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AUTOMATIC CONTROL OF THE VESSEL IN A STORM

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Adverse weather and sea conditions are the most difficult sailing conditions on the route. Long rolling, need for constant concentration of attention greatly exhausts the crew and leads to wrong decisions. Existing methods of storming are not very effective, as they have low accuracy, significant time delays between obtaining data for calculation and determining safe movement parameters, lack of possibility of constant determination of safe movement parameters, difficulty in identifying the dominant factor from the system of dangerous factors, intuitive assessment of the level of danger. The purpose of the research is to develop a method of automatic storming that will ensure safe sailing in storms. The method, algorithmic and software of the automatic ship control module in the storm have been developed, which allows forming safe and optimal parameters of the ship's movement. The obtained results are explained by the use of an on-board computer, solving, at each step of the on-board computer, an optimization problem with nonlinear constraints. The use of nonlinear constraints allows to optimize the objective function taking into account the dangers of stormy sailing: synchronous and parametric resonance, loss of stability in following seas, impact of group waves in the stern of the ship, exceeding permissible loads on the structure of the ship's hull, etc. The obtained results differ from known solutions in that for the first time the problem of automatic optimal control of ship in a storm is solved, which allows to significantly reduce the influence of human factor on storm processes and increase the safety of shipping. The results obtained are reproducible and scalable. Extensibility is explained by taking into account other hazards in the form of restrictions on optimization parameters. The theoretical significance of the obtained results lies in the application of the nonlinear optimization method with linear and nonlinear constraints of the type of inequalities to find optimal and safe storm parameters. The practical significance of the obtained results lies in the possibility of applying the developed methods in automatic ship control module in a storm, which allows to reduce the influence of human factor on storming processes, reduce fatigue of the crew, and increase the safety of navigation.

Key words: *navigation safety; human factor; intelligent vehicles; automatic control; storm diagrams; optimization with constraints; dangerous areas.*

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Introduction. Adverse weather conditions are the most difficult sailing conditions on the route. Long rolling, need for constant concentration of attention greatly exhausts the crew and leads to wrong decisions. The situation worsens also due to the fact that during a storm, such dangerous phenomena as synchronous and parametric resonances occur [1], much more often, deforming forces and moments increase, which can reach the maximum allowable values and lead to the destruction of the hull, the lateral stability of the ship in following seas, decreases, etc. Guidelines and Recommendations for safe sailing in difficult weather conditions are given in IMO documents.

The existing methods of storming are not very effective, as they have low accuracy, due to the use of visual methods of estimating the parameters of turbulence and manual graphic constructions, significant time delays between obtaining data for calculation and determining safe parameters of movement, lack of constant measurement of parameters of turbulence and refinement of safe parameters of movement, the difficulty of identifying the dominant factor from the system of dangerous factors, intuitive assessment of the level of danger. Therefore, improving the safety of storm sailing is an urgent scientific and technical task.

Problem statement. Develop a module of automatic control vessel in a storm that will ensure ship controllability, avoidance of capsizing hazards, synchronous and parametric resonances, loss of stability in following seas, and avoidance of group waves impacts on the stern.

Analysis of recent research and publications. The question of safe sailing in a storm has been previously considered by many authors.

Thus, the book [2] provides information on: automated means of monitoring the seaworthiness of ships (ASCM); data on ASCM information sensors; theoretical foundations of seaworthiness calculation; concept of methods for choosing the optimal transition plan; current samples of ship ASCM; advantages of using ASCM.

In the book [3], the author provides data on: the linear theory of oscillation on calm water, on regular rolling and pitching; basics of the nonlinear theory of rolling; calculation of forces, bending and torques acting on the ship's hull; calculation of the safe speed and course of the ship during a storm using the universal storm chart.

