dynamic system with a time of fading of the transition process from 30 minutes to 6 hours. Such a system suppresses high frequencies well, and, therefore, the residual measurement noises present in the output signal of the δ filter affect the AGC operation insignificantly. It was also taken into account that the constant component of the accelerometer error does not affect the systematic error of AGC readings [15].

Since the ballistic deviance of AGC is determined mainly by the northern component W_η of the acceleration of the ship's movement [1, 5, 13], we take as a basis for further research the equation of AGC movement in the accelerated movement of the vessel:

$$\dot{\alpha} - r_x\delta = 0,$$

$$\dot{\beta} + \omega_\eta\alpha + r_z\delta = 0,$$

$$B_1\dddot{\delta} + B_2\ddot{\delta} + B_3\dot{\delta} + \delta - \beta = W_\eta/g, \quad (1)$$

where α, β are the angles of deviation of the main axis of the gyroscope from the plane of the true meridian and the plane of the horizon; δ is the output signal of the accelerometer filter (horizon indicator);

B_1, B_2, B_3 – accelerometer signal filter coefficients; ω_η is the northern component of the angular speed of rotation of the base (vessel) in the inertial coordinate system; r_x, r_z is the steepness of characteristics of specific pendulum and damper control moments;

$$\omega_\eta = \Omega \cdot \cos\varphi,$$

where Ω is the angular speed of rotation of the Earth, φ is the latitude of the place.

In comparison with the equations given in [1, 5, 13], changes were made to the third equation of the system: instead of the filter of the first order of the form $T\dot{\delta} + \delta$, where T is the time constant of the accelerometer filter, a third-order filter was applied $B_1\dddot{\delta} + B_2\ddot{\delta} + B_3\dot{\delta} + \delta$. This makes it possible to significantly reduce intercardinal deviance during pitching due to the use of an odd order filter [13].

As a model of AGC movement, we select the equations similar in structure to equations (1):

$$\dot{\hat{\alpha}} - r_{xm}\hat{\delta} = u_x;$$

$$\dot{\hat{\beta}} + \omega_{\eta m}\hat{\alpha} + r_{zm}\hat{\delta} = u_z;$$

$$B_{1m}\dddot{\hat{\delta}} + B_{2m}\ddot{\hat{\delta}} + B_{3m}\dot{\hat{\delta}} + \hat{\delta} - \hat{\beta} = 0, \quad (2)$$

where $\hat{\alpha}$, $\hat{\beta}$, $\hat{\delta}$ are the coordinates of the model corresponding to the true coordinates of AGC α, β, δ; the index "m" denotes the parameters of the AGC model, and $\omega_\eta = \omega_{\eta m}$; u_x, u_z are the control influences. Since the current value of vessel acceleration W_η is unknown, the accepted model of AGC (2) did not include a term that depends on this acceleration.

We denote through Δα, Δβ, Δδ the evaluation errors using model (2) of the true AGC coordinates α, β, δ:

$$\Delta\alpha = a - \hat{\alpha}; \quad \Delta\beta = \beta - \hat{\beta}; \quad \Delta\delta = \delta - \hat{\delta}. \quad (3)$$

The output signal of the accelerometer filter δ is subject to measurement. To assess the error of measuring the course α according to the available signal δ, we shall synthesize the observation device. The block diagram of AGC with such a device (the gyrocompass AGC-01, designed by the Igor Sikorsky KPI in 2021) takes the form shown in Fig. 1.

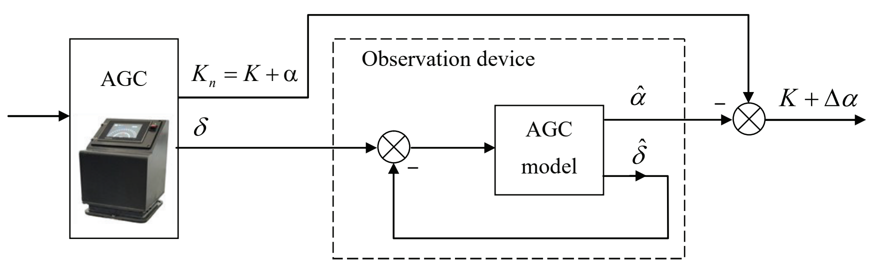

Fig. 1. Block diagram of AGC-01 with an observation device

In Fig. 1, the following designations are used: K is the true course of the ship; K_i=K+α is the "instrument" value of the course angle measured using the AGC. Subtracting from the measured angle of the course K_i the error estimate $\hat{\alpha}(t)$ (t is time) performed by the observation device, it is possible to compensate for the AGC error α(t) with accuracy to the error of measuring Δα.

The task of synthesis of the observation device is to ensure that the error Δα is no worse than that in the classic technique of compensation for ballistic deviance. According to the requirements by IMO Resolution A.424 (XI) and ISO 8728:2014, this error should not exceed 2°.

Choose the control influences u_x, u_z for model (2) by the proportional deviations of the coordinate of the model from the true output of the accelerometer filter:

$$u_x = k_1\left(\delta - \hat{\delta}_m\right);$$

$$u_z = k_2\left(\delta - \hat{\delta}_m\right), \tag{4}$$

where k_1, k_2 are transmission coefficients.

We believe that the parameters of the model r_{xm}, r_{zm}, B_{1m}, B_{2m}, B_{3m} are equal to the actual parameters r_x, r_z, B_1, B_2, B_3 of the control circuit of AGC. Subtracting from the equations of AGC movement (1) equations (2) and (3), taking into consideration ratios (4), we obtain a model of gyrocompass errors:

$$\Delta\dot{\alpha} - \left(r_x - k_1\right)\Delta\delta = 0;$$

$$\Delta\dot{\beta} + \omega_\eta\,\Delta\alpha + \left(r_z + k_2\right)\Delta\delta = 0;$$

$$B_1\Delta\dddot{\delta} + B_2\Delta\ddot{\delta} + B_3\Delta\dot{\delta} + \Delta\delta - \Delta\beta = W_\eta / g, \tag{5}$$

where W_η is the northern component of the acceleration of the vessel during a maneuver.

