Electrical, Control and Communication Engineering
ISSN 2255-9159 (online)
ISSN 2255-9140 (print)
2022, vol. 18, no. 1, pp. 66–74
https://doi.org/10.2478/ecce-2022-0009
https://content.sciendo.com

Automatic Vessel Steering in a Storm

Serhii Zinchenko* (*Associate professor, Kherson State Maritime Academy, Kherson, Ukraine*),
Oleh Tovstokoryi (*Head of the ship handling department*, *Kherson State Maritime Academy, Kherson, Ukraine*),
Vadym Mateichuk (*Senior Lecturer, Kherson State Maritime Academy, Kherson, Ukraine*),
Pavlo Nosov (*Associate Professor, Kherson State Maritime Academy, Kherson, Ukraine*),
Ihor Popovych (*Full Professor, Kherson State University, Kherson, Ukraine*),
Igor Gritsuk (*Full Professor, Kherson State Maritime Academy, Kherson, Ukraine*)

Abstract – **The issues of automatic vessel control in a storm are considered in the paper. Vessel control in a storm is the most difficult stage in the vessel's wiring, as it requires quick decisions to be made in difficult conditions. Practical experience shows that the deterioration of the working conditions of the crew is usually associated with an increase in the number of control errors, which is completely unacceptable in stormy conditions. To assess the safe speed and course in a storm, Yu. V. Remez has proposed a universal storm diagram, which allows identifying unfavourable combinations of vessel speed and course angles of the waves – the resonant zones, and avoid them. The universal Remez diagram provides for graphical calculations, which, in combination with the visual determination of the wave parameters, gives a very low accuracy. The article examines the possibility of automatic control of a vessel in a storm by automatic measurement of motion parameters and wave parameters, automatic calculation in the on-board controller of the vessel optimal safe speed and course during a storm, automatic maintenance of the optimal safe speed and course of the vessel. The automatic control significantly increases the accuracy of calculations, excludes the human factor, reduces the depletion of the crew, and increases the reliability of the vessel control in a storm. The efficiency and effectiveness of the method, algorithmic and software were tested on Imitation Modelling Stand in a closed loop with mathematical vessel models of the navigation simulator Navi Trainer 5000.**

Keywords – **Automatic control, digital simulation, human factors, intelligent vehicles, steering systems.**

I. INTRODUCTION

Steering a vessel in a storm is an important stage in the vessel's wiring. During a storm, the vessel experiences heavy hull loads, which can increase significantly if the wrong steering is selected. To facilitate the task of vessel control in storm, a number of scientists have proposed special diagrams for choosing the course and speed in storm conditions. The most widespread is the universal diagram of the Yu. V. Remez, which allows determining unfavourable combinations of velocity and course angles of waves (resonant zones) for any vessel and any wavelength and choosing a safe speed and course of the vessel outside the resonance zone.

However, there are a number of factors that prevent the effective use of storm diagrams. First, the sea wave parameters are measured by available means (using a direction finder or radar), without the use of special equipment, which already at this stage introduces significant errors in the calculations. Secondly, the measured information is processed manually, using graphical diagrams, which further increases the errors. Thirdly, calculations require time, which may simply not be in critical situations, and calculations cannot be performed continuously to track changes in traffic conditions and sea disturbance. It is also impossible not to take into account the human factor [1]–[5]. All this leads to the fact that in practice the steering of the vessel in storm is usually performed intuitively, without the use of storm diagrams and any calculations.

The use of automatic control systems of the vessel allows significantly reducing the impact of the human factor and increasing the safety of navigation [6]–[12], especially in difficult sailing conditions [13]–[20]. Therefore, the development of a vessel automatic storm system is an urgent scientific and technical task.

The object of the research is the processes of automatic vessel control in a storm.

The subject of the research is the method, algorithmic and software of the automatic vessel control system in a storm.

The aim of the research is to develop methods of automatic control of a ship in a storm, increase the efficiency and reliability of control in comparison with known solutions.

II. PROBLEM SATEMENTS

Mathematical model of the control object $f(\bullet)$, meter model and the law of control $\mathbf{F}(\bullet)$ is represented by vector equations (1).

$$\begin{cases} \dfrac{d\mathbf{X}}{dt} = \mathbf{f}(\mathbf{X},\mathbf{U},\mathbf{W},T_B,T_L), \\ \mathbf{X}_m = \mathbf{C}\mathbf{X} + \varsigma, \\ \mathbf{U} = \mathbf{F}(\mathbf{X}_m,\mathbf{X}^*), \\ \mathbf{X}^* \subseteq \bar{\Omega} \end{cases} \tag{1}$$

---

[*] Corresponding author.
E-mail: srz56@ukr.net

where $\mathbf{X}=(V,K,\omega_z)$ is the state vector of control object parameters, V is the vessel speed, K is the vessel course, ω_z is the vessel yaw rate, $\mathbf{U}=(\Theta,\delta)$ is control vector, Θ is the telegraph deflection angle, δ is the ruder deflection angle, $\mathbf{W}(\lambda,q)$ is external wave influence vector, λ is wavelength, q is wave approach angle (the angle between the wave speed vector and the diametrical plane of the vessel), T_B,T_L are periods of the vessel's own oscillations in the roll and trim channels, $\mathbf{X}_m$ is measurement vector, $\mathbf{C}$ is meter matrix, ς is measurement error vector, $\mathbf{X}^*=(V^*,K^*,\omega_z^*)$ is program vector, $\overline{\Omega}$ is non-resonant zone. It is required to define such $|\mathbf{U}|\le\mathbf{U}^{\max}$, for which the control quality function is $Q(\mathbf{X}_m)\to\text{extr}$ and $\mathbf{X}_m\subseteq\overline{\Omega}$.

III. Literature Review

In patent [21], a vessel wave heading control apparatus is disclosed for use on a floating vessel. Linear acceleration signals from two accelerometers, which sense the rotational acceleration of the vessel due to waves which impact the vessel from a particular direction, are processed by a computer which subsequently produces vessel heading change signals to the steering and propulsion means of the vessel. These signals indicate the required heading and required rate of change of vessel heading necessary to turn the vessel into the direction of the oncoming waves in a timely manner.

The article [22] describes a program – hardware device for preventing emergency situations at sea. The device determines the length and speed of sea waves using vessel's radars and recommends a safe course for navigators.

The paper [23] deals with the influence of parametric resonance on the safety of the ship. In October 1998, a Post-Panamax C11 class container ship was exposed to extreme weather conditions and suffered significant losses and damage to the containers stacked on deck. The movements of the vessel during this storm were investigated using a series of model tests and numerical analysis, which confirmed the presence of parametric resonance of the vessel in high seas. The studies carried out made it possible to establish that the container ships of the Post-Panamax type will experience parametric rolling, as well as to determine the values of possible accelerations, speeds and displacements that might arise in this case. The effects of these extreme stresses on the structure and fastening system of containers are also considered.