In the work [4], the author cites dangerous phenomena that can occur during storm sailing, in particular: surf-riding and broaching, which occur when the vessel is on the steep front slope of a high following wave. In this case, the ship can be accelerated by going down the wave, but there is a danger of capsizing with a sudden change of course; reduction of intact stability when riding a wave crest amidships, occurs when the ship moves on the crest of a wave. The danger of the situation is a significant decrease in stability, especially when the wavelength is (0.6–2.3) the length of the vessel; synchronous rolling motion, also known as synchronous resonance, occurs when the period of the ship's own oscillations coincides with the period of oncoming waves; parametric roll motions, also known as parametric resonance, leads to a sharp increase in roll amplitude due to a periodic change in stability at the crests and troughs of waves. The author describes the possible situations of occurrence of parametric resonance: the period of natural oscillations of the vessel coincides with the period of waves, the stability of the vessel decreases to a minimum once per oscillation period, the situation is characterized by asymmetric oscillations, when the roll amplitudes in different directions differ from each other, the transition of this type of parametric resonance is synchronous; when the period of the ship's own oscillations is twice as long as the wave period, the stability of the vessel decreases to a minimum of two times during the oscillation period, the situation is characterized by symmetrical oscillations; when there is a consistent and periodic submersion and surfacing of the stern and bow part of the vessel, which can lead to serious rolling movements, even if the vessel is stable; when the periods of pitching and drifting coincide with the period of the waves. The work also includes mathematical formulas that describe the conditions for the occurrence of dangerous phenomena.

In the article [5] researchers generate realistic ocean environmental fields and analyze actual sea data. Then, derive a modular maneuvering model reflecting environmental disturbances for further simulations. The correlation and multi-regression analyses are performed based on measured data and environmental factors, which illustrate that the abnormal rudder angles are caused by reduced steering effectiveness. The maneuvers are simulated by adopting the attenuation function, and the simulation results show fair agreement with the measured data. Significant wave height, wind speed, mean wave period, current speed, wind apparent direction, and wave encounter angles are found to be the most statistically considerable factors of rudder attenuation in the studied cases. The results and conclusions obtained from this study are of great significance for the further exploration of actual ship maneuvering behaviors in seas.

In the article [6], the issue of increasing speed and reducing energy consumption during cargo and ballast voyages of a tanker is considered. Based on the results of experiments and observations carried out on the tanker itself, a method of increasing speed and reducing fuel consumption in stormy conditions is proposed. It is shown that an increase in speed and fuel saving can be achieved with the same wind and wave encounting angles. This rule must be taken into account both at the stage of voyage planning and in conditions of stormy sailing. The obtained results can be extended to other types of vessels.

The paper [7] investigated the occurrence of parametric resonance in October 1998 on the Post-Panamax C11 container ship. The vessel was exposed to extreme weather conditions and suffered significant losses and damage to containers stacked on deck. The conducted research made it possible to establish that a parametric resonance can occur in the roll channel on Post-Panamax container ships. The values of possible accelerations and speeds were also determined, and the impact of these loads on the structure and lashing system of containers was determined.

The structure of the ship safety system at the stages of designing and operating ships is proposed in [8]. The composition of ship systems necessary to ensure the safety of sailing in stormy seas is considered. The use of multi-agent information processing technologies in the navigation safety system is proposed, and recommendations for the shipmaster regarding the choice of safe parameters of the ship's movement have been developed.

In the works [9, 10], methods of automatic control of a ship in a storm are considered. A universal storm diagram was constructed in relative coordinates, and resonance zones were determined. It is shown that the out-of-resonance zone is significantly smaller, compared to the out-of-resonance zone of Remez, which is explained by a decrease in the maximum speed of the vessel in a storm. Methods of automatic control under storm conditions are proposed, which allow to reduce the influence of human factor on the processes of controlling a ship in a storm, reduce crew fatigue, optimize control processes and increase the safety of navigation in general. The workability and efficiency of the developed methods are verified by mathematical modeling.

In the works [11], the method, algorithm and software of the automatic storming module were developed. Given that the ship's oscillatory process is dampened by dissipative forces and moments, low-energy wave frequencies are safe for the ship and do not lead to resonant rolling. Taking this into account, it is proposed to integrate a fast Fourier transform unit into the storm system to determine the spectrum of external influences, to consider only those components of the spectrum, whose energy does not exceed a critical value, which made it possible to reduce resonant zones and expand the possibilities of safe sailing.

The requirements of the Rule Note [12] apply to analysis criteria and ship motion modeling calculation of ships intended to be granted the additional class notation PaRoll1 and PaRoll2, as defined in NR467 Rules for Steel Ships, Pt. A, Ch. 1, Sec. 2. This Rule Note deals with the part of motion analysis which aims at performing parametric resonance and based on hydrodynamic calculations including ship motions response.

