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INCREASING THE ACCURACY OF THE VESSEL'S COURSE ORIENTATION

The object of the study is the process of increasing the accuracy of measuring the vessel's course and course orientation by using the mathematical model of the gyrocompass in the on-board computer. On modern vessels, the gyrocompass is the main course measuring device. Its advantages lie in measuring the current course relative to the geographic meridian, its readings are not affected by magnetic anomalies, as was the case when using magnetic compasses, which led to a partial or complete loss of orientation of control objects. At the same time, gyrocompasses also have their drawbacks. The most significant of them is the inertial deviation of the sensitive element caused by the curvature of the Earth's surface, a change in course, acceleration or deceleration of the vessel. With the appearance of the moments of these forces, the axis of the gyrocompass leaves the equilibrium position and begins to make precessional movements. To reduce the inertial deviation, constructive solutions and recommendations to shipmasters regarding the consideration of deviational errors are used. Structural solutions lead to an increase in weight, complexity of the design, a decrease in reliability, and an increase in cost. The recommendations of regulatory documents regarding the consideration of the inertial deviation of the sensitive element of the gyrocompass are difficult to implement in practice, but they can be implemented in the on-board computer of the vessel control system by using a mathematical model of the sensitive element. The paper developed a method of increasing the accuracy of gyrocompass course measurement and the accuracy of course orientation by using an observation device built on the basis of a mathematical model of the gyrocompass in the on-board computer of the course control system. This makes it possible to estimate the useful component of course measurement and deviational errors from changes in speed and course, the curvature of the earth's surface. The useful component, without deviational errors, is used in the vessel's course control channel. The developed method can be used on vessels, provided it is integrated into the existing automated system of the on-board computer to solve the problem of monitoring the components of the gyrocompass measurement.

Keywords: *intelligent transport systems, automatic control, navigational safety, human factor, inertial deviation, course orientation accuracy.*

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1. Introduction

Most modern vessels use a gyrocompass to measure the ship's heading. There are several reasons for this: compared to a magnetic compass, a gyrocompass indicates the heading relative to the geographic meridian, as its operation is based on the interaction of the kinetic moment vector of the sensitive element (SE) with the Earth's rotational angular velocity vector. Gyrocompass readings are not prone to magnetic anomalies, as is the case with magnetic compasses, which led to partial or complete loss of orientation of control objects. Therefore, gyrocompasses remain the primary source of information on the ship's heading today. At the same time, gyrocompasses also have their drawbacks. The most significant of these is the inertial deviation of the sensitive element caused by the curvature of the Earth's surface, changes in course, acceleration, or deceleration of the vessel. When these forces occur, the gyrocompass axis moves from its equilibrium position and begins to make precessional movements. The variable error resulting from a maneuver is called the gyrocompass's inertial error. It is inherent in most modern gyrocompasses regardless of their design. In practice, during maneuvers that are often repeated, any calculations to determine inertial errors are not performed. Instead, ship operators are recommended by regulatory documents to critically assess their possible magnitude and nature of change. The recommendations of regulatory documents regarding the consideration of the gyrocompass's inertial deviation of the sensitive element are difficult to implement in practice. However, they can be implemented in the onboard computer of the ship's control system by using a mathematical model of the sensitive element.

The question of using a gyrocompass for course measurement and reducing measurement errors has been the subject of many studies by authors. For instance, in [1], the basic theoretical information about: angular velocity sensors; integrating gyroscopes; GPC-48, GPC-52 directional gyroscopes; gyro-magnetic compasses; «Course-3», «Mayak» gyrocompasses, ground pendulum gyrocompass, aviation horizon AGI-1; remote aviation horizon AGD-1 is provided. Their designs, advantages, and drawbacks are discussed.

In the work [2], mathematical models of the following navigation systems are considered: inertial navigation system; heading system; air signaling system; Doppler velocity and drift angle measuring system; short-range radio navigation system; long-range radio navigation system; onboard radar station and radio navigation equipment; astro navigation system; satellite radio navigation system; barometric altimeter; radio altimeter. The main calculation formulas and errors in determining navigation parameters are provided.