The article [24] focuses on the fact that the seas and oceans are a great danger to people and vessels. This risk is caused by the strong, devastating storms, which are capable of destroying the ship and her crew immediately. They can be assessed by a 12-point scale, ranging from zero point, and finishing with the twelfth – the most deadly point. The consequences of stormy phenomena are described. The reason of their appearance is analysed. Precaution measures and recommendations for navigation in rough weather are also enumerated in the paper.

The paper [25] deals with the automation of vessel control in a storm. It is shown that the existing recommendations for the organisation of navigational service on vessels are general rules for navigating a vessel in a storm. They, in particular, prescribe the use of storm charts by the navigator. The most famous diagrams include the storm diagrams of Yu. V. Remez and A. I. Bogdanov. It should be recognized that the "manual" use of diagrams by Yu. V. Remez and especially A. I. Bogdanov in real conditions of storm sailing is difficult: the navigator must perform calculations and graphical constructions, interpolate between the lines of the diagrams. On the basis of the diagrams of Yu. V. Remez and A. I. Bogdanov, a diagram of dangerous phenomena was developed and proposed, carried out by calculations in the publicly available program Excel. The developed diagram is equally applicable for unlimited and limited bottom depths. The Excel program automatically calculates and displays on the diagram the zones of the main resonance of the side, pitching and heaving, as well as the parametric resonance, considering the dimensions of the vessel, its landing and stability, and the wave parameters. The proposed diagram also makes it possible to predict the appearance of resonance when the vessel enters a new course. Implementation of this diagram on vessels is not difficult, since the data required for the program to work can be obtained in the vessel's environment.

The paper [26] proposes the structure of the navigation safety system at the stages of design and operation of vessels. The composition of ship systems required to ensure the safety of navigation in a stormy sea is considered. The use of multi-agent technologies for information processing in the system for ensuring the safety of navigation and the development of recommendations for the navigator on the choice of safe parameters of the vessel's movement is proposed.

The article [27] discusses the issues of increasing the speed and reducing energy consumption during cargo and ballast crossings of the tanker. A method for increasing the speed and reducing fuel consumption in stormy conditions is proposed, based on the results of experiments and observations carried out on the tanker itself. This made it possible to consider the operating experience of a particular tanker, as well as the history of changes in the parameters of its propeller over time. In addition to special experiments and observations, data from ship logs were used. The article provides examples of using the processed information of navigation and machine logs. It is shown that an increase in speed and fuel economy can be achieved at the same angles of wind and waves. This rule must be taken into account both at the stage of planning the transition and in conditions of stormy sailing. The results obtained can be extended to other types of vessels.

As can be seen from the above review of open literature sources, the authors did not consider systems for automatic control of a ship in a storm, including those that optimize the control quality function. Therefore, the development of such systems is an urgent scientific and technical task.

IV. Materials and Methods

Important characteristics of the ship, characterising its sensitivity to the frequency of external influences, are the period of natural oscillations in the roll and trim channels

$$T_B = \frac{kB}{\sqrt{h}}, \quad T_L \approx 2.8\sqrt{\chi T},$$

where k is a coefficient equal to 0.81 for cargo vessels, B[m] is vessel width, h[m] is transverse metacentric height, χ is a coefficient of the vessel vertical fullness and T[m] is the vessel draft. Pitching and rolling of the vessel are excited by forced oscillations of waves. In the absence of vessel movement, the period of forced oscillations coincides with the period of waves. When the vessel is moving, the period of forced oscillations differs from the period of waves due to the change in the speed of the waves relative to the vessel by the value of the vessel's speed. This period of forced oscillations is called the apparent period of waves. Apparent period of waves τ depends on the wave length λ, vessel speed V and the course angle of the wave q – the angle between the wave direction and the vessel diametrical plane

$$\tau = \frac{\lambda}{1.25\sqrt{\lambda} + 0.514V\cos q}. \tag{2}$$

By sea disturbance, the vessel is subject to swaying, pouring and splashing decks and bridges, a strong dynamic load on the hull. At the same time, when speed decreases, controllability of the vessel worsens. Particularly dangerous is the case of resonant oscillation, in which the period of free oscillations of the vessel coincides with the period of forced oscillations or is close to it. The amplitude of the oscillation increases sharply when the period of forced oscillations coincides with the period of free oscillations (resonance phenomenon). Resonant modes of oscillation are considered practically dangerous when

$$0.7 \le \frac{T_B}{\tau} \le 1.3; \tag{3}$$

$$0.7 \le \frac{T_L}{\tau} \le 1.3. \tag{4}$$

Inequalities (3), (4) determine the resonance zone Ω for the rolling and pitching, respectively. The task control in the storm is to create such conditions for the movement of the vessel, under which inequalities (3)–(4) are not fulfilled. This can be achieved either by properly changing the parameter $\tau(n)$, or the parameters T_B and T_L.

From (2), it is seen that by changing the speed of the vessel V and/or the course angle of the wave q, we can change the apparent period of the waves τ. It is due to the change of these parameters, as a rule, the vessel is controlled in a storm.

Block diagram of the vessel automatic storm system is shown in Fig. 1. The vessel automatic storm system includes a sensor unit (linear speed sensor, wave parameters sensor, course sensor, yaw rate sensor), storage device for storing and adjusting the constants used in the calculations, on-board controller, which provides receiving of information measured by sensors, processing of this information together with storage device constants according to the algorithms and formation of control signals on power plant automatic equipment and stern rudder automatic equipment.

The linear speed sensor (see Fig. 1) measures the vessel linear speed V, the wave parameters sensor measures the wave course K_W and wave length λ, the course sensor measures the vessel's course K, the yaw rate sensor measures the vessel angular rate ω_z. The first adder calculates the wave incursion angle $q = K - K_W$, which is fed to the third input of the safe speed and course calculation unit. Also, the vessel speed V and wave length λ are fed on the first and second inputs of the safe speed and course calculation unit. The safe speed and course calculation unit calculates the resonant Ω and non-resonant $\overline{\Omega}$ zone, considering the minimum and maximum speed of the vessel in a storm.