At the time of the maneuver, we accept

$$k_1 = r_x;\quad k_2 = r_z' - r_z, \tag{6}$$

where r_z' is the value of the r_z coefficient in the AGC control circuit used for the gyroscope azimuth mode.

In this case, the error model equations (5) take the form:

$$\Delta\dot{\alpha} = 0;$$

$$\Delta\dot{\beta} + \omega_\eta\,\Delta\alpha + r_z'\Delta\delta = 0;$$

$$B_1\Delta\dddot{\delta} + B_2\Delta\ddot{\delta} + B_3\Delta\dot{\delta} + \Delta\delta - \Delta\beta = W_\eta / g. \tag{7}$$

As can be seen from equations (7), the error $\Delta\alpha$ of evaluation using the observation device of AGC error during a maneuver does not depend on the magnitude of acceleration of the vessel W_η and is determined only by the initial deviation $\Delta\alpha_0$ of the model coordinate $\hat{\alpha}$ from the AGC error α.

The proposed observation device, while limiting the ballistic deviance of AGC, has the same disadvantage as the gyroscope azimuth: the error in determining the angle of the course $\Delta\alpha$, as follows from the first equation in (7), is equal to the initial deviation $\Delta\alpha_0$ of the estimate $\hat{\alpha}$ from the AGC error α and does not decrease. Moreover, similar to the error of indicating the course of gyroscope azimuth, error $\Delta\alpha$ will accumulate at the rate of azimuthal drift of the gyroscope. Therefore, after the end of the maneuver, it is necessary to change the transmission coefficients k_1, k_2 of the observation device so as to ensure the reduction of the error $\Delta\alpha$.

If, after completing the maneuver (W_η=0), we select the transmission coefficients k_1, k_2 equal to zero

$$k_1=0;\ k_2=0, \tag{8}$$

then equation (5) of the gyrocompass error models with the accuracy of the designations will coincide with the equations of AGC free movement (1):

$$\Delta\dot{\alpha} - r_x\Delta\delta = 0;$$

$$\Delta\dot{\beta} + \omega_\eta\Delta\alpha + r_z\Delta\delta = 0;$$

$$B_1\Delta\dddot{\delta} + B_2\Delta\ddot{\delta} + B_3\Delta\dot{\delta} + \Delta\delta - \Delta\beta = 0. \tag{9}$$

Since the coefficient values in equations (9) and (1) are the same, the errors of the observation device will demonstrate the same dynamics as the errors of AGC.

Thus, during a maneuver, it is necessary to use the value of transmission coefficients (6) in the AGC observation device, and, after the end of the maneuver, values from (8). By integrating the equations of model (2) with the input variables u_x, u_z (4) with the specified values of the transmission coefficients, we will have the current value of the ballistic deviance assessment $\hat{\alpha}(t)$, which can be taken into consideration in AGC readings as a correction. As a result, the level of AGC accuracy will be determined not by the ballistic deviance $\alpha(t)$ but by the error of its assessment in the observation device $\Delta\alpha = \alpha - \hat{\alpha}$. If the values of coefficients (6) and (8) are consistently used, then, during a maneuver, the error of the observation device will be the same as the ballistic deviance of AGC during the physical switching to a gyroscope azimuth mode. At the end of the maneuver, the error of the observation device under the above conditions will be the same as when the AGC switches back to a regular gyrocompass mode. To change the values of the transmission coefficients of the observation device during a maneuver and after its completion, information is required about the presence or absence of acceleration of the vessel's movement. This information can be obtained by analyzing the level of the output signal δ of the horizon indicator (a vessel performs a maneuver if the signal δ exceeds a certain level).

The compensation for ballistic deviance described above is termed the analytical gyroscope azimuth mode since, in this case, gyrocompass always works under a gyrocompass mode while the calculation and compensation of deviance occur analytically.

5. 2. Comparing the effectiveness of the modes of analytical gyroscope azimuth and classical gyroscope azimuth

To assess the effectiveness of the proposed improved technique, it is necessary to compare the ballistic deviation of the compass when using it, employing the classical compensation technique and in the absence of compensation for the ballistic error of the compass.

To compare the effectiveness of the improved compensation technique and the classical mode of gyroscope azimuth, we consider the gyrocompass AGC-01, designed at the Igor Sikorsky Kyiv Polytechnic Institute. For the gyrocompass, the parameters of the mathematical model take the following values: B_1=133516.48352, B_2=3708.79121, B_3=87.36264, r_x=0.049/cos(φ), r_z=0.00117, $r_z' = r_x$. We also believe that the values of the model parameters in the observation device r_{xm}, r_{zm}, B_{1m}, B_{2m}, B_{3m} are equal to the true values of the control circuit parameters of AGC r_x, r_z, B_1, B_2, B_3.

To reproduce the gyrocompass motion, a mathematical model is used in the state space, which includes a set of variables of input, output, and state, interconnected by first-order differential equations that are written in matrix form. Taking into consideration system (1) we obtain:

$$\begin{cases} \dot{x} = Ax + Bu, \\ y = Cx + Du, \end{cases} \tag{10}$$

where $x=\begin{bmatrix}\alpha\\ \beta\\ \delta_1\\ \delta_2\\ \delta_3\end{bmatrix}$ is the state vector $\left(\delta_1=\delta;\delta_2=\dot{\delta};\delta_3=\ddot{\delta}\right)$,

$y=\begin{bmatrix}y_1\\ y_2\\ y_3\end{bmatrix}=\begin{bmatrix}\alpha\\ \beta\\ \delta\end{bmatrix}$ is the output vector,

$u=W_\eta/g$ is the control vector,

$A=\begin{bmatrix}0 & 0 & r_x & 0 & 0\\ -\omega_\eta & 0 & -r_z & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 1\\ 0 & \frac{1}{B_1} & -\frac{1}{B_1} & -\frac{B_3}{B_1} & -\frac{B_2}{B_1}\end{bmatrix}$ is the system's matrix,

$B=\begin{bmatrix}0\\ 0\\ 0\\ 0\\ 1/B_1g\end{bmatrix}$ is the control matrix,

$C=\begin{bmatrix}c_1 & 0 & 0 & 0 & 0\\ 0 & c_1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\end{bmatrix}$ is the output matrix, c_1=3437.75 is the scale coefficient for converting from radians to angular minutes,

$D=\begin{bmatrix}0\\ 0\\ 0\end{bmatrix}$ is the direct link matrix.