In the works [13, 14], synchronous or parametric rolling has been investigated and recommendations have been made to enable captains to recognize and avoid the risk of synchronous or parametric rolling before it becomes a threat. This helps to avoid losing containers.

Purpose and objectives of the research. The purpose of the research is to develop a method, algorithm and software of the automatic ship control module in a storm, which will allow automatic and optimal sailing in a storm that is safe from capsizing. Automatic ship control module in a storm allows determining optimal safe movement parameters in a storm, more accurate and faster than in manual mode by the navigator. Also automatic ship control module in a storm neutralizes human factors, which is very important in stressful conditions. The goal is achieved through the use of an on-board computer, and using it for finding the optimal and safe parameters of the ship's movement by conditional optimization of the given objective function, taking into account the restrictions on the movement parameters that ensure the ship's controllability, the absence of synchronous and parametric resonance, loss of stability in following seas, absence of broaching, absence of group wave impacts on the stern; maintenance of safe traffic parameters by the control system.

Materials and methods. We aim to solve the problem of automating navigation in storm by employing nonlinear optimization methods for the objective function with inequality constraints.

$$\begin{cases} F(V,K) \to opt \\ f_1(V,K) \le 0 \\ f_2(V,K) \le 0 \\ \ldots \\ f_n(V,K) \le 0 \end{cases} \tag{1}$$

where $F(V,K)$ is the objective function to be optimized, $f_j(V,K) \le 0, j = 1..n$ is the constraint type of inequalities.

The given objective function and specified constraints (1) depend on the parameters of the ship's movement (speed V, *m/s* and course K, *degrees*), as well as on the parameters of the waves (direction, speed and wavelength). Of all the named parameters, only two are available for control – the ship's speed and course, which we will use for conditional optimization. Other parameters that we cannot influence during storm sailing (wave parameters, range of permissible speeds and courses, etc.) are used as external data when solving the optimization problem.

Known methods of determining dangerous zones of controls in adverse weather conditions consider only one harmonic of wave [3, 15]. By Fast Fourier transformation it is possible to obtain frequency-based representation (spectrum) from a time-based representation signal of the wave. Therefore, having a sequence of frequencies for calculating dangerous zones of controls in adverse weather conditions, choose only that frequency, which has high amplitude, that cannot fade away by damping coefficient. After that, automatic ship control module in a storm calculates dangerous zones of controls in adverse weather conditions separately for each frequency, with dangerous amplitude. The final dangerous zone should be a zone that is a union of zones of all frequencies.

Fig. 1 shows scheme of automatic ship control module in a storm in vessel control system. Navigational sensors measure the angular speed vector $\boldsymbol{\omega}$ of vessel, the vessel speed vector $\boldsymbol{V_m}$ and course vessel K_m, the wave parameters sensors measure the wave course *Kw*, wave speed *C*, amplitude *A* and wave length *λ*. Information about wave parameters sensors fed on the safe movement parameters determining module for calculating safe speed and course of vessel in adverse weather conditions. Also, for this purpose, module needs to get navigational data and dangerous components of the spectrum for taking into account only frequencies with dangerous amplitudes. Components of the spectrum determining by Fast Fourier transformation module. Components of the spectrum are fed into the module of determination dangerous components of the spectrum. After that, dangerous components are sent to Safe movement parameters determining module. The Safe movement parameters determining module calculates the resonant Ω and non-resonant $\overline{\Omega}$ zone, considering the minimum and maximum speed of the vessel in a storm, in optimal way choose safe course K^* and safe speed V^* of vessel, taking into account the set of restrictions. Parameter V^*, is fed into the Engine Remote Control System which determines control signal Θ to Main engine control unit. Parameter K^* together with navigational data (Course of vessel K_m, angular yaw rate ω_z) is fed into the input of the PID controller. Deflection angle δ is fed into the Steering gear unit to maintain a safe course.