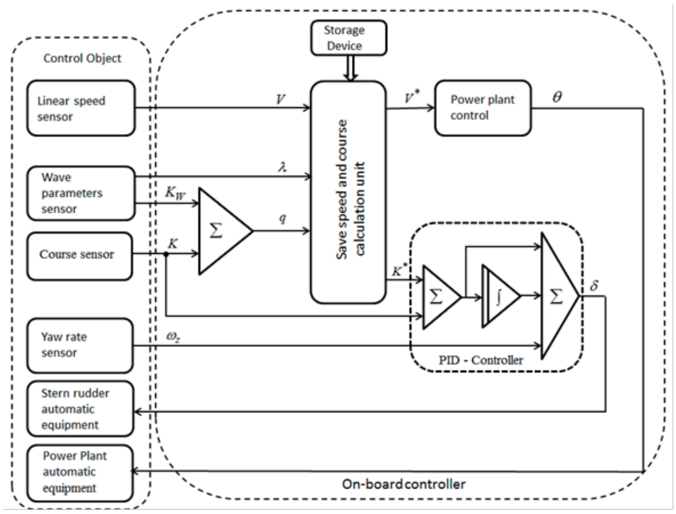

Fig. 1. Block diagram of the vessel automatic storm system.

The presence of the non-resonant zone $\overline{\Omega}$ means the presence of an infinite number of allowable storm parameters $\{V_m, K_m\}$, from which the optimal ones can be selected according to the established optimality criterion $Q(\mathbf{X}_m)$. Thus, the problem of calculating the safe speed and course of the vessel in a storm is reduced to the problem of optimizing the control quality function $Q(\mathbf{X}_m)$ under the restrictions conditions $\mathbf{X}_m \subseteq \overline{\Omega}$ and $V_{\min}^{st} \le V \le V_{\max}^{st}$, where $V_{\max}^{st}$ is the vessel maximum speed in a storm, $V_{\min}^{st}$ is the vessel minimum speed in a storm.

Parameters $\{V^*, K^*\}$ from the safe speed and course calculation unit are fed to the power plant control unit to form the telegraph deflection angle θ and to the PID controller to form the deflection angle δ of the stern rudder. Also, to ensure high-quality transient control processes in the yaw channel, the angular yaw rate ω_z, measured by the yaw rate sensor, is also fed to the input of the PID controller. The telegraph deflection angle θ and deflection angle δ are fed to the power plant automatic equipment and to the stern rudder automatic equipment, respectively, to maintain a safe speed and course.

Let us define the resonant zones in roll and trim channels, from inequalities (3), (4), considering (2)

$$\begin{cases} 1.42\dfrac{\lambda}{T_B}-2.31\sqrt{\lambda}\le V\cos q\le 2.64\dfrac{\lambda}{T_B}-2.31\sqrt{\lambda}, \\ 1.42\dfrac{\lambda}{T_L}-2.31\sqrt{\lambda}\le V\cos q\le 2.64\dfrac{\lambda}{T_L}-2.31\sqrt{\lambda}. \end{cases} \tag{5}$$

Let us divide the equations of system (5) into $V_{\max}$

$$\begin{cases} \dfrac{1}{V_{\max}}\left(1.42\dfrac{\lambda}{T_B}-2.31\sqrt{\lambda}\right)\le e\cos q\le \dfrac{1}{V_{\max}}\left(2.64\dfrac{\lambda}{T_B}-2.31\sqrt{\lambda}\right), \\ \dfrac{1}{V_{\max}}\left(1.42\dfrac{\lambda}{T_L}-2.31\sqrt{\lambda}\right)\le e\cos q\le \dfrac{1}{V_{\max}}\left(2.64\dfrac{\lambda}{T_L}-2.31\sqrt{\lambda}\right), \end{cases} \tag{6}$$

where $\mathbf{e}=\dfrac{\mathbf{V}}{V_{\max}}$ is the reduced speed. Fig. 2 shows the dependence of the reduced upper and lower boundaries of the resonant zone Ω on the wave length λ.

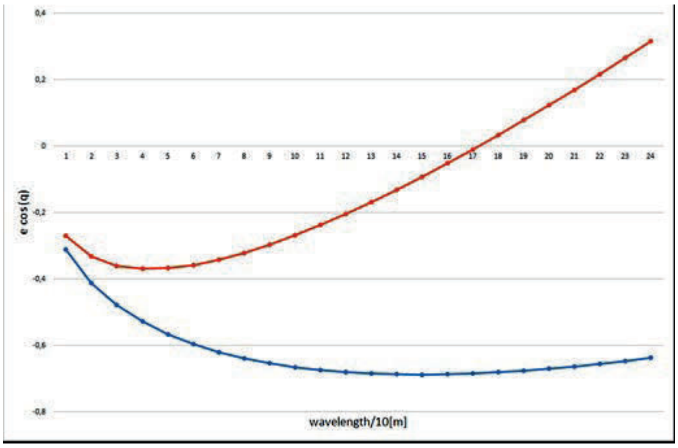

Fig. 2. The dependence of the resonant zone width on the wave length λ.

From system (6) we determine non-resonant zones in the roll and trim channels

$$\begin{cases} \dfrac{1}{V_{\max}}\left(2.64\dfrac{\lambda}{T_B}-2.31\sqrt{\lambda}\right)\le e\cos q\le \dfrac{1}{V_{\max}}\left(1.42\dfrac{\lambda}{T_B}-2.31\sqrt{\lambda}\right), \\ \dfrac{1}{V_{\max}}\left(2.64\dfrac{\lambda}{T_L}-2.31\sqrt{\lambda}\right)\le e\cos q\le \dfrac{1}{V_{\max}}\left(1.42\dfrac{\lambda}{T_L}-2.31\sqrt{\lambda}\right). \end{cases} \tag{7}$$

As can be seen from Fig. 3, the unit circle of possible directional movements $\mathbf{e}_{\max}=1$ is divided into three parts: the resonance zone Ω and two areas of the non-resonance zone $\overline{\Omega}$. Fig. 3 also illustrates the area of permissible directional and reduced speeds, limited by the reduced vectors of maximum $\mathbf{e}_{\max}^{st}$ and minimum $\mathbf{e}_{\min}^{st}$ speed in the storm.

There are four possible cases of mutual placement of the resonant zone Ω and $\mathbf{e}_{\max}^{st}$; $\mathbf{e}_{\max}^{st}$ completely lies in the resonant zone Ω. In this case, the allowable storm area is absent and there are no safe storm parameters; $\mathbf{e}_{\max}^{st}$ does not lie completely in the resonant zone Ω. In this case, the allowable storm area lies between $\mathbf{e}_{\min}$ and $\mathbf{e}_{\max}^{st}$; $\mathbf{e}_{\max}^{st}$ crosses one boundary of the resonant zone Ω, as shown in Fig. 3.

Fig. 3 shows the resonant Ω and non-resonant $\overline{\Omega}$ zones in coordinates *e*sin*q* – *e*cos*q*.

