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AUTOMATIC CONTROL OF THE VESSEL MOVEMENT IN A STORM

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АВТОМАТИЧНЕ КЕРУВАННЯ РУХОМ СУДНА У ШТОРМ

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Steering a vessel in a storm is an important stage in the vessel's wiring. Vessel control methods in storm have always depended on technological capabilities. In ancient times and the Middle Ages, vessel control in a storm was performed in such a way as to coordinate their actions with the actions of the element and not to contradict it. As a rule, this is the period of using human muscular strength, and the traditional vessel control method was lag to the wave. With the advent of the sail, active vessel control methods emerged. This is the movement on the wave used by the Pomors, or the orientation across the wave used by the Phoenicians on warships. Medieval shipbuilding (during the Roman Empire) was characterized by the fact that there were requirements for maximum speed of the vessel to protect merchant ships from pirates. There were created light and high-speed sailing-oars vessels – liburns, in which the seaworthiness was optimized together with the achievement of maximum speed. It is believed that the liburns became the prototype of the Mediterranean galley, which lasted until the XVIII century. At the same time, there were created sailing vessels of unlimited areas and autonomy. The seaworthiness of modern ships, their speed and size have changed a lot. The range of their possible applications has also expanded. For example, in articles [1–3], recommendations for control a modern ship in a storm are considered. To facilitate the task of a vessel control in storm, a number of scientists have proposed special diagrams for choosing the course and speed in storm conditions. The first general diagrams, based on a joint account of the dangerous effects of the storm, were proposed by V. B. Lipis and D. V. Kondrikov in 1972. The diagrams were made taking into account the strength and direction of the wind; intensity and direction of irregular sea waves; keel, vertical and on-board rocking, phase shift between them and the profile of the oncoming waves; additional resistance to the movement of the vessel due to sea waves and wind; limitation of power of the main engine on protective parameters; slamming; reducing the efficiency of the propeller; acceleration of the propeller; flooding the vessel's deck; accelerations in the process of rocking. Storm diagram of the V. G. Vlasov is a prototype of the storm diagram of the Remez. Vlasov storm diagram is clearer, and for sea disturbance close to regular, more precisely gives recommendations on the choice of safe course and speed. In Vlasov diagrams in polar coordinates, where the rays determine the course angles, and concentric circles – the speed, there are resonant – hazardous zones, calculated for a specific vessel and a certain excitation spectrum, characterized by the wavelength λ.

The most widespread is the universal diagram of the Yu. V. Remez, which allows to determine unfavorable combinations of velocity and course angles of waves (resonant zones) for any vessel and any wavelength λ and choose a safe speed and course of the vessel outside the resonance zone.

However, there are number of factors that prevent the effective use of storm diagrams. First, the excitation 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 [4–6]. 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 to significantly reduce the impact of the human factor and increase the safety of navigation [7–13], especially in difficult sailing conditions.

This paper proposes an automatic storm system, which does not have disadvantages of manual control, namely: the automatic storm system uses specialized equipment to measure the parameters of the wave; measurement of vessel motion parameters and excitation parameters, as well as their processing and formation of controls is automatic and constant, with the clock of the vessel's on-board controller, which allows to constantly monitor any changes in vessel motion and wave parameters; software, if it is tested and does not contain errors, always calculates the correct result and can work in any storm conditions; moreover, unlike manual storming, the problem can be solved optimally.

Therefore, the development of a vessel automatic storm system is an urgent scientific and technical task.

Mathematical model of the control object $\mathbf{f}(\bullet)$, meter model and the law of control $\mathbf{F}(\bullet)$ represented by vector equations, respectively (1)–(3).

$$\frac{d\mathbf{X}}{dt} = \mathbf{f}(\mathbf{X}, \mathbf{U}, \mathbf{W}, T_B, T_L)\,, \tag{1}$$

$$\mathbf{Y} = C\mathbf{X} + \varsigma\,, \tag{2}$$

$$\mathbf{U} = \mathbf{F}(\mathbf{Y}, \mathbf{Y}^*(n-1))\,, \tag{3}$$

$$\mathbf{Y}^*(n-1) \subseteq \mathbf{\Omega}\,,$$

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, Y is measurement vector, C is meter matrix, ς is meter error vector, $\mathbf{Y}^*(n-1)=(V^*(n-1), K^*(n-1))$ is program vector (program speed and program course), $\mathbf{\Omega}$ is resonance zone.