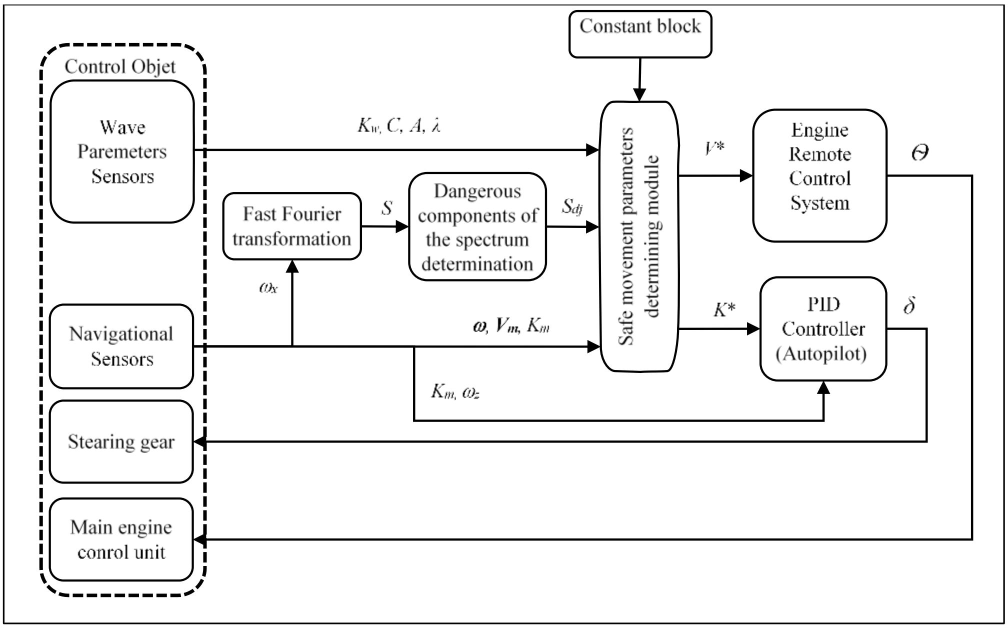

Figure 1 – Automatic ship control module in a storm in vessel control system

For safe sailing, it is necessary to ensure: the necessary speed of the ship to maintain controllability, the absence of conditions for the occurrence of phenomena dangerous for the ship to overturn, such as synchronous and parametric resonances, broaching, loss of stability in following seas, impacts of group waves on the stern.

Permissible vessel speeds consideration. The speed of the vessel cannot be less than the minimum speed $V_{\min}$ at which controllability is lost and more than the maximum speed $V_{\max}$ in storm conditions

$$V_{\min} \le V \le V_{\max} \tag{2}$$

Synchronous *resonance consideration*. In the work [3] it is stated that synchronous resonance occurs under the condition that the ratio of the period of the ship's own oscillations T_C, *sec* to the period of encounter of the waves τ, *sec* waving the ship is within

$$0{,}7 \le \frac{T_C}{\tau} \le 1{,}3 \tag{3}$$

Using inequality (3), we identify a safe area outside the synchronous resonance zone.

$$\begin{gathered} 1{,}3 \le \frac{T_C}{\tau}, \frac{T_C}{\tau} \le -0{,}3 \to 0{,}3 \le \frac{T_C}{\tau} - 1, \frac{T_C}{\tau} - 1 \le -0{,}3 \\ \left| \frac{T_C}{\tau} - 1 \right| \ge 0{,}3 \end{gathered} \tag{4}$$

The period of encounter τ of the waves is determined by the formula

$$\tau = \frac{\lambda}{C + V\cos q} \tag{5}$$

Here, where λ represents the wavelength in meters, C is the wave propagation speed in m/s, V is the vessel speed in m/s, and q is the angle of encounter, in degrees.