By analogy with expressions (10), for gyrocompass model equations in the state space used in the observation device, we obtain:

$$\begin{cases}\dot{\hat{x}}_m=A_m\hat{x}+B_mu,\\ \hat{y}_m=C_m\hat{x}+D_mu,\end{cases}\qquad(11)$$

where $\hat{x}_m=\begin{bmatrix}\hat{\alpha}_m\\ \hat{\beta}_m\\ \hat{\delta}_{1m}\\ \hat{\delta}_{2m}\\ \hat{\delta}_{3m}\end{bmatrix}$ is the state vector

$\left(\delta_{1m}=\delta_m;\delta_{2m}=\dot{\delta}_m;\delta_3=\ddot{\delta}_m\right)$,

$\hat{y}_m=\begin{bmatrix}\hat{y}_{1m}\\ \hat{y}_{2m}\end{bmatrix}=\begin{bmatrix}\hat{\alpha}\\ \hat{\delta}\end{bmatrix}$ is the output vector,

$u=\begin{bmatrix}u_x\\ u_z\end{bmatrix}$ is the control vector,

$A=\begin{bmatrix}0 & 0 & r_{xm} & 0 & 0\\ -\omega_{\eta m} & 0 & -r_{zm} & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 1\\ 0 & \frac{1}{B_{1m}} & -\frac{1}{B_{1m}} & -\frac{B_{3m}}{B_{1m}} & -\frac{B_{2m}}{B_{1m}}\end{bmatrix}$

is the system's matrix,

$B_m=\begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & 0\\ 0 & 0\\ 0 & 0\end{bmatrix}$ is the control matrix,

$C_m=\begin{bmatrix}c_1 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\end{bmatrix}$ is the output matrix,

$D_m=\begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix}$ is the direct link matrix.

Consider the movement of a vessel with acceleration W_η=0.172 m/s^2 over t_m=1 minute, which corresponds to a speed gain of 20 knots. The latitude of the vessel φ=46°29'10" N. The gyrocompass control system AGC-01 is completely digital, so, for modeling, equations (10) and (11) were converted into a discrete form. Therefore, the lines on the below plots showing the simulation results are not smooth but take the form of "steps".

In Fig. 2, line 1 shows the AGC ballistic deviance α(t) with the recommended parameter values without switching it to a gyroscope azimuth mode or using the analytical gyroscope azimuth mode. Line 2 is the ballistic deviance of the gyrocompass during its physical switching to a gyroscope azimuth mode during a maneuver; line 3 – when using the mode of analytical gyroscope azimuth. The time points of change in the values of transfer coefficients k_1, k_2 (values from (6) – at the time of maneuver, values from (8) – after the end of the maneuver) were determined by comparing the output signal δ of the accelerometer filter with the limit value δ_{lim3}=5 angular min. Switching between the modes is performed with delays introduced to exclude the effect on the transition to the mode of gyroscope azimuth mechanical shocks. The value of the switching threshold and delays was calculated for use from the classical compensation technique (switching to a gyroscope azimuth mode) according to the procedure given in [13]. The algorithm for switching between the modes of operation of the device is left unchanged.

The comparison of plots shown in Fig. 2 reveals the following:

– the error of compensation for ballistic deviance by the observation device during AGC operation under a gyrocompass mode (line 3) differs slightly from the ballistic deviance of AGC during physical switching to a gyroscope azimuth mode (line 2);

– the error of the observation device is higher than the ballistic deviance of AGC, which physically switches from mode to mode after the end of the maneuver.

The latter is caused by a greater deviation β(t) of the main axis of AGC from the horizon plane during the constant operation of AGC under a gyrocompass mode than with the automatic switching of AGC to a gyroscope azimuth mode during the maneuver (Fig. 3).

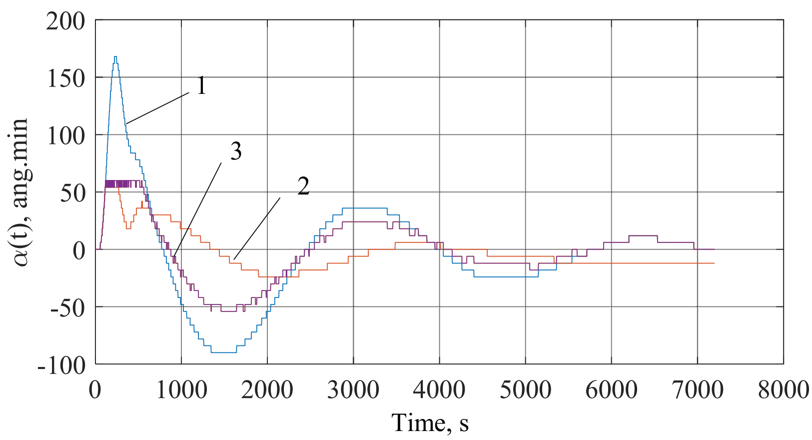

Fig. 2. Ballistic deviation of AGC: 1 – with the constant operation of AGC under a gyrocompass mode, 2 – with physical switching to a gyroscope azimuth mode, 3 – when using the mode of analytical gyroscope azimuth