It is required to define such $\mathbf{Y}^*(n)=(V^*(n), K^*(n)) \not\subset \mathbf{\Omega}$, for which the control quality function is $Q(\mathbf{Y}^*(n), \mathbf{Y}^*(n-1)) \rightarrow \min$.

Block diagram of the vessel automatic storm system is shown in Fig. 1.

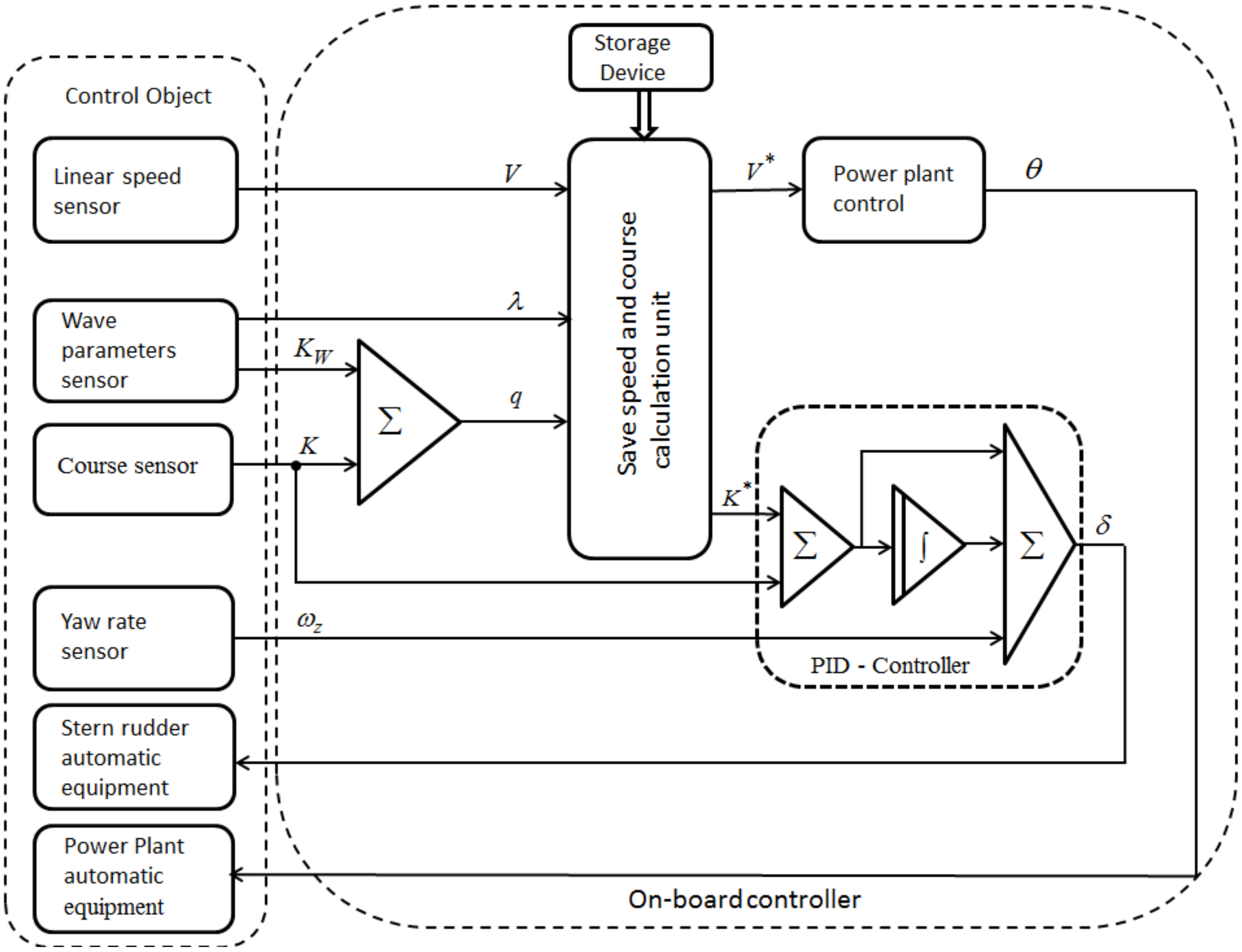

Fig. 1 – Block diagram of the vessel automatic storm system

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 put 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 adder 1 calculates the wave course angle $q = K - K_W$, which is fed to safe speed and course calculation unit. Also, the wave length λ and vessel speed V are fed to safe speed and course calculation unit. The safe speed and course calculation unit calculates the resonance zone $\mathbf{\Omega}$ and allowable storm areas that lie outside the resonance zone Ω and between the minimum vessel speed and the maximum vessel speed in a storm. The presence of allowable storm areas means the presence of an infinite number of allowable storm parameters $\{ V^*(n),\ K^*(n)\}$, from which the optimal ones can be selected according to the established optimality criterion. 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 under the conditions of restrictions $\mathbf{Y}^*(n) \not\subset \mathbf{\Omega}$ and $V_{\min} \le V(n) \le V_{\max}^{st}$, where $V_{\max}^{st}$ is the vessel maximum speed in a storm. Parameters $\{ V^*(n),\ K^*(n)\}$ 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, 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.

Define out-of-resonance zones $\mathbf{\Omega}_1, \mathbf{\Omega}_2$

$$e(n)\cos q(n) < \frac{1}{V_{\max}}(1{,}42\frac{\lambda}{T_B} - 2{,}31\sqrt{\lambda}), \tag{4}$$

$$e(n)\cos q(n) > \frac{1}{V_{\max}}(2{,}64\frac{\lambda}{T_B} - 2{,}31\sqrt{\lambda}), \tag{5}$$

$$e(n)\cos q(n) < \frac{1}{V_{\max}}(1{,}42\frac{\lambda}{T_L} - 2{,}31\sqrt{\lambda}), \tag{6}$$

$$e(n)\cos q(n) > \frac{1}{V_{\max}}(2{,}64\frac{\lambda}{T_L} - 2{,}31\sqrt{\lambda}). \tag{7}$$