The angle of encounter of the wave is the angle between the diametrical plane of the vessel and the wave speed vector, it can be represented as the difference between the courses of the own vessel K and the wave direction K_W, in degrees

$$q = K - K_W + 180^0 \tag{6}$$

By combining inequality (4) and equations (5), (6), we derive a secure zone beyond the bounds of synchronous resonance.

$$\left| \frac{T_C\left(C + V\cos q\right)}{\lambda} - 1 \right| \ge 0{,}3 \tag{7}$$

Parametric resonance consideration. Parametric resonance leads to a sharp increase in roll amplitude due to a periodic change in stability at the crests and troughs of the waves. The most dangerous is parametric resonance, when the period of the vessel's own oscillations is twice the period of the waves [16]. In this case, the stability of the vessel decreases to a minimum twice during the oscillation period, the situation is characterized by symmetrical oscillations. The safe region outside the limits of this type of parametric resonance can be written as

$$\left| \frac{T_C}{2} - \tau \right| \ge \Delta T \tag{8}$$

where ΔT is the difference between the half period of the vessel's natural oscillations and the period of encounter of the waves, at which parametric resonance of this type does not yet occur.

The occurrence of parametric resonance is also possible, when the period of the vessel's own oscillations coincides with the period of the waves, the stability of the vessel decreases to a minimum once per oscillation period, the situation is characterized by asymmetric oscillations, when the roll amplitudes in different directions differ from each other. The safe region outside the limits of this type of parametric resonance can be written as

$$|T_C - \tau| \geq \Delta T \tag{9}$$

Decrease in stability in following seas consideration. Decrease in stability in following seas occurs due to a significant decrease in the underwater volume of the vessel's hull and the restoring moment. The area of the vessel's movement parameters, which is safe in terms, decreases in stability in following seas, is determined by a system of inequalities

$$\begin{cases} |\lambda - L| \geq \Delta\lambda \\ |V - C| \geq \Delta V \\ |K - K_w| \leq \Delta K \end{cases} \tag{10}$$

where $\Delta\lambda$ is the largest difference between the wave length λ and the length L of the vessel, at which decrease in stability in following seas occurs, ΔV is the largest difference between the vessel's speed and the wave speed, at which decrease in stability in following seas occurs, ΔK is the largest difference between the vessel's and the wave courses, at which it is possible to consider the motion in following seas.

Broaching consideration. The danger of broaching consists in turning the vessel along the wave with its subsequent capsizing [17]. The area of the vessel's movement parameters, which is safe with respect to broaching, is determined by a system of inequalities

$$\begin{cases} |\lambda - L| \geq \Delta\lambda \\ V \leq V_W \end{cases} \tag{11}$$

Wave grouping phenomena consideration. Taking into account the dangerous impacts of group waves on the stern. Ocean waves are a collection of irregular waves of different length, height and direction. When the waves come in from the stern and their speed is slightly higher than the ship's speed, the ship is continuously hit repeatedly and severely by a series of high waves, causing her maneuverability to become uncontrollable. Also, the impact of these waves leads to damage to the hull and steering. The dangerous area of the relationship between the ship's motion parameters and the waves is represented by the V/T diagram in “Revised guidance to the master for avoiding dangerous situations in adverse weather and sea conditions,” (IMO MSC.1/Circ.1228) [15].

Using the diagram and carrying out transformations similar to those given for equation (4), we will write down safe relations between the parameters of the ship's movement and the waves, which exclude the impact of group waves on the stern

$$\begin{cases} |K - K_W - 180| \geq 50 \\ \left| \dfrac{V}{T_W} - 1{,}65 \right| \geq 0{,}35 \end{cases} \tag{12}$$

Navigational limitations consideration. It is also important to take into account navigational restrictions. Information about dangers may be fed from other automatic analysis systems such as target vessels, navigational dangers, etc. The following inequality can be used to approximately find the course limit

$$K^* \neq K_{Dg} \pm \frac{2}{D_{Dg}} \tag{13}$$

where K^* is the calculated safe course in degrees, K_{Dg} is the course to navigational danger in degrees, D_{Dg} is the distance to navigational danger in miles, taken from radar.

Similarly, other restrictions are recorded, which exclude entering into dangerous regions of optimal parameters.

For the objective function, you may opt for a function, such as

$$F = (K^* - K_{SET})^2 \to \min \tag{14}$$

which will guarantee the minimum deviation of the safe course K^* from the specified K_{SET} or function

$$F = (V^* - V_{SET})^2 \to \min \tag{15}$$

which will ensure the minimum deviation of the safe speed V^* from the goal speed V_{SET} ,or other functions that will provide the desired control quality.