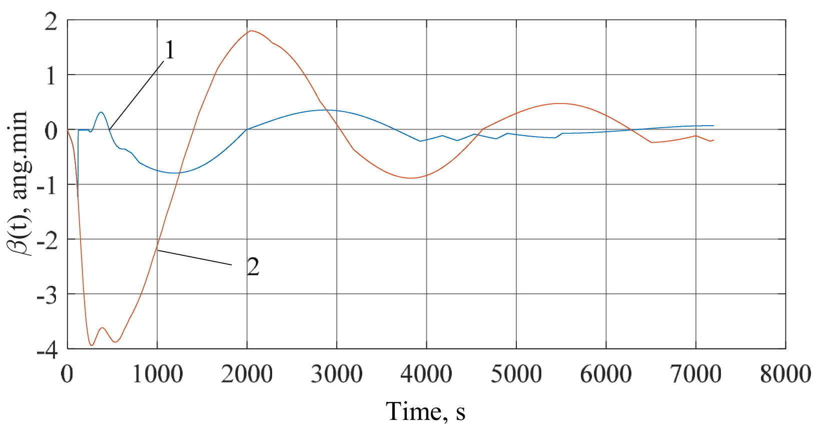

Fig. 3. Deviation of the main axis of AGC from the plane of the horizon during a maneuver and after its completion: 1 – with physical switching to a gyroscope azimuth mode, 2 – with the constant operation of AGC under a gyrocompass mode (analytical gyroscope azimuth)

In Fig. 2, line 3 shows the angle $\beta(t)$ when physically switching AGC to the gyroscope azimuth and gyrocompass modes; line 2 corresponds to the constant AGC operation under a gyrocompass mode (analytical gyroscope azimuth mode). As one can see from Fig. 3, since the accelerometer signal is not disconnected from the azimuthal channel under an analytical gyroscope azimuth mode, the angle $\beta(t)$ is greater than when physically switching to a gyroscope azimuth mode.

5. 3. Procedure for determining the switching time between AGC modes

As noted above, the error $\Delta\alpha$ of estimating the error of AGC during a maneuver with the help of an observation device is determined only by the initial deviation $\Delta\alpha_0$ of the model coordinate $\hat{\alpha}$ from the AGC error α. To reduce this error, one can reduce the delay when switching between the modes of AGC. These delays were introduced in order to ensure the return of AGC to a gyrocompass mode after switching to a gyroscope azimuth mode and eliminating false switching operations between the modes. For AGC-01, the delay time is 60 s. Since when using the analytical gyroscope azimuth mode, the device works all the time under a gyrocompass mode, there is a possibility of a significant reduction in delays. To this end, consider the movement of gyrocompass in the equilateral movement of the vessel, which is described by equations (1).

The solution to the last equation of system (1) at W_η=const and zero initial conditions takes the form:

$$\delta=\frac{W_\eta}{g}+C_1e^{-\lambda t}+e^{-\lambda_0 t}\left(\begin{array}{l}-\left(\frac{W_\eta}{g}+C_1\right)\cos(\rho t)+\\+\frac{1}{\rho}\left(\begin{array}{l}C_1\lambda-\\-\left(C_1+\frac{W_\eta}{g}\right)\lambda_0\end{array}\right)\times\\\times\sin(\rho t)\end{array}\right),\tag{12}$$

where $-\lambda$, $-\lambda_0\pm j\rho$ are the roots of the characteristic equation

$$C_1=\frac{-W_\eta\left(\rho^2+\lambda_0^2\right)}{g\left(\rho^2+(\lambda-\lambda_0)^2\right)}.$$

It should be noted that with the rapid maneuvering of the vessel, the angle β can be neglected in comparison with the accelerometer signal δ, and, therefore, when solving the last equation in (1), β=0 was accepted.

By integrating the first equation in (1) taking into consideration expression (12) under zero initial conditions, one can obtain an analytical expression to deflect the main axis of AGC from the plane of the true meridian during a ship's maneuver:

$$\alpha(t)=r_x\left[\begin{array}{l}\frac{tW_\eta}{g}+\frac{C_1}{\lambda}\left(1-e^{-\lambda t}\right)-\frac{\left(C_1+\frac{W_\eta}{g}\right)}{\rho^2+\lambda_0^2}\times\\\times\left(e^{-\lambda_0 t}\left(\rho\sin(\rho t)-\lambda_0\cos(\rho t)\right)+\lambda_0\right)+\\+\frac{C_1\lambda-\left(C_1+\frac{W_\eta}{g}\right)\lambda_0}{\rho^2+\lambda_0^2}\times\\\times\left(1-\frac{e^{-\lambda_0 t}}{\rho}\left(\rho\cos(\rho t)+\lambda_0\sin(\rho t)\right)\right)\end{array}\right].\tag{13}$$

Let's set the task of selecting the delay time in such a way as to ensure ballistic deviance is no more than the specified value α_{lim} when the vessel sets the speed of 20 knots over time T_m=60 s.

$$\delta_1(t)=\begin{cases}\delta(t), 0\le t\le T_m,\\ \delta(t)-\delta(t-T_m), T_m<t<T_{\delta 0},\end{cases}\tag{14}$$

and ballistic deviance will be determined by the expression

$$\alpha_1(t)=\begin{cases}\alpha(t), 0\le t\le T_m,\\ \alpha(t)-\alpha(t-T_m), T_m<t<T_{\delta 0},\end{cases}\tag{15}$$

where $T_{\delta 0}$ is the time during which the accelerometer filter signal will become zero for the first time after the start of the maneuver.

According to the specified values of the parameters of AGC control circuit, the plot $\delta_1(t)$ will take the form shown in Fig. 4; time $T_{\delta 0}$=240 s. Considering that the limit of the output signal of the accelerometer filter, at which the delay time begins to switch to the analytical gyroscope azimuth mode, is δ_{lim}=5', Fig. 4 shows that the start time of the delay countdown is $t_1 \approx 45$ s.