Define the control quality function as follows

$$Q = (e(n)\cos q(n) - e(n-1)\cos q(n-1))^2 + (e(n)\sin q(n) - e(n-1)\sin q(n-1))^2, \tag{8}$$

where $e(n) = \frac{V(n)}{V_{\max}}$ is the safe reduce speed in a storm, $e(n-1) = \frac{V(n-1)}{V_{\max}}$ is the actual reduce speed in a storm, $q(n), q(n-1)$ is the safe wave angle and actual wave angle, respectively.

The safe speed and course calculation unit determines the optimal pair of parameters $\{e(n),\ q(n)\}$ by minimizing the control quality function (8), in the presence of constraints (4)–(7) and $e(n)_{\min} \le e(n) \le e(n)_{\max}^{st}$. For nonsmooth functions, more complex global optimization methods are used, for example [14–16]. In our case the control quality functions (8) is smooth, the search for the optimal solution does not present much difficulty and can be carried out in a small number of iterations. To solve this optimization problem with linear and nonlinear constraints in the form of inequalities $e(n)_{\min} \le e(n) \le e(n)^{st}_{\max}$ and (4)–(7), we used the standard gradient optimization procedure fmincon of the MATLAB Optimization Toolbox library

$$\mathbf{y} = \text{fmincon}(@\ \text{myfun},\ \mathbf{y0}, \mathbf{A}, \mathbf{b}, \mathbf{Aeq}, \mathbf{beq}, \mathbf{lb}, \mathbf{ub}, @\,\text{mycon}),$$

where $\mathbf{y} = (V^*(n), K^*(n))$ is the vector of optimized parameters, $@\,\text{myfun}$ is the link to file with optimized quality function (7), $\mathbf{y}0 = (V(n-1), K(n-1))$ is the starting vector of optimized parameters, $\mathbf{A} = []$, $\mathbf{b} = []$ 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, $\mathbf{lb} = (V\,\text{min}, -\pi)$ is the limiting the vector of optimized parameters from below, $\mathbf{ub} = (V^{st}_{\max}, \pi)$ is the upper bounds on the vector of optimized parameters, $@\,\text{mycon})$ is the link to file with nonlinear constraints (4)–(7).