In [3], issues related to the development of a mathematical model of the technological production process are discussed, which can be applied both in an automated control system and in an automatic system to optimize parameters. The advantages of using a mathematical model are as follows: the possibility of obtaining an adequate and accurate mathematical model of the production process, relatively simple implementation of such an approach, and the availability of objective data generated by the control object itself. The obtained dynamic model allows adequately describing the nature of parameter changes within a range that significantly exceeds regulatory limits. This is particularly important when applied in reactor safety control systems and technological simulators. As a result of the research, it was found that considering the chemical reaction process in the model allows controlling such a complex parameter as the catalyst activity change. This indicator is crucial in determining the need for model adaptation.

In work [4], research on the optimization of the technological process is described. A method of identifying the control object using its transient characteristics has been developed. The advantages of this approach include: the use of objective data generated by the control object itself, simple implementation, and obtaining an adequate and accurate mathematical model. As a result of the research, it was found that the control object can be described with sufficient accuracy by a system of second-order differential equations. This significantly simplifies the analysis and synthesis of the control system. During the research, the following questions were addressed: the necessary number of points on the control object's acceleration curve was determined; an identification algorithm was defined; a method of placing points on the control object's acceleration curve was developed; the influence of the number and location of points on the approximation error was determined. The proposed method of obtaining a mathematical model allows obtaining optimal process output parameters by adjusting the input variables.

In [5], errors of strapdown inertial navigation system algorithms and methods for their reduction are considered. The main task is to confirm the possibility, in the presence of conical motion, of using simple algorithms with high sampling frequency while maintaining accuracy compared to more accurate and structurally complex algorithms implemented at lower frequencies.

In work [6], a method of horizontal correction of the strapdown inertial platform from accelerometers tuned to the Schuler frequency is developed, based on the use of differential equations and quaternion calculus. The equations of errors of the mathematical platform are derived and analyzed. Experimental studies were conducted aboard a moving object using a prototype strapdown inertial platform. The results of the experiment confirmed the effectiveness of the developed method.

In [7], the principle of operation, schematic solution, and design of a fundamentally new electronic device that registers the Earth's magnetic field and accurately indicates the true direction to the North are described. The electronic device has no moving mechanical parts or mechanisms. It is proposed to increase the sensitivity of the magnetic field sensor based on a two-collector magneto-transistor by using magnetic field concentrators. As a result of experiments, it was possible to achieve a 400-fold increase in sensor sensitivity. Magnetic field concentrators also allow improving the signal-to-noise ratio at the output of the electronic circuit by 100 times.

In [8], issues related to compensating for the lateral shift of the vessel caused by inertial errors of the gyrocompass are considered. Inertial errors occur during vessel maneuvering, leading to the appearance of lateral shift after the vessel turns, which can result in accidents. The task is to reduce the magnitude of the lateral shift. The paper conducts an analysis of literary sources addressing this problem and obtains a dependency of the total inertial deviation on the nature of the maneuver and the geographic latitude of the vessel's navigation. It is shown that the lateral shift is an integral function relative to the deviation function. It is noted that the lateral shift provides a more complete characterization of the gyrocompass accuracy over extended time intervals, as it reflects the effects of maneuvering on the gyrocompass in a «smoothed» form. From these perspectives, it is evident that inertial deviation is an indicator of the gyrocompass's instantaneous accuracy. A computer program is developed to calculate and plot the dependency curve of the total inertial error over time. The results of computer modeling indicate that the total inertial error and lateral shifts increase with geographic latitude growth; however, with partial compensation, the total lateral shift decreases approximately fivefold, and with variable additional course correction, the lateral shift of the vessel is eliminated.