In order to determine the switching time, the ballistic deviance plot $\alpha_1(t)$ should be used to determine the time t_2 at which ballistic deviance will take the predefined value. Given the value α_{lim}=15', we obtain $t_2 \approx 63$ s from Fig. 5. Therefore, the time of switching delay between the modes should be $t_2 - t_1$=18 s.

It should be noted that the lower limit of the delay time will be determined not so much by the limit value α_{lim} but by the duration of shocks and vibrations, the effect of which on the accelerometer should be discarded to eliminate false switching between the modes of the device.

Fig. 6 shows ballistic deviance plots for the gyrocompass AGC-01 for delays of 60 s (line 1) and 18 s (line 2).

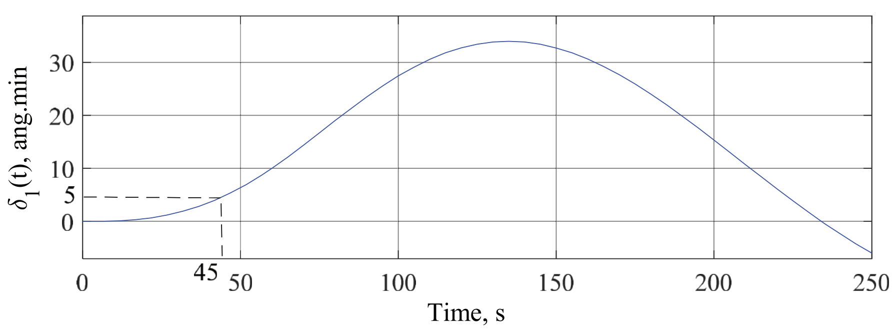

Fig. 4. Accelerometer filter output signal plot

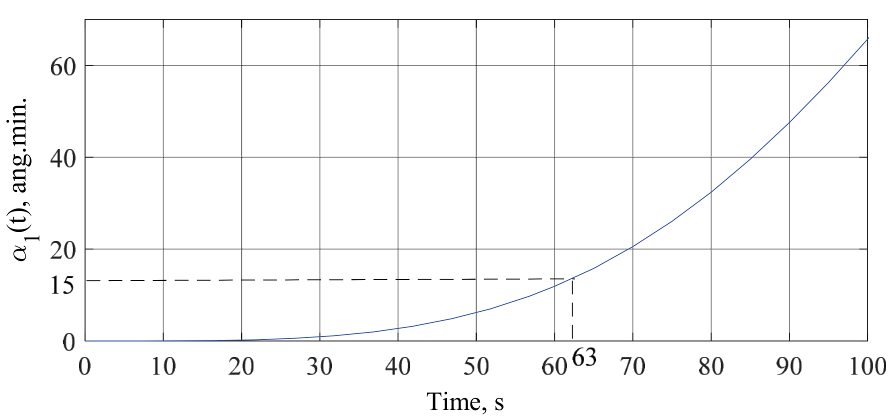

Fig. 5. Ballistic deviance plot

Fig. 6 demonstrates that reducing the delay in switching between the modes in the AGC-01 compass reduces ballistic deviance from 1.0° to 0.3° (20'). The difference between the given deviance value of 15' and the real value of 20' obtained from AGC-01 is explained by the nonlinearity of the digital gyrocompass control system (discreteness of the ADC, limitation of the accelerometer signal, etc.).

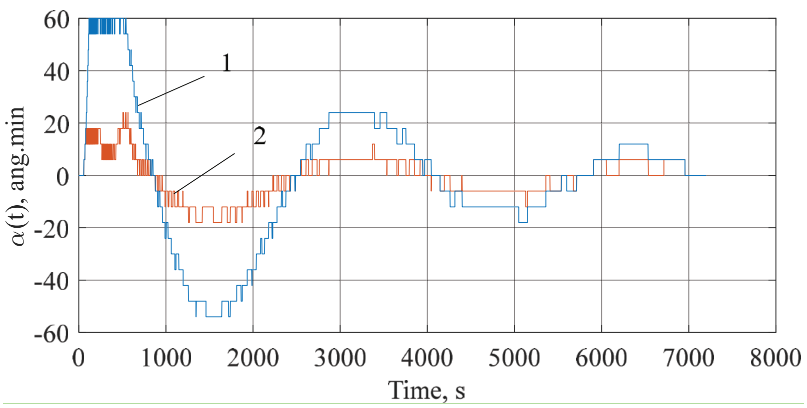

Fig. 6. Ballistic deviation of AGC-01:
1 – with a delay of 60 s, 2 – with a delay of 18 s

At the same time, the use of the observation device in the constant operation of AGC under a gyrocompass mode has an advantage over the two-mode AGC since there is no issue of bringing the main axis into the meridian from large initial deviation angles. Therefore, there is no need to increase the steepness of the control signal r_z for the duration of AGC operation under a gyroscope azimuth mode to the value r_z'. Moreover, by selecting $r_z'=0$ in expression (6) for the gear factor k_2 of the observation device at the time of the ship's maneuver, it is possible to reduce the error $\Delta\beta$ of the observation device at the time of maneuver (the second equation in (9)). At the same time, the error $\Delta\alpha$ of the compensation for ballistic deviance in the observation device after the end of the maneuver will be less.

5. 4. Impact of inaccuracy of parameters of the observation device on the accuracy of error assessment

For the practical application of the proposed approach, it is also necessary to assess the impact of inaccuracy of the parameters of the observation device (for example, due to the scattering of nominal values of electronic elements) on the accuracy of the assessment of gyrocompass errors.