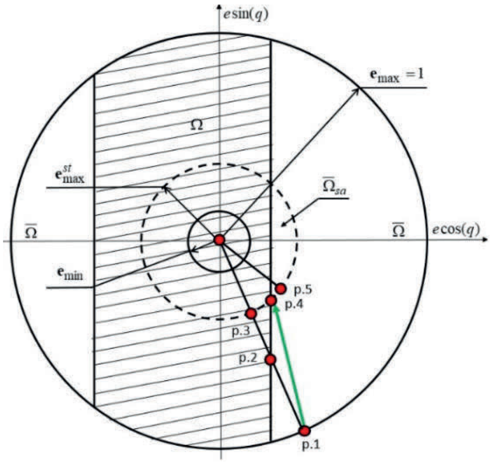

Fig. 3. The resonant zone in coordinates *e*sin*q* − *e*cos*q*.

In this case, the allowable storm area is limited by this side of the resonant zone Ω and $\mathbf{e}_{\max}^{st}$; $\mathbf{e}_{\max}^{st}$ crosses two boundaries of the resonant zone Ω. In this case, there are two permissible areas of vessel control in a storm, one of which is limited by the left side of the resonant zone and $\mathbf{e}_{\max}^{st}$, and the other is limited by the right side of the resonant zone Ω and $\mathbf{e}_{\max}^{st}$. These areas are separated by a resonant zone and the transition from one area to another is not possible. In all the cases considered, the permissible vessel control area in a storm is much smaller than the non-resonance zone $\overline{\Omega}$ constructed for the reduced maximum vessel speed and is determined by the reduced maximum speed that the vessel can maintain during a storm. In fact, it is not the zone $\overline{\Omega}$ that is safe for driving in a storm, but a much smaller area $\overline{\Omega}_{sa}$ formed by the intersection of zone $\overline{\Omega}$ and area between the circles $\mathbf{e}_{\max}^{st}$ and $\mathbf{e}_{\min}^{st}$. If at the beginning of the manoeuvre the phase parameters $\{e(0), q(0)\}$ are in p.1, then you need to move to p.4, which belongs to the safe area $\overline{\Omega}_{sa}$. This will be the shortest route of transferring phase parameters to the safe area $\overline{\Omega}_{sa}$. The presence of save areas $\overline{\Omega}_{sa}$ means the presence of an infinite number of save storm parameters, among which the optimal ones can be found according to the established optimality criterion.

Let us define the control quality function as follows:

$$\begin{aligned} Q={}&\big(e(T)\cos q(T)-e(n)\cos q(n)\big)^2+ \\ &+\big(e(T)\sin q(T)-e(n)\sin q(n)\big)^2, \end{aligned} \tag{8}$$

where $e(n)=\dfrac{V(n)}{V_{\max}}$ is the actual reduce speed in a storm, $e(T)=\dfrac{V(T)}{V_{\max}}$ is the reduce speed at a point belonging to the safe area $\overline{\Omega}_{sa}$, $q(n)$, $q(T)$ are the actual wave angle and the safe wave angle, respectively.

The physical meaning of function (8) is to minimize the distance on the diagram (Fig. 3) between the actual parameters (p.1) $\{e(n)\cos q(n), e(n)\sin q(n)\}$ and the safe parameters (p.4) $\{e(T)\cos q(T), e(T)\sin q(T)\}$.

Thus, the safe speed and course calculation unit determines the optimal pair of parameters $\{e(T),\ q(T)\}$ by minimizing the control quality function (8), in the presence of constraints (7) and $e_{\min}^{st}\le|\mathbf{e}(n)|\le e_{\max}^{st}$. Since the quality function (8) is smooth, to solve this optimization problem with linear and nonlinear constraints, we used the standard gradient optimization procedure like fmincon(•) of the MATLAB Optimization Toolbox library

$$\mathbf{X}^{*}(\mathrm{n})=\mathrm{fmincon}(\mathbf{@\ myfun}, \mathbf{X}^{*}(\mathrm{n}\text{-}1), \mathbf{A}, \mathbf{b}, \mathbf{Aeq}, \mathbf{beq}, \mathbf{lb}, \mathbf{ub}, \mathbf{@mycon}),$$

where $\mathbf{X}^{*}(n)=(V^{*}(n),K^{*}(n))$ is the vector of optimized parameters, $@\mathrm{myfun}$ is the link to file with optimized quality function (7), $\mathbf{X}^{*}(n-1)=(V^{*}(n-1),K^{*}(n-1))$ is the initial vector of optimized parameters (its value is taken from the previous calculated cycle), $\mathbf{A}=[\,]$, $\mathbf{b}=[\,]$ are the matrix and vector of the system of linear inequalities for specifying constraints, are absent, $\mathbf{Aeq}=[\,]$, $\mathbf{beq}=[\,]$ are the matrix and vector of the system of linear equalities for specifying constraints, are absent, $\mathbf{lb}=(V_{\min}^{st},-35^{0})$ is the lower bound of optimized parameters, $\mathbf{ub}=(V_{\max}^{st},35^{0})$ is the upper bound of optimized parameters, $@\mathrm{mycon}$ is the link to file with nonlinear constraints (6).

V. EXPERIMENTS

To carry out the experiment, we used an Imitation Modelling Stand developed by the authors on the basis of the Navi Trainer 5000 simulator [28]. The Imitation Modelling Stand includes the Navi Trainer 5000 simulator itself and an additional Control System Model integrated into its local network. Control System Model is built on the basis of one or several personal computers with software for exchanging information with the simulator and functional control system software. The Imitation Modelling Stand allows working out the functional software of the control system in a closed circuit with mathematical models of the simulator, using all capabilities of the simulator, namely: various swimming areas, weather conditions, objects of the simulator scene, navigation equipment simulators, visualization channels, etc. In the experiment being carried out, the automatic storming module was used as the functional software of the control system model, which was tested in a closed circuit with the mathematical model of the Ro-Ro passenger ferry 13 vessel. The characteristics of the vessel Ro-Ro passenger ferry 13 are shown in Table I.

TABLE I
CHARACTERISTICS OF THE VESSEL RO-RO PASSENGER FERRY 13

Parameter name	**Value**
Displacement, *t*	7796.8
Maximum speed $V_{\max}$, kn	20.5
Length *L*, m	125
Width *B*, m	23.4
Submersion *d*, m	5.3

Fig. 2 shows the dependence of the reduced upper and lower boundaries of the resonant zone Ω on the wave length λ in roll channel of the Ro-Ro passenger ferry 13.