In [9], it is noted that one of the main errors of the gyrocompass is ballistic deviation, which occurs during vessel maneuvering. The known method of reducing ballistic deviation (physical switching of the device to the gyro azimuth mode) has a drawback: under certain conditions, the gyrocompass may not return to the meridian after maneuvering and become inoperative. Another known method, algorithmic compensation by calculating ballistic deviation, requires information from external devices such as a log and/or GPS (Global Positioning System) receiver. As part of the study, it is proposed to improve azimuth measurement by using an accelerometer with a third-order filter for filtration, which allows compensating for ballistic deviation and smoothing the signal. The proposed method can be applied to standard gyrocompasses without switching to azimuth mode and achieve residual deviation errors of no more than 0.3°.

In [10], a study of an astatic compensating gyrocompass built on the basis of a hybrid type modulation micromechanical gyroscope (MMG) is conducted. The kinematic scheme is presented, and the operating principle of the device is described. The device utilizes modulation principle based on obtaining information about the angular motion of the rotor and creating control moments in the rotating coordinate system, which allows eliminating such a significant drawback of MMG as «zero bias». A distinctive feature of the discussed gyrocompass is the use of two channels for controlling the MMG rotor, namely: a channel for forming the guiding moment that aligns the main axis with the true meridian and a channel for compensating this guiding moment. A linearized mathematical model is constructed, based on which an algorithm for the operation of the astatic compensating gyrocompass is implemented. The developed device can be used to determine the true azimuth along the longitudinal axis of a moving object, it has a higher measurement speed compared to devices built on three-stage «heavy» gyroscopes, and it has good resistance to external influences such as vibrations, impacts, etc.

From the analysis of the literature, it is evident that various structural solutions [1, 7] and methods [5, 6, 8, 9] are utilized to reduce measurement errors of the course. Additionally, mathematical models are employed for control process optimization, as seen in references [3, 4, 10]. However, methods for enhancing the accuracy of course measurement through the use of a mathematical model of the measuring device (gyrocompass) in the onboard computer of an automated system have not been identified by the authors. Therefore, the development of such methods remains a relevant scientific and technical task.

The aim of research is to develop a method to enhance the accuracy of ship heading and orientation measurements by utilizing a mathematical model of the gyrocompass in the onboard computer of an automated system. This method involves automatically assessing the useful component of heading measurement and deviations, utilizing only the useful component in the control system, excluding deviations. This approach will enhance the precision of the ship's heading, reduce the maneuvering area, mitigate human factors' influence on control processes, and enhance maritime safety.

2. Materials and Methods

The object of research is the process of increasing the accuracy of measuring the vessel's course and course orientation by using the mathematical model of the gyrocompass in the on-board computer. The research employed a systematic approach, analysis and synthesis, mathematical analysis, methods of automatic control theory, and experimental procedures. Additionally, the equipment included a personal computer with Windows 10 operating system and MS Office 2016 application suite, as well as the MATLAB environment.

3. Results and Discussion

The mathematical model of the SE gyrocompass in projections onto the axes of the gyroscopic coordinate system can be represented as [9]:

$$\begin{cases} H\dot{\Theta} = \sum_{j=1}^{n} M_{yj}, \\ -H\cos\Theta\,\dot{\Psi} = \sum_{j=1}^{n} M_{zj}, \end{cases} \qquad (1)$$

where H is the kinetic moment of the rotor; Θ, Ψ are the angles of displacement of the gyrocompass frame in the gyroscopic coordinate system; M_{yj}, M_{zj} are the moments of external influences from the rotation of the Earth, the curvature of the Earth's surface and the maneuvering of the vessel in projections onto the axes of the gyroscopic coordinate system.

After expanding the right-hand sides, system of equations (1) takes the form:

$$\begin{cases} \dot{\Theta} = -\omega_3\cos\sigma\sin\Psi - \dfrac{V}{R}\left(\sin K\sin\Psi - \cos K\cos\Psi\right), \\ \dot{\Psi} = \omega_3\left(\cos\sigma\cos\Psi\,\mathrm{tg}\,\Theta - \sin\sigma\right) + lmg\,\mathrm{tg}\,\Theta - \\ -\dfrac{V}{R}\mathrm{tg}\,\Theta\left(\cos K\sin\Psi - \sin K\cos\Psi\right) - \dfrac{V_r}{r} - \\ -mal\left(\cos K\cos\Psi + \sin K\sin\Psi\right), \end{cases} \qquad (2)$$

where ω_3 is the angular velocity of the Earth's rotation; σ is the geographic latitude; V is the ship's speed; K is the ship's course; R is the radius of the Earth; m is the displaced mass of the gyrocompass casing; l is the arm of the displaced mass; g is the acceleration due to gravity; V_r is the circulation speed; r is the circulation radius; a is the acceleration of the vessel.