Let the errors Δ_{rx}, Δ_{rz}, Δ_{B1}, Δ_{B2}, Δ_{B3} in setting the parameters of the gyrocompass control circuit be defined as:

$$\Delta_{rx} = r_x - r_{xm}; \quad \Delta_{rz} = r_z - r_{zm};$$

$$\Delta_{B1} = B_1 - B_{1m}, \quad \Delta_{B2} = B_2 - B_{2m},$$

$$\Delta_{B3} = B_3 - B_{3m}. \qquad (16)$$

Subtracting from the equations of movement of gyrocompass (1) expressions (7) and (16), the equation for errors of the observation device was obtained:

$$\Delta\dot{\alpha} - (r_{xm} - k_1)\Delta\delta = \Delta_{rx}\delta;$$

$$\Delta\dot{\beta} + \omega_\eta \Delta\alpha + (r_{zm} + k_2)\Delta\delta = -\Delta_{rz}\delta;$$

$$B_1\Delta\dddot{\delta}+B_2\Delta\ddot{\delta}+B_3\Delta\dot{\delta}+\Delta\delta-\Delta\beta=W_\eta/g-\Delta_T\dot{\delta}. \qquad (17)$$

The main difference between equations (17) and error model (5) with precisely known values of parameters r_x, r_z, B_1, B_2, B_3 is their right-hand side. In the right-hand sides (17) there are terms depending on the output signal of the accelerometer filter δ and its derivative.

With the equilateral movement of the vessel, the error equations of the observation device will take the form:

$$\Delta\dot{\alpha}=\Delta_{rx}\delta;$$

$$\Delta\dot{\beta}+\omega_\eta\,\Delta\alpha=-\Delta_{rz}\delta;$$

$$B_{1m}\Delta\dddot{\delta}+B_{2m}\Delta\ddot{\delta}+B_{3m}\Delta\dot{\delta}+$$
$$+\Delta\delta-\Delta\beta=W_\eta/g-\Delta_T\dot{\delta}. \qquad (18)$$

The solution to the last equation of system (1) at W_η=const and zero initial conditions takes the form of (12). By integrating the first equation in (18) taking into consideration expression (12) under zero initial conditions, one can obtain an analytical expression for the error of the observation device during the maneuver of a vessel:

$$\Delta\alpha(t)=\Delta_{rx}\times\left[\begin{array}{l}\dfrac{tW_\eta}{g}+\dfrac{C_1}{\lambda}\left(1-e^{-\lambda t}\right)-\\ -\dfrac{\left(C_1+\dfrac{W_\eta}{g}\right)}{\rho^2+\lambda_0^2}\times\\ \times\left(e^{-\lambda_0 t}\left(\begin{array}{l}\rho\sin(\rho t)-\\-\lambda_0\cos(\rho t)\end{array}\right)+\lambda_0\right)+\\ +\dfrac{C_1\lambda-\left(C_1+\dfrac{W_\eta}{g}\right)\lambda_0}{\rho^2+\lambda_0^2}\times\\ \times\left(1--\dfrac{e^{-\lambda_0 t}}{\rho}\left(\begin{array}{l}\rho\cos(\rho t)+\\+\lambda_0\sin(\rho t)\end{array}\right)\right)\end{array}\right]. \qquad (19)$$

When the vessel gains the speed of 20 knots over time T_m=60 s, similar to (15), the error of the observation device during a maneuver will be determined by the formula

$$\Delta\alpha_1(t)=\begin{cases}\Delta\alpha(t),\ 0\le t\le T_m,\\ \Delta\alpha(t)-\Delta\alpha(t-T_m),\ T_m<t<T_{\delta 0}.\end{cases} \qquad (20)$$

In practice, the error Δ_{rx} in the r_x control contour parameter model is much smaller than the value of r_x. Therefore, the error of the observation device during the maneuver of a vessel, caused by the inaccuracy of setting the control contour parameters, will be much less than the ballistic deviance of the gyrocompass. As a result, the impact of inaccuracy of setting gyrocompass parameters on the accuracy of error compensation is negligible.

Visually, the work of the observation device when its parameters deviate from the actual values of the parameters of AGC control circuit can be estimated by computer simulation. The behavior of AGC is reproduced according to equations (1), and the work of the observation device is reproduced according to equations (5) and (20) by means of the MATLAB software package at the switching delay between the modes of 60 s (Fig. 7) and 18 s (Fig. 8).

In Fig. 7, 8, line 1 shows an error in assessing the ballistic deviance of AGC in the proposed observation device when its parameters coincide with the actual parameters of AGC. Line 2 shows the error of the observation device when the r_{xm} value deviates from r_x by +10 %, line 3 – when r_{xm} deviates from r_x by −10 %.

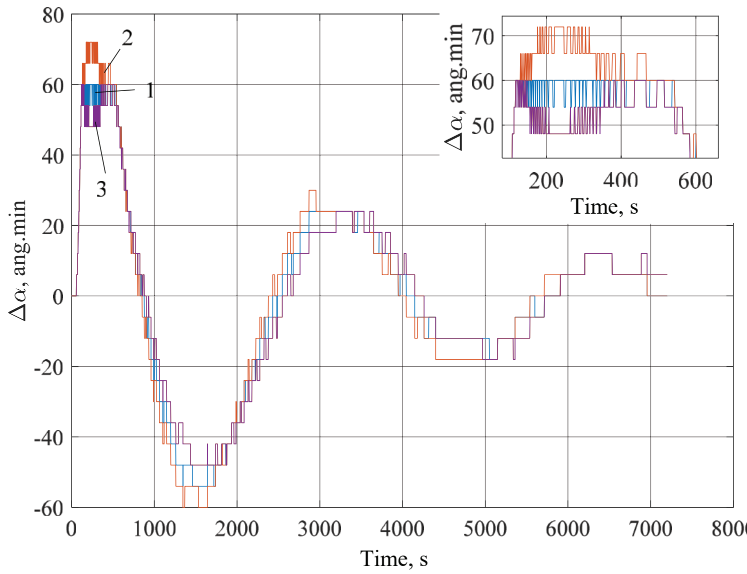

Fig. 7. Error in assessing the ballistic deviance of AGC with a delay of 60 s and a deviation of the value of model parameter r_{xm} from the real value r_x: 1 — when the parameters of the observation device coincide with the real parameters of AGC; 2 — when the r_{xm} value deviates from r_x by +10 %, 3 — when the r_{xm} value deviates from r_x by −10 %

The plots in Fig. 7 demonstrate that with a delay of 60 s and the specified inaccuracy in setting the parameter model r_x, the error of the observation device changes by no more than 15–20 %. At the same time, with a delay of 18 s (Fig. 8), the deviation at +10 % is 15', and at –10 % is –20'. That is, with a decrease in the value of ballistic deviance, the influence of inaccuracy in determining the r_x parameter on its assessment increases significantly.