To find safe motion parameters V^*, K^*, which optimize the objective function (14), (15) with linear (2), nonlinear constraints (7) - (12) and taking into account inequality (13), we use the nonlinear optimization function like $f\min con(\bullet)$ MATLAB

$$f\min con\left(@\,fun, \mathbf{x}0, \mathbf{A}, \mathbf{b}, \mathbf{A}eq, \mathbf{b}eq, \mathbf{l}b, \mathbf{u}b, @\,nonlcon\right) \tag{16}$$

where $@\,fun$ is a link to the file with the objective function,

$\mathbf{x}0 = (V(0), K(0))$ is the initial vector of parameters to be optimized,

$\mathbf{A}$ is the matrix of the system of linear constraints of the type of inequalities, which is absent in our case,

$\mathbf{b}$ is the vector of the right parts of the system of linear constraints of the type of inequalities, which is absent in our case,

$\mathbf{A}eq$ is the matrix of the system of linear constraints of the equalities type, which is absent in our case,

$\mathbf{b}eq$ is the vector of the right parts of the system of linear constraints of the equalities type, which is absent in our case,

$\mathbf{l}b = [-V_{\min}, -\pi]$ is the vector and components defining the lower limit of the change of the optimization parameters,

$\mathbf{u}b = [V_{\max}, \pi]$ is the vector and components determining the upper limit of the change of the optimization parameters,

$@\,nonlcon$ is the link to a file with a system of nonlinear constraints on optimization parameters

Realization of ship movement with optimal parameters V^*, K^*. To implement the movement of the vessel with the found parameters V^*, K^* the following system of automatic regulation of the ship's movement is used

$$\begin{cases} \Theta = \dfrac{V^*}{V_{\max}} \Theta_{\max} \\ \delta = k_{\varphi}(K - K^*) + k_{\omega}\omega + k_{\int} \int \left(K - K^*\right) dt \end{cases} \tag{17}$$

where Θ is the deviation of the telegraph of the power plant, Θ_{max} is the maximum deviation of the telegraph, δ is the deviation of the stern, K is the current rate, ω is the yaw angular velocity, k_{φ}, k_{ω}, $k_{\int}$ is the gain coefficients of the PID - regulator.

Below are the results of mathematical modeling of storm processes of the Ro-Ro passenger ferry 13 on the Navi Trainer 5000. In all experiments, the wind direction is $K_W = 0^{\circ}$ (north wind), $q = K - K_W = K$.

Fig. 2 shows graphs of changes in roll angle, trim angle, speed and course 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 $T_B = 15\,\text{sec}$. and in the trim channel is $T_L = 5\,\text{sec}$.

Fig. 3 shows graphs of changes in roll angle, trim angle, speed and course of the vessel for the initial course $K(0) = 45^{\circ}$, initial speed $V(0) = 0\,kn.$, initial sea disturbance 2 points. The vessel, moving on course $K(n) = 45^{\circ}$, 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 $V(n) = 7\,kn.$, but the vessel does not capsize. This is due to the fact that the parameters $\{V(n) = 7kn, K(n) = 45^{\circ}\}$ lie outside the resonance zone.

Fig. 4 shows graphs of changes in roll angle, trim angle, speed and course of the vessel for the initial course $K(0) = 75^{\circ}$, initial speed $V(0) = 0\,kn.$, initial sea disturbance 2 points. The vessel, moving on course $K(n) = 75^{\circ}$, 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 $V(n) = 7\,kn.$, 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 speed $V(n) = 7\,kn.$ and course $K(n) = 75^{\circ}$.

Fig. 5 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.

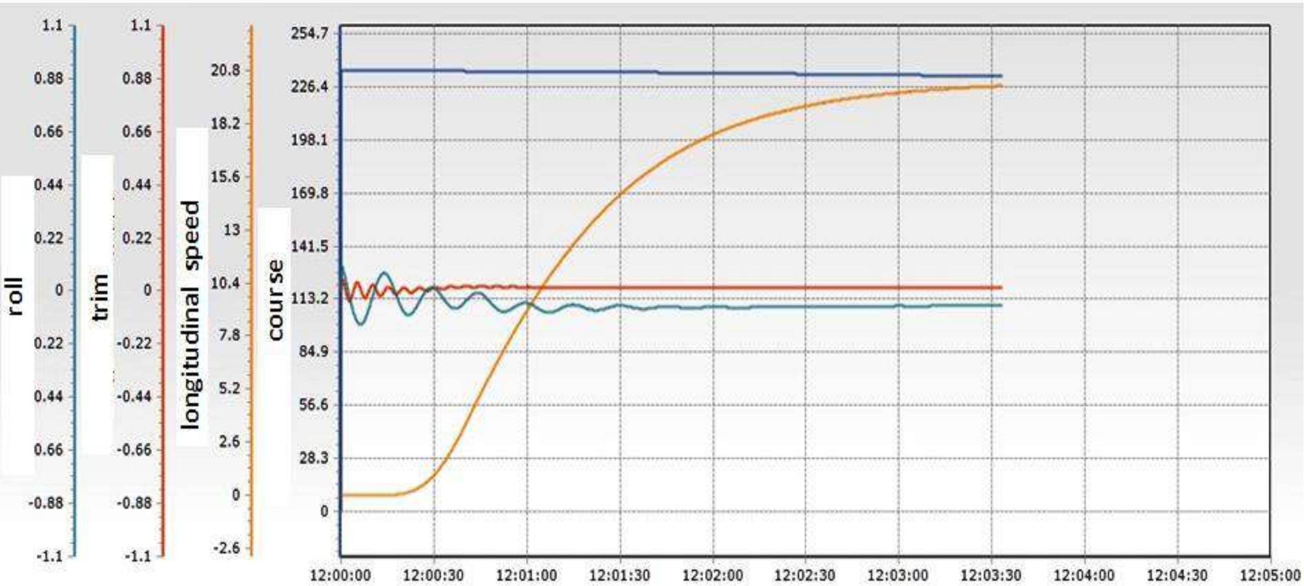

Figure 2 – Graphs of changes in roll angle, trim angle, speed and course during the vessel acceleration

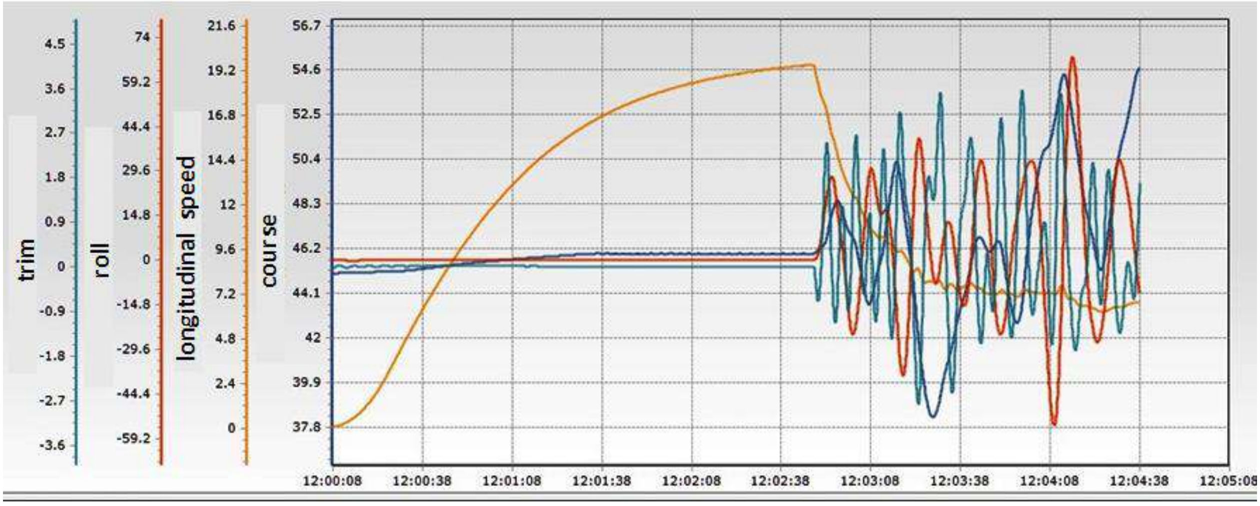

Figure 3 – Parameters of the Ro-Ro passenger ferry 13 movement by course $K(n)=45^{\circ}$