In the equations of system (2), the components:

$$\begin{cases} f_0^{\Theta} = -\omega_3\cos\sigma\sin\Psi, \\ f_0^{\Psi} = \omega_3(\cos\sigma\cos\Psi\,\mathrm{tg}\,\Theta - \sin\sigma), \end{cases} \qquad (3)$$

define the deviations of the gyrocompass SE in the vertical and horizontal planes caused by the angular velocity of the Earth's rotation. These components are beneficial as they align the gyrocompass SE with the meridian.

Components:

$$\begin{cases} f_1^{\Theta} = -\dfrac{V}{R}(\sin K\sin\Psi - \cos K\cos\Psi), \\ f_1^{\Psi} = -\dfrac{V}{R}\mathrm{tg}\,\Theta(\cos K\sin\Psi - \sin K\cos\Psi), \end{cases} \qquad (4)$$

determine the deviations of the gyrocompass SE caused by the curvature of the Earth's surface.

Components:

$$\begin{cases} f_2^{\Psi} = lmg\,\mathrm{tg}\,\Theta, \\ f_3^{\Psi} = -\dfrac{V_r}{r}, \\ f_4^{\Psi} = -mal(\cos K\cos\Psi + \sin K\sin\Psi), \end{cases} \qquad (5)$$

determine the deviations of the gyrocompass SE from the moments of changes in course and ship speed.

As seen from the equations of system (2), the mathematical model of the gyrocompass SE includes both useful and deviation components of motion that affect the accuracy of course determination.

To assess these components, let's formulate the observation device's system of equations based on the mathematical model of the gyrocompass (2):

$$\begin{cases} \dfrac{d\hat{\Theta}_{0m}}{dt} = f_0^{\Theta} + \lambda_0^{\Theta}(\Theta_m - \hat{\Theta}_m), \\ \dfrac{d\hat{\Theta}_{1m}}{dt} = f_1^{\Theta} + \lambda_1^{\Theta}(\Theta_m - \hat{\Theta}_m), \end{cases} \qquad (6)$$

$$\begin{cases} \dfrac{d\hat{\Psi}_{0m}}{dt} = f_0^{\Psi} + \lambda_0^{\Psi}(\Psi_m - \hat{\Psi}_m), \\ \dfrac{d\hat{\Psi}_{1m}}{dt} = f_1^{\Psi} + \lambda_1^{\Psi}(\Psi_m - \hat{\Psi}_m), \\ \dfrac{d\hat{\Psi}_{2m}}{dt} = f_2^{\Psi} + \lambda_2^{\Psi}(\Psi_m - \hat{\Psi}_m), \\ \dfrac{d\hat{\Psi}_{3m}}{dt} = f_3^{\Psi} + \lambda_3^{\Psi}(\Psi_m - \hat{\Psi}_m), \\ \dfrac{d\hat{\Psi}_{4m}}{dt} = f_4^{\Psi} + \lambda_4^{\Psi}(\Psi_m - \hat{\Psi}_m), \end{cases} \tag{7}$$

$$\begin{cases} \hat{\Theta}_m = \hat{\Theta}_{0m} + \hat{\Theta}_{1m}, \\ \hat{\Psi}_m = \hat{\Psi}_{0m} + \hat{\Psi}_{1m} + \hat{\Psi}_{2m} + \hat{\Psi}_{3m} + \hat{\Psi}_{4m}. \end{cases} \tag{8}$$