A much less critical is the observation device to the inaccuracy of setting another parameter of the control circuit of AGC – r_z. As follows from the analysis above, the inaccuracy of setting this parameter does not significantly affect the error Δα of the observation device during the maneuver of a vessel. Differences are observed only in the transition process of reducing the error Δα after the end of the maneuver. Fig. 9, 10 show simulation results for a delay time of 60 s and 18 s, respectively. Line 1 in both figures corresponds to the exact parameters of AGC specified in the model, line 2 corresponds to the deviation of the r_{zm} value from r_z by +10 %, line 3 corresponds to the deviation of r_{zm} from r_z by –10 %.

The plots in Fig. 9, 10 confirm the slight impact of the inaccuracy of setting the r_z parameter on the operation of the observation device.

The coefficients of the digital filter B_1, B_2, B_3 are determined programmatically and, therefore, can be set completely identical both in the gyrocompass and in the observation device, so it makes no sense to consider them.

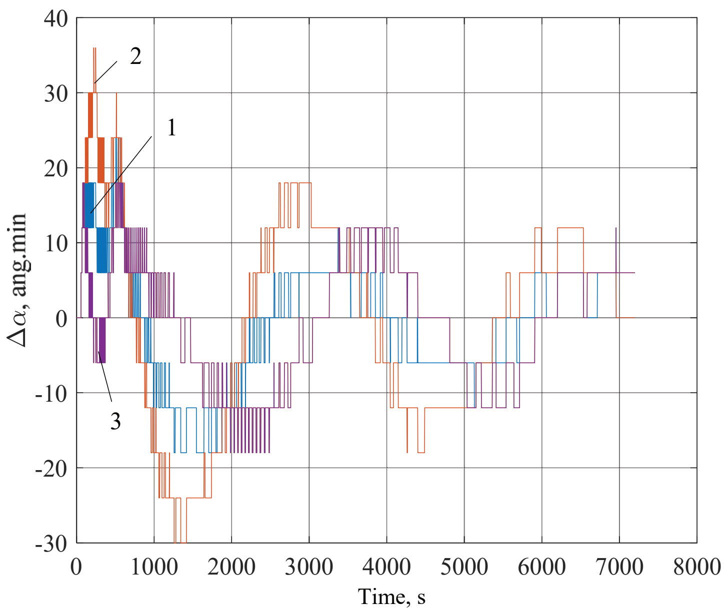

Fig. 8. Error in assessing the ballistic deviance of AGC with a delay of 18 s and a deviation of the value of model parameter r_{xm} from the real value r_x: 1 – when the parameters of the observation device coincide with the real parameters of AGC; 2 – when the r_{xm} value deviates from r_x by +10 %, 3 – when the r_{xm} value deviates from r_x by –10 %

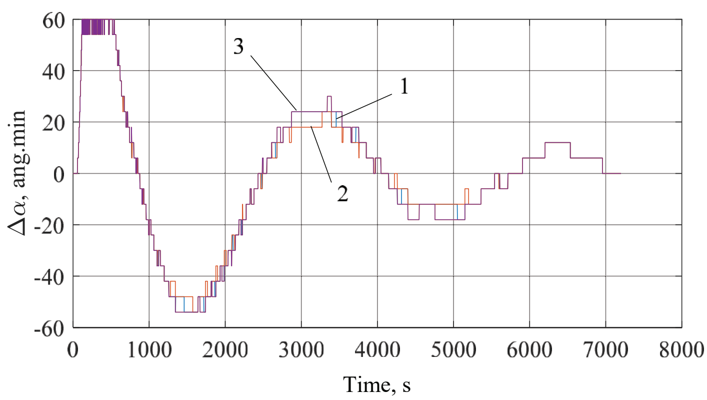

Fig. 9. Error in assessing the ballistic deviance of AGC with a delay of 60 s and a deviation of the value of the r_{zm} model parameter from the real value r_z: 1 – the parameters of AGC precisely specified in the model; 2 – deviation of r_{zm} from r_z at +10 %; 3 – deviation of r_{zm} from r_z by –10 %

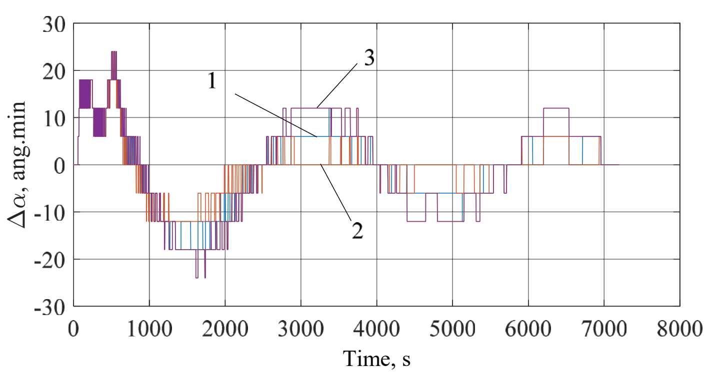

Fig. 10. Error in assessing the ballistic deviance of AGC when delaying for 18 s and deviating the value of the r_{zm} model parameter from the real value r_z: 1 – the parameters of AGC precisely specified in the model; 2 – deviation of r_{zm} from r_z at +10 %; 3 – deviation of r_{zm} from r_z by –10 %