Fig. 3 shows the roll channel resonant zone Ω and non-resonant zone $\overline{\Omega}$ for wave length λ = 230 *m*. The outer circle $\mathbf{e}_{\max}$ corresponds to the reduced maximum speed of the vessel $|\mathbf{e}_{\max}|=\dfrac{V_{\max}}{V_{\max}}=1$, the inner circle $\mathbf{e}_{\min}$ corresponds to the reduced minimum speed of the vessel $|\mathbf{e}_{\min}|=\dfrac{V_{\min}}{V_{\max}}=0.1$, the dashed circle $\mathbf{e}_{\max}^{st}$ corresponds to the reduced maximum speed of the vessel during a storm $|\mathbf{e}_{\max}^{st}|=\dfrac{V_{\max}^{st}}{V_{\max}}=0.35$. This speed depends on the storm disturbance, the bigger the storm, the smaller $\mathbf{e}_{\max}^{st}$. Fig. 3 shows the reduced maximum speed of the vessel Ro-Ro passenger ferry 13 for a 11-point storm.

Below are the results of mathematical modelling of storm processes of the Ro-Ro passenger ferry 13 on the Imitation Modelling Stand. In all experiments, the wind direction is $K_W(n)=0^{\circ}$ (north wind), $q(n)=K(n)-K_W(n)=K(n)$.

Fig. 4 shows graphs of changes in roll angle, trim angle, longitudinal speed and course Ro-Ro passenger ferry 13 during the vessel acceleration to maximum speed in the absence of sea disturbance. As can be seen from the graphs, the vessel performs in one minute four full oscillations in the roll channel and twelve full oscillations in the trim channel, that is the period of natural oscillations of the vessel in the roll channel is T_B = 15 s and in the trim channel is T_L = 5 s. These periods of natural oscillations were used to find the upper and lower boundaries of the resonant zone (Figs. 2 and 3).

Fig. 5 shows graphs of changes in roll angle, trim angle, longitudinal speed and course Ro-Ro passenger ferry 13 for the initial course *K*(0) = 45°, initial speed *V*(0) = 0 kn., initial sea disturbance 2 points. The vessel, moving on course *K*(*n*) = 45°, accelerates to speed *V*(*n*) = 19 kn., after which the simulator is set to sea disturbance 11 points. During the sea disturbance, the speed of the vessel decreases to *V*(*n*) = 7.2 kn., *e*(*n*) = 0.35, but the vessel does not overturn. This is due to the fact that resonance conditions are not satisfied for the reduced speed $e(n) = 0.35$ and course $K(n) = 45°$ (p.5, Fig. 3).

Fig. 6 shows graphs of changes in roll angle, trim angle, longitudinal speed and course Ro-Ro passenger ferry 13 for the initial course $K(0) = 75°$, initial speed $V(0) = 0$ kn., initial sea disturbance 2 points. The vessel, moving on course $K(n) = 75°$, accelerates to speed $V(n) = 19$ kn., after which the simulator is set to sea disturbance 11 points. During the sea disturbance, the speed of the vessel decreases to $V(n) = 7.2$ kn., $e(n) = 0.35$, there is a resonance in the roll channel, the roll angles go beyond the allowable values and the vessel overturns (horizontal lines on graphs). This is due to the fact that the resonance conditions are satisfied for the reduced speed $e(n) = 0.35$ and course $K(n) = 75°$ (p.3, Fig. 3).

Fig. 7 shows graphs of changes in roll angle, trim angle, longitudinal speed and course of the vessel with automatic control of the vessel Ro-Ro passenger ferry 13 in a storm.

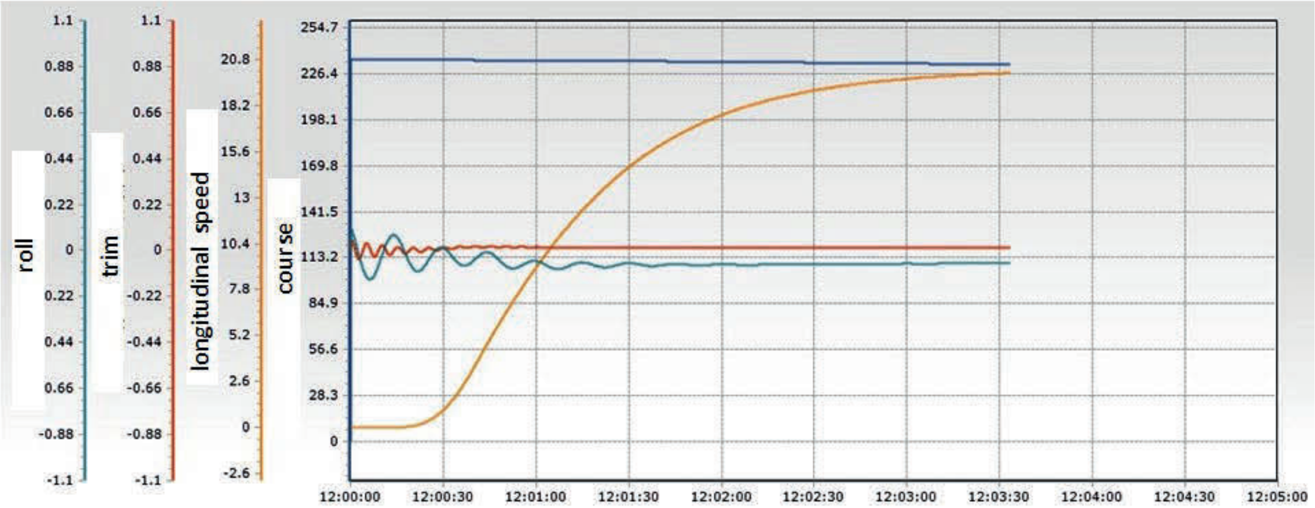

Fig. 4. Parameters of the Ro-Ro passenger ferry 13 movement with course $K = 0$ at full calm.