The systems of differential equations (6), (7) and the system of algebraic equations (8) of the observer devices are integrated in the onboard computer of the automated system. The component $\hat{\Psi}_{0m}$ of the first equation of system (7) provides an estimation of the useful component of the heading measurement without deviation components $\hat{\Psi}_{jm}$, $j=1...4$. Using this component allows to increase the accuracy of the course movement of the controlled object:

$$\delta = f_u(\hat{\Psi}_{0m}, \Psi^*, C_u). \tag{9}$$

The functionality and effectiveness of the method were verified through mathematical modeling in the MATLAB environment. Fig. 1 and Fig. 2 depict the time evolution graphs of the following parameters: yaw angular velocity ω_z, degr/sec, measured yaw angular velocity ω_{zm}, degr/sec, estimated yaw angular velocity ω_{zw}, degr/sec, course ψ, degr, measured course ψ_m, degr, estimated course ψ_w, degr, ship speed V, m/sec difference $\Delta\psi$, degr between the measured heading angle of the gyrocompass SE and its estimation, estimation of the useful component of the gyrocompass SE deviation angle $\hat{\psi}_{0m}$, degr, measured gyrocompass SE deviation angle ψ_m, degr in the horizontal plane, measured gyrocompass SE deviation angle Θ_m, degr in the vertical plane, estimation of the gyrocompass deviation SE angle $\hat{\psi}_m$, degr in the horizontal plane.

Fig. 1 presents the results of mathematical modeling of ship acceleration.

Initial conditions: longitudinal ship velocity $V(0)=0$ m/s, yaw rate $\omega_z(0)=0$ degr/sec, ship heading $\psi(0)=0°$, initial deviation of the gyrocompass SE frame from the meridian $\Psi_m(0)=0°$. Starting from time $t=2000$ seconds, the ship begins to accelerate to the velocity $V=10$ m/sec. As seen from the provided graphs, the deviations Ψ_m, $\hat{\Psi}_m$ of the gyrocompass SE and its estimation increases up to 10 degrees due to disturbing moments during the ship's acceleration. However, the deviation of the useful component of the estimation does not exceed 0.5 degrees during this time.

In Fig. 2, there are the results of the mathematical modeling of the change in ship heading are presented.

Initial conditions: longitudinal speed of the vessel $V(0)=10.4$ m/s, yaw angular velocity $\omega_z(0)=0$ degr/sec, vessel heading $\psi(0)=0°$, initial deviation of the gyrocompass SE frame from the meridian $\Psi_m(0)=0°$. Starting from the moment $t=2000$ seconds, the vessel begins to change its course from $\psi(0)=0°$ to $\psi=90°$. As seen from the graphs ψ_m, $\hat{\psi}_m$, the deviation of the gyrocompass SE and its deviation estimate increase to 20 degrees due to disturbing moments from the change in course. At the same time, the estimate of the useful component $\hat{\Psi}_{0m}$ changes almost perfectly.

In conclusion, considering the experimental results, it can be stated that the developed methods, models, and tools allow for the assessment of deviation errors in heading measurements and increase the accuracy of heading and course measurements by 5–10 times. The achieved result is attributed to the utilization of the mathematical model of the gyrocompass in the onboard computer, evaluation of the useful component of heading measurements and deviation errors, and utilization of only the useful component in the control system, without deviation errors. Compared to known solutions, the developed method enables automatic consideration of gyrocompass deviation errors, reduces the influence of human factors on control processes, improves the accuracy of course control, reduces the maneuvering area, and enhances maritime safety.