6. Discussion of results of the proposed improvement of the analytical gyroscope azimuth regime

The improved technique of compensating for ballistic deviance using the synthesized observation device makes it possible to compensate for the ballistic deviance of AGC based on the information available in the device, namely the horizon indicator signal (accelerometer). At the same time, the error $\Delta\alpha$ of evaluation when using the synthesized observation device of AGC error on the maneuver does not depend on the magnitude of the acceleration of vessel W_η and is determined only by the initial deviation $\Delta\alpha_0$ of the model coordinate $\hat{\alpha}$ from the error of AGC α. This can be seen from equations (7) that describe the error model of the observation device, in particular, the first equation in (7). As a result, with the exact equality of the model parameters to the real parameters r_x, r_z, B_1, B_2, B_3 of the control circuit of AGC, the accuracy of compensation for the error $\Delta\alpha$ is determined by the amount of the switching delay time between the gyrocompass modes.

Compared to classical algorithmic compensation [12], the technique does not require the use of additional devices (a lag or GPS receiver) to assess ballistic deviance. The use of the observation device also has an advantage over the two-mode AGC [13]: there is no issue with bringing the main axis into the meridian from large initial deviation angles and the device retains the property of selectivity relative to the meridian. This is because the device physically works all the time under a gyrocompass mode (the horizon indicator signal is connected to the azimuthal channel).

The comparison showed that the use of the analytical gyroscope azimuth mode is as effective as the application of the classic switching of AGC to a gyroscope azimuth mode at the time of a maneuver (Fig. 2). This is because the synthesized observation device and gyrocompass are described by the same mathematical models with equal values of coefficients, which determines the proximity of deviance and its evaluation.

It should be noted that the error in compensation for ballistic deviance of the gyrocompass with a rapid change in the speed of a vessel by 20 knots is no more than ±1.0°, which meets the requirements of IMA Resolution A.424 (XI).

The proposed procedure for calculating the time of switching delay between the AGC modes makes it possible to determine the delay time for the predefined value of the maximum ballistic deviance of AGC. As shown in Fig. 5, by reducing the switching time between gyrocompass modes, it is possible to reduce ballistic deviance to a value of about 0.3° (Fig. 6). This can be explained by the fact that with a decrease in switching time, the initial deviation $\Delta\alpha_0$ decreases. At the same time, for the gyrocompass AGC-01, the really defined value of deviance turned out to be higher than the predefined one, which is explained by the presence in the gyrocompass of nonlinearities inherent in the digital control system (discreteness of ADC, limitation of the magnitude of the accelerometer signal, etc.).

The limitation for the practical application of the presented technique could be the inaccuracy of setting the error model but the proposed observation device is little sensitive to changes in the parameters of the AGC error model. With a switching delay between the modes of 60 s, the inaccuracy of setting the parameters of the observation device affects the assessment of ballistic deviance in the range of 15–20 % when changing the r_x parameter by 10 % (Fig. 7). At the same time, with a decrease in the switching time between the modes, the assessment of ballistic deviance when changing the r_x parameter by 10 % changes by 15'–20' (Fig. 8). This is commensurate with the given deviance estimate of 15' but is still 6–8 times less than the requirements of IMO Resolution A.424 (XI) (up to ±2°). Changing the r_z parameter with an observation device has virtually no effect on assessing ballistic deviance (Fig. 9, 10). The effect of parameters B_1, B_2, B_3 was senseless to consider since when using digital filtering, the values of these coefficients in AGC and in the observation device will be exactly equal.

Thus, the disadvantage of the synthesized observation device is to increase its sensitivity to the accuracy of setting the r_x parameter while reducing the switching time between the modes. To reduce the sensitivity of the observation device to the accuracy of setting the r_x parameter, additional research is required.

The low sensitivity of the observation device to changing the model parameters over a relatively long switch delay time (about 60 s) allows such a device to be used on standard compasses. At the same time, there is no need to reconfigure the parameters of the model for a particular device and one can get the predefined value of the residual error of compensation for deviance.

Outside our study is the issue of automating the setting up of the observation device to compensate for the drifts of the gyroscope, which may be the subject of further research. The main problem in such studies could be the synthesis of the corresponding observation device.

7. Conclusions

1. During our work, based on the gyrocompass model, an observation device was synthesized. This device makes it possible to evaluate the ballistic deviance of AGC based on the information available in the device, namely the horizon indicator signal (accelerometer). The error in a compensation for the ballistic deviance of a gyrocompass with a rapid change in the speed of the vessel by 20 knots is no more than ±1.0°.

2. Comparing the effectiveness of the modes of analytical gyroscope azimuth and the classic switching of AGC to a mode of gyroscope azimuth has revealed that the mode of analytical gyroscope azimuth makes it possible to compensate for the ballistic error of the gyrocompass as effectively as the classic switching of the device.

3. A procedure for calculating the switching time between the modes of AGC has been proposed. By applying the proposed technique for switching between the modes, it was possible to reduce ballistic deviance to a value of about 0.3° by reducing the delay from 60 s to 18 s. However, this increased the sensitivity of the monitoring device to the inaccuracy of setting the parameter r_x.

4. An analytical expression was built for an error of the observation device during the maneuver of a vessel, which makes it possible to estimate this error. According to our results, an inaccuracy of 10 % in setting the parameter r_x of the observation device during a delay of 60 s affects the assessment of ballistic deviance in the range of 15–20 %. Changing the r_z parameter by 10 % has no effect on the assessment of ballistic deviance. At a delay time of 18 s, the measurement of deviance when changing the r_x parameter changes significantly (by a value of +15'/–20'), and the change in the r_z parameter has almost no effect on deviance estimation.

Acknowledgments

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