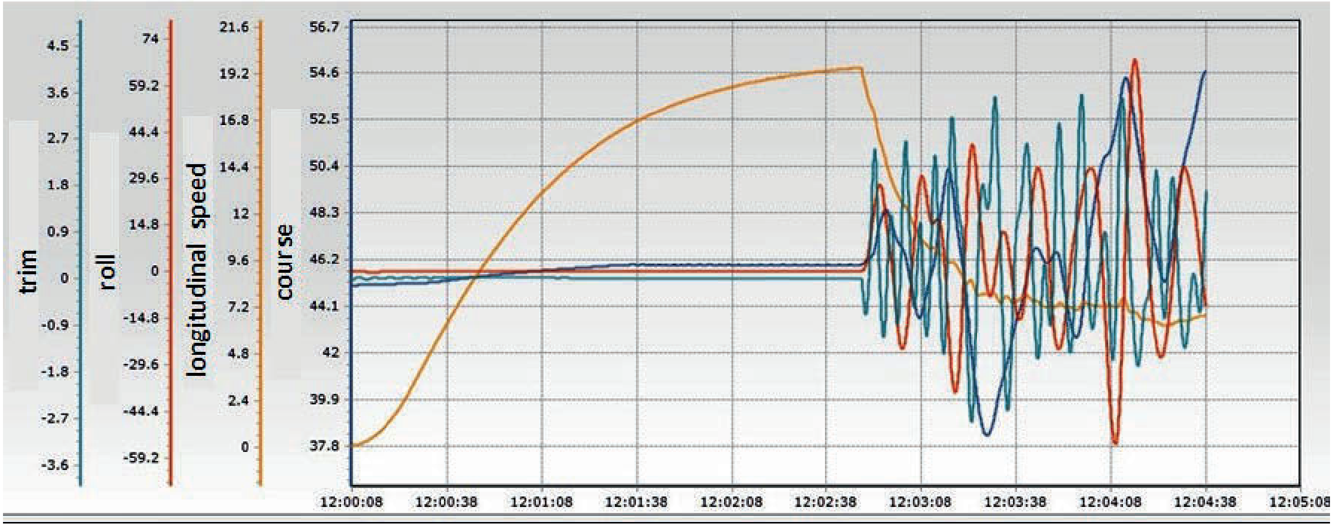

Fig. 5. Parameters of the Ro-Ro passenger ferry 13 movement for the initial course $K = 45$ dg.

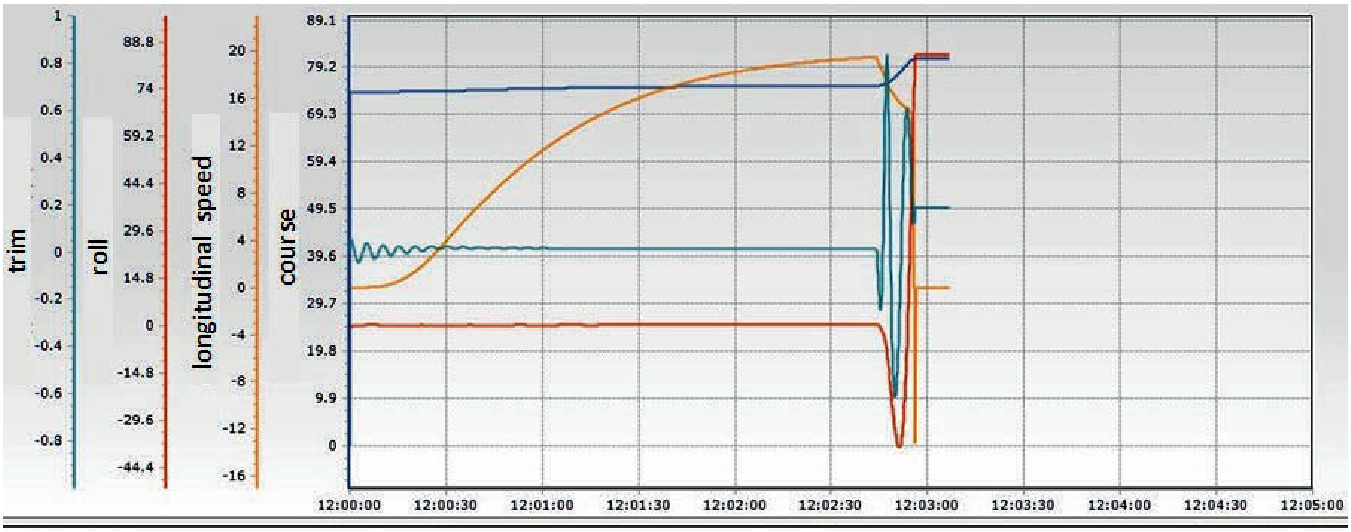

Fig. 6. Parameters of the Ro-Ro passenger ferry 13 movement by course $K(n) = 75^{\circ}$.

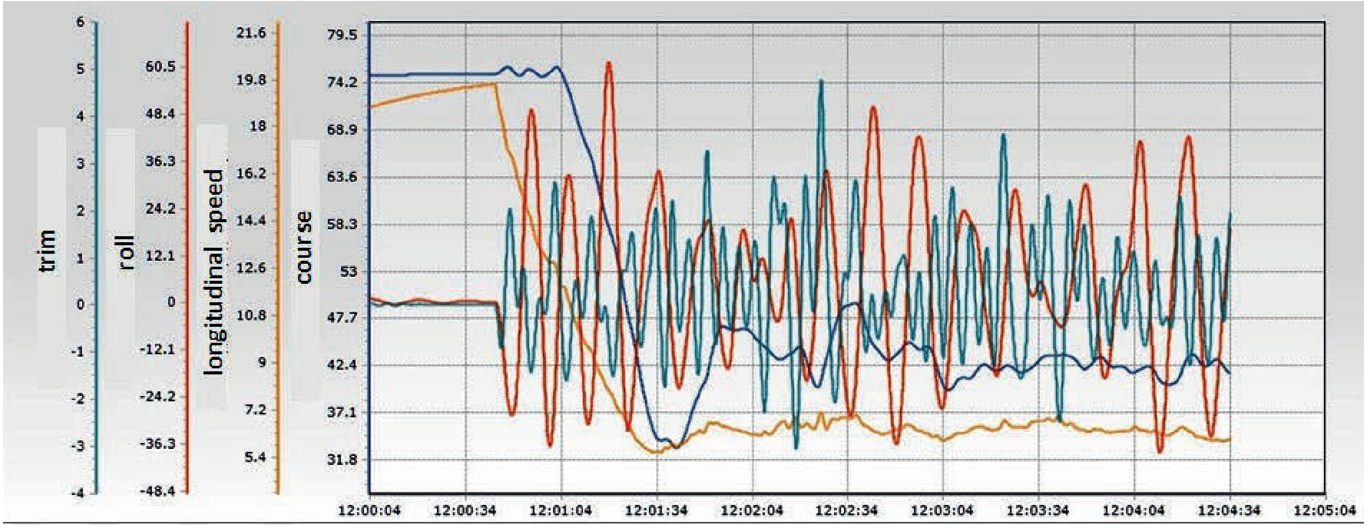

Fig. 7. Automatic control of the vessel Ro-Ro passenger ferry 13 in a storm.

Initial course of the vessel is $K(0) = 75°$, initial speed is $V(0) = 18.5$ kn., initial sea disturbance is 2 points. The vessel, moving on the course $K(n) = 75°$, accelerates to speed $V = 19$ kn., after which the simulator is set to sea disturbance 11 points. As can be seen from the graphs, during the storm the speed of the vessel begins to decrease to $V(n) = 7$ kn., $e(n) = 0.35$. At the same time, the automatic storm system begins to change course from $K(n) = 75°$ to safe $K(n) = 45°$ to exit the resonance zone. In Fig. 3, this corresponds to the movement from p.1 to p.4.

VI. CONCLUSION

The issues of automatic control of the vessel in a storm have been considered in the paper. Sailing in a storm is the most difficult part of piloting a ship, as it requires quick decision making in difficult conditions. The scientific novelty of the results obtained lies in the fact that for the first time the design features of the original automatic vessel control module in a storm have been theoretically substantiated, which consist in constant, with the onboard controller cycle, automatic measurement of the vessel's motion and wave parameters, automatic calculation of the boundaries of the resonant zone, taking into account the boundaries of the resonant zone and allowable range of speeds during a storm, minimizing the distance on the phase plane to the current values of speed and course, automatic maintenance of a safe speed and course in a storm, and providing fundamentally new technical characteristics: the possibility of automatic control of the vessel in a storm, the possibility of optimal control of the vessel in a storm, reducing the fatigue of the crew, increasing the accuracy and reliability of control in a storm.

The practical value of the obtained results is that the developed method and algorithms are implemented in the software of the vessel automatic storm system and investigated by mathematical modelling on the imitation modelling stand in a closed loop with vessel mathematical models for different types of vessel, sailing areas and meteorological conditions.

Further research can be related to the statistical processing of the measured wave parameters, the use of the Fast Fourier Transform for the selection and use in the calculations of the dominant frequencies of the wave spectrum.

ACKNOWLEDGEMENT

The research has been conducted in the framework of the research "Development of Software Solutions for Dynamic Functions of Dynamically Positioning Systems of Marine Vessels", (state registration number 0119U100948), Department of Navigation and Electronic Navigation Systems of Kherson State Maritime Academy.

REFERENCES

[1] I. Popovych, V. Cherniavskyi, S. Dudchenko *et al*., "Experimental research of effective "The Ship's Captain and the Pilot" interaction formation by means of training technologies," *Revista Espascios,* vol. 41, no. 11, pp. 30, 2020. http://www.revistaespacios.com/a20v41n11/20411130.html

[2] I. Popovych, O. Blynova, J. Álvarez, P. Nosov, and S. Zinchenko, "A historical dimension of the research on social expectations of an individual," *Revista Notas Históricas y Geográficas*, vol. 27, pp. 190–217, Jul.-Dec. 2021. https://www.researchgate.net/publication/353588439_A_historical_dimension_of_the_research_on_social_expectations_of_an_individual

[3] R. Shevchenko, V. Cherniavskyi, S. Zinchenko, M. Palchynska, S. Bondarevich, P. Nosov, and I. Popovych, "Research of psychophysiological features of response to stress situations by future sailors," *Revista Inclusiones*, vol. 7, no. Especial, Oct.-Dec., pp. 566–579, 2020. http://ekhsuir.kspu.edu/handle/123456789/12273

[4] P.S. Nosov, I.S. Popovych, V.V. Cherniavskyi, S.M. Zinchenko, Yu.A. Prokopchuk, and D.V. Makarchuk, "Automated identification of an operator anticipation on marine transport," *Radio Electronics, Computer Science, Control,* vol. 3, pp. 158–172, 2020. https://doi.org/10.15588/1607-3274-2020-3-15

[5] P. Nosov, V. Cherniavskyi, S. Zinchenko, I. Popovych, Yu. Prokopchuk, and M. Safonov, "Identification of distortion of the navigator's time in model experiment," *Bulletin of University of Karaganda. Instrument and experimental techniques*, vol. 4, no. 100, pp. 57–70, 2020. https://doi.org/10.31489/2020Ph4/57-70

[6] H. Shen, H. Hashimoto, A. Matsuda *et al*. "Automatic collision avoidance of multiple ships based on deep Q-learning," *Applied Ocean Research Journal*, vol. 86, pp. 268–288, May 2019. https://doi.org/10.1016/j.apor.2019.02.020

[7] L. Yishan, G. Zhiqiang, Y. Jie *et al*., "Prediction of ship collision risk based on CART," *IET Intelligent Transport Systems*, vol. 12, no. 10, pp. 1345–1350, Oct. 2018. https://doi.org/10.1049/iet-its.2018.5281

[8] J. Park, J. Choi, and H.T. Choi, "COLREGS-compliant path planning considering time-varying trajectory uncertainty of autonomous surface vehicle," *Electronics Letters*, vol. 55, no. 4, pp. 222–224, Feb. 2019. https://doi.org/10.1049/el.2018.6680

[9] E. Tu, G. Zhang, L. Rachmawati *et al*., "Exploiting AIS date for intelligent maritime navigation: A comprehensive survey," *IEEE Transactions on Intelligent Transportation System*, vol. 19, no. 5, pp. 1559–1582, May 2016. https://doi.org/10.1109/TITS.2017.2724551

[10] S. M. Zinchenko, A. P. Ben, P. S. Nosov, I. S. Popovych, P. P. Mamenko, and V. M. Mateichuk, "Improving the accuracy and reliability of automatic vessel moution control system," *Radio Electronics, Computer Science, Control*, vol. 2, pp. 183–195, 2020. https://doi.org/10.15588/1607-3274-2020-2-19

[11] P. S. Nosov, I. S. Popovych, V. V. Cherniavskyi, S. M. Zinchenko, Yu. A. Prokopchuk, and D. V. Makarchuk, "Automated identification of an operator anticipation on marine transport," *Radio Electronics, Computer Science, Control*, vol. 3, pp. 158–172, 2020. https://doi.org/10.15588/1607-3274-2020-3-15

[12] S. Zinchenko, P. Nosov, V. Mateichuk, P. Mamenko, I. Popovych, and O. Grosheva, "Automatic collision avoidance system with many targets, including maneuvering ones," *Bulletin of University of Karaganda, Technical Physics*, vol. 4, no. 96, pp. 69–79, 2019.

[13] International Maritime Organization, "Guidance to the master for avoiding dangerous situations in following and quartering seas," IMO MSC/Circ.707., Ref. T1/2.04/, 1995. [Online]. Available: https://docplayer.net/8648247-Imo-msc-circ-707-19-october-1995-ref-t1-2-04-guidance-to-the-master-for-avoiding-dangerous-situations-in-following-and-quartering-seas.html

[14] International Maritime Organization, "Revised guidance to the master for avoiding dangerous situations in adverse weather and sea conditions," IMO MSC.1/Circ.1228, 2007. [Online]. Available: https://www.liscr.com/revised-guidance-master-avoiding-dangerous-situations-adverse-weather-and-sea-conditions

[15] Maritime Consultative Organization, "Recommendation on intact stability for passenger and cargo ships under 100 meters in length, IMCO Resolution A.167, Nov. 1968. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.167(ES.IV).pdf

[16] International Maritime Organization, "Recommendation on a severe wind and rolling criterion (weather criterion) for the intact stability of passenger and cargo ships of 24 meters in length and over, IMO Resolution A.562(14), Nov. 1985. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.562(14).pdf

[17] T. Okada, "Marine weather ship handling in rough sea," *Japan P&I Club. P&I Loss Prevention Bulletin*, vol. 45, Apr. 2019. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.piclub.or.jp/wp-content/uploads/2019/04/Loss-Prevention-Bulletin-Vol.45-Full.pdf

[18] Ships Business, "Ships navigation in heavy weather and recommended action by master," 2015. [Online]. Available: http://shipsbusiness.com/navigation-in-heavy-weather.html

[19] Marine Sight, "What to do when ship encounters rough weather?" 2019. [Online]. Available: https://www.marineinsight.com/marine-safety/what-to-do-when-ship-encounters-rough-weather

[20] North Sails News, "How to a sail safety in a storm", 2016. [Online]. Available: https://www.northsails.com/sailing/en/2016/09/how-to-sail-safely-through-a-storm

[21] Jr. Shatto, "Vessel wave heading control apparatus," U.S. Patent no. 4 769 773, Sep. 6, 1988.

[22] D. Akmaykin and D. Khomenko, "Use of ships radar for improvement of navigation in rough sea condition," in *Proceedings of the 2011 International Siberian Conference on Control and Communications (SIBCON'2011)*, Krasnoyarsk, Russia, Sep. 2011, pp. 147–148. https://doi.org/10.1109/SIBCON.2011.6072616

[23] W. France, M. Levadou, T. Treakle, J. Paulling, R. Michel, and C. Moore, "An investigation of head-sea parametric rolling and its influence on container lashing systems," *Marine Technology*, vol. 40, no. 1, pp. 1–19, Jan. 2003. https://doi.org/10.5957/mt1.2003.40.1.1

[24] S. Korolyova and Yu. Marchuk, "The concept of storm and its influence on the navigation," in *Profmarket: Education. Language. Success*, Sevastopol State University, Mar. 2017, pp. 195–196.

[25] A. Ershov, S. Solnov, and A. Boyarinov, "Diagram for determining dangerous zones when sailing in heavy weather," *Bulletin of the Astrakhan State Technical University. Series: Marine Engineering and Technology*, vol. 2018, no. 2, 2018. https://doi.org/10.24143/2073-1574-2018-2-22-27

[26] A. Eremenko and Y. Zhukov, "Smart onboard seafaring safety assurance system," *Electrical and computer systems*, vol. 22, no. 98, pp. 293–300, 2016. https://doi.org/10.15276/eltecs.22.98.2016.48

[27] A. Ershov and P. Buklis, "Ways to increase speed and save fuel tanker n storm conditions," *Bulletin of the State Maritime and River Fleet University named after Admiral S.O. Makarov*, vol. 10, no. 6, pp. 1122–1131, 2018. https://doi.org/10.21821/2309-5180-2018-10-6-1122-1131

[28] S. Zinchenko, V. Mateichuk, P. Nosov, I. Popovych, O. Solovey, P. Mamenko, and O. Grosheva, "Use of simulator equipment for the development and testing of vessel control systems," *Electrical, Control and Communication Engineering*, vol. 16, no. 2, pp. 58–64, Dec. 2020. https://doi.org/10.2478/ecce-2020-0009

Serhii Zinchenko graduated in 1979 from Kharkov Aviation Institute (now the Aerospace University) with a specialty of aircraft engineer. Since 1979, he has worked at the scientific production association Hartron, developed software for spacecraft control systems. In 1993, he obtained the degree of the Candidate of Technical Sciences in a specialty of Systems for Special Purposes, Information Processing and Control. In 2021, he defended the Doctoral Thesis in specialty 05.13.07 – Automation of Control Processes.
Current position – Associate Professor of the Ship Handling Department, Kherson State Maritime Academy, Ukraine. Fields of research interest: systems of automatic, automated control and ship handling.
E-mail: srz56@ukr.net
ORCID iD: https://orcid.org/0000-0001-5012-5029

Vadym Mateichuk received the B.Sc. degree in Computer Science from Kherson State University and B. sc. degree in Navigation from Kherson State Maritime Academy, Kherson, Ukraine, in 2010 and 2017, respectively.
Current position – Senior Lecturer of the Ship Handling Department, Kherson State Maritime Academy, Ukraine. Fields of research interest: systems of automatic, automated control and ship handling.
E-mail: mateichykv@gmail.com
ORCID iD: https://orcid.org/0000-0001-9328-0651

Oleh Tovstokoryi graduated from Odessa Higher Maritime Engineering School in 1979 with a degree in Navigation on Sea Routes and obtained the qualification of Navigation Engineer. In 1993, he received the diploma of Captain of Long-Distance Sailing. In 2013, he received the degree of Candidate of Technical Sciences in specialty 05.22.13 – Navigation and Traffic Management. Work experience at sea – 42 years, 17 of them – captain.
Current position – Head of the Ship Handling Department, Kherson State Maritime Academy, Ukraine. Fields of research interest: the latest training technologies in ship handing during marine professionals' training.
E-mail: otovstokory@gmail.com
ORCID iD: https://orcid.org/0000-0003-3048-0028

Pavlo Nosov received the degree of Candidate of Technical Sciences from Odessa National Polytechnic University, specialty – Systems and Means of Artificial Intelligence, in 2007. He is the author of more than 200 scientific works, including 4 monographs.
Current position – Associate Professor of the Navigation Department, Kherson State Maritime Academy, Ukraine. Fields of research interest: computer science, mathematical model of the human factor in maritime transport.
E-mail: pason@ukr.net
ORCID iD: https://orcid.org/0000-0003-3157-5096

Ihor Popovych received the degree of Candidate of Psychological Sciences in Social Psychology; Psychology of Social Work in 2008. He defended his Doctoral Thesis in 2017. He is the author of more than 150 scientific works, including 6 monographs.
Current position – Professor of the General and Social Psychology Department, Kherson State University, Kherson, Ukraine. Fields of research interest: psychology of social expectations of the personality, psychology of constructing the future.
E-mail: ihorpopovych999@gmail.com
ORCID iD: https://orcid.org/0000-0002-1663-111X

Igor Gritsuk graduated from Donetsk Polytechnic Institute with a degree in automobiles and automotive industry in 1979. Since 1986, he has been working in the scientific and technical sector of the Kyiv Automobile and Road Institute. In 1988, he defended his PhD Thesis in the specialty 05.04.02 – Internal Combustion Engines. In 2016, he defended his Doctoral Dissertation in the specialty 05.22.20 – Operation and Repair of Vehicles. Since 2017, he has been working at the Kherson State Maritime Academy. He delivers the courses "Organisation of the Technical Operation of Ship Power Plants", "Using Methods of Technical Diagnostics in the Operation of Ship Equipment" and other.