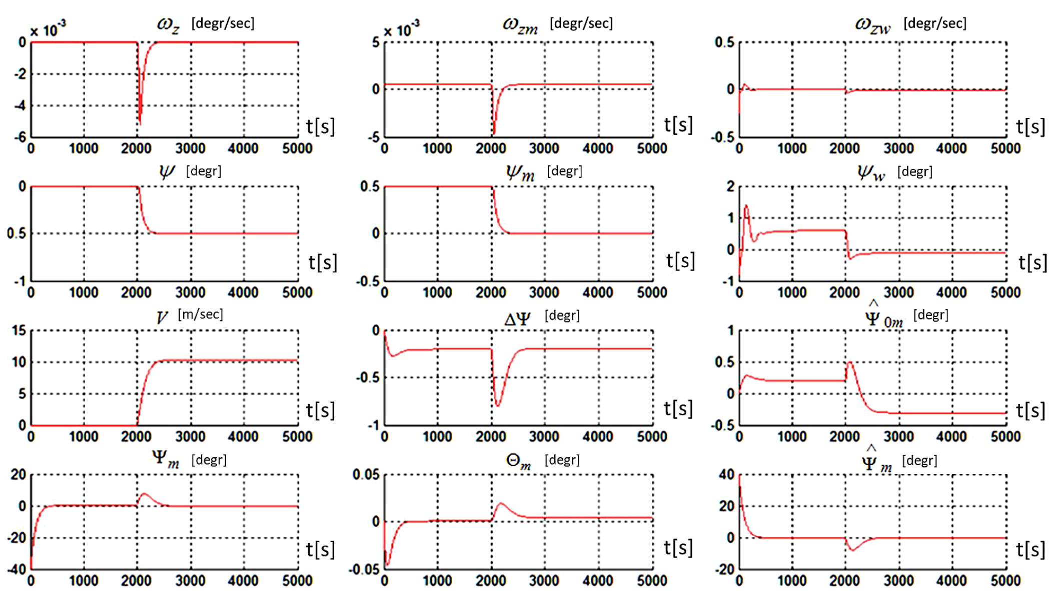

Fig. 1. The results of ship acceleration modeling

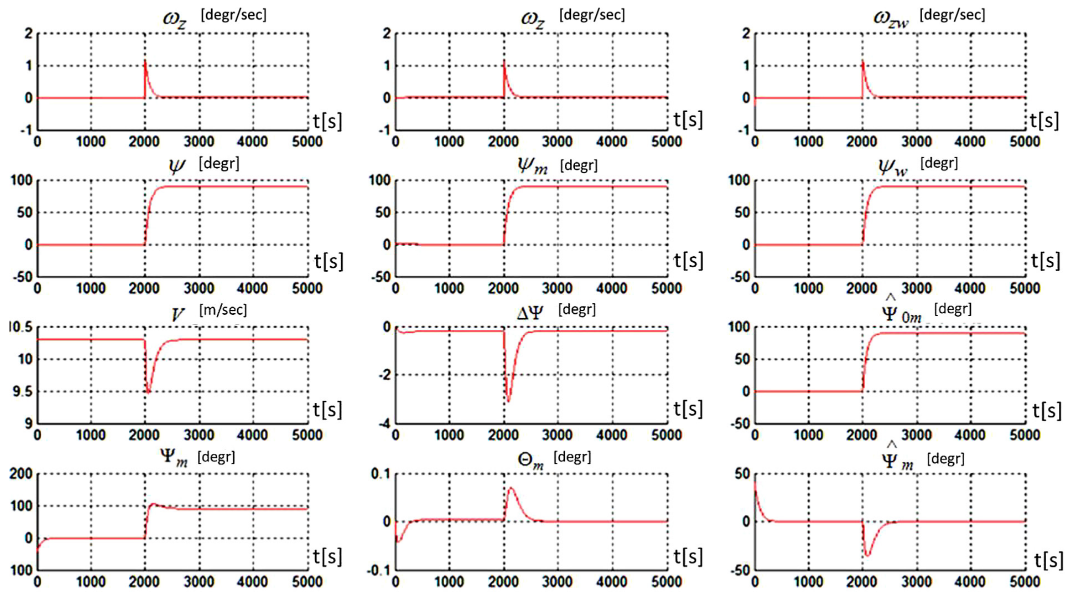

Fig. 2. The results of simulating the change in the ship's course

The developed method can be implemented on vessels by integrating it into existing automated onboard computer systems with the mathematical model of the gyrocompass.

The theoretical significance of the obtained result lies in the development of a method to increase the accuracy of ship course control. The practical significance of the obtained result lies in the development of models and tools to improve course accuracy, with potential applications in the development of automated course control systems. This would enable improved course accuracy, reduced maneuvering area, decreased human influence on control processes, and enhanced maritime safety.