At the imitation modeling stand [17, 18], in a closed circuit with mathematical models of the Navi Trainer 5000 simulator, there were performed mathematical modeling of the automatic control of the Ro-Ro passenger ferry 13 in a storm.

Fig. 2 shows graphs of changes in roll angle, trim angle, speed and course of the vessel with automatic control of the vessel Ro-Ro passenger ferry 13 in a storm. Initial course of the vessel is $K(0) = 75^\circ$, initial speed is $V(0) = 18{,}5\,kn.$, initial sea disturbance is 2 points. The vessel, moving the course $K(n) = 75^\circ$, accelerates to speed $V(n) = 19\,kn.$, 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 $V(n) = 7\,kn.$ At the same time, the automatic storm system begins to change course from $K(n-1) = 75^\circ$ to safe $K(n) = 45^\circ$ to exit the resonance zone.

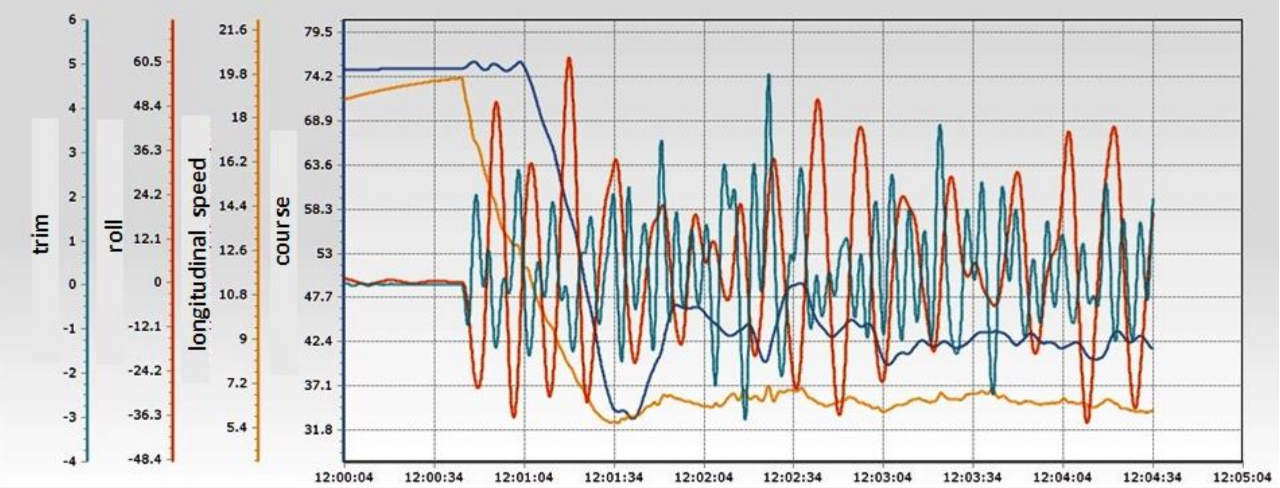

Fig. 2 – Automatic control of the vessel Ro-Ro passenger ferry 13 in a storm

Conclusion. The issues of automatic vessel control in a storm are considered. The scientific novelty of the obtained results is that for the first time theoretically substantiated design features of the original system of automatic control of the vessel in a storm, which consist in constant, with the onboard controller cycle, automatic measurement of vessel and wave motion parameters, automatic calculation outside resonant zones, taking into account resonant zone boundaries, minimum vessel speed and maximum vessel speed in a storm, automatic selection of safe optimal motion parameters from outside resonant zones according to the specified criterion of optimality, automatic maintenance of safe optimum parameters of movement in a storm, and provide fundamentally new technical characteristics: the ability to automatically control the vessel in a storm, the ability to optimally control the vessel in a storm, reduce depletion of the vessel's crew when sailing in difficult conditions, increase the accuracy and reliability of the vessel control in a storm, which determine its advantages over known solutions. 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 modeling on the imitation modeling stand in a closed loop with vessel mathematical models for different types of vessel, sailing areas and meteorological conditions.

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