Limitations of the developed method include its inability to be applied for manual control.

Future work aims to investigate the feasibility of using simpler and more reliable gyrocompasses with mathematical models in onboard computers for course control.

4. Conclusions

A method has been developed for increasing the accuracy of gyrocompass course measurement and the accuracy of course orientation by using an observation device built on the basis of a mathematical model of the gyrocompass in the on-board computer of the course control system. This makes it possible to estimate the useful component of course measurement and deviational errors from changes in speed and course, the curvature of the earth's surface. The useful component, without deviational errors, is used in the vessel's course control channel. The developed method can be implemented in the onboard computer of an automated system or in the onboard computer of an automatic course control module. This will increase the accuracy of heading measurement, accuracy of ship course, reduce the maneuvering area, diminish the influence of human factors on control processes, and enhance maritime safety.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Nesterenko, O. I., Sapehin, O. M. (2022). *Hiroskopichni i navihatsiini prylady*. Kyiv: KPI im. Ihoria Sikorskoho, 138.
2. *Matematychni modeli datchykiv informatsii*. Available at: https://er.nau.edu.ua/bitstream/NAU/11005/4/4-%D0%93%D0%BB_3.pdf
3. Kulikov, D. O., Kupina, O. A., Loriia, M. H., Tselishchev, O. B. (2022). Use of a mathematical model for optimization of dynamic parameters of ammonia production processes. *Visnik of the Volodymyr Dahl East Ukrainian National University, 5 (275),* 49–54. doi: https://doi.org/10.33216/1998-7927-2022-275-5-49-54
4. Kupina, O. A., Loriia, M. H., Tselishchev, O. B., Homa Akhmed, H. A. (2021). Identification of dynamic characteristics of control objects. *Visnik of the Volodymyr Dahl East Ukrainian National University, 6 (270),* 129–134. doi: https://doi.org/10.33216/1998-7927-2021-270-6-129-134
5. Melashchenko, O. M., Volovyk, B. V. (2012). *Analiz tochnosti alhorytmiv intehruvannia kinematychnykh rivnian rukhu tverdoho tila*. Available at: https://ela.kpi.ua/bitstream/123456789/7305/1/p_09.pdf
6. Plotnikov, P. K., Mikheev, A. V., Naumov, S. G. (2013). *Pogreshnosti besplatformennogo girokompasa dlia obektov s neogranichennymi uglami povorotov*. Available at: http://optolink.ru/documents/Publications/Our/%D0%9C%D0%9A%D0%98%D0%9D%D0%A1-2013%20%D0%9F%D0%BB%D0%BE%D1%82%D0%BD%D0%B8%D0%BA%D0%BE%D0%B2.pdf
7. Vikulin, I. M., Mikhailov, N. S., Mikhailov, S. A. (2020). Electronic compass for unmanned ships. *Shipping & Navigation, 30 (1),* 42–50. doi: https://doi.org/10.31653/2306-5761.30.2020.42-50

ISSN 2664-9969

8. Alekseychuk, M. S., Chapchay, P. A., Avramenko, E. A. (2020). Decline of lateral displacement of ship after a maneuver by the input of additional amendment of the course. *Shipping & Navigation, 30 (1),* 8–15. doi: https://doi.org/10.31653/2306-5761.30.2020.08-15
9. Ivanov, S., Oliinyk, P., Virchenko, G. (2022). Improving an analytical gyroscope azimuth mode to compensate for the ballistic deviation of a marine gyrocompass. *Eastern-European Journal of Enterprise Technologies, 3 (5 (117)),* 36–46. doi: https://doi.org/10.15587/1729-4061.2022.259024
10. Bogolyubov, V., Bakhtieva, L. (2021). Compensation Gyrocompass Based on MEMS. *Journal of Physics: Conference Series, 2096 (1),* 012203. doi: https://doi.org/10.1088/1742-6596/2096/1/012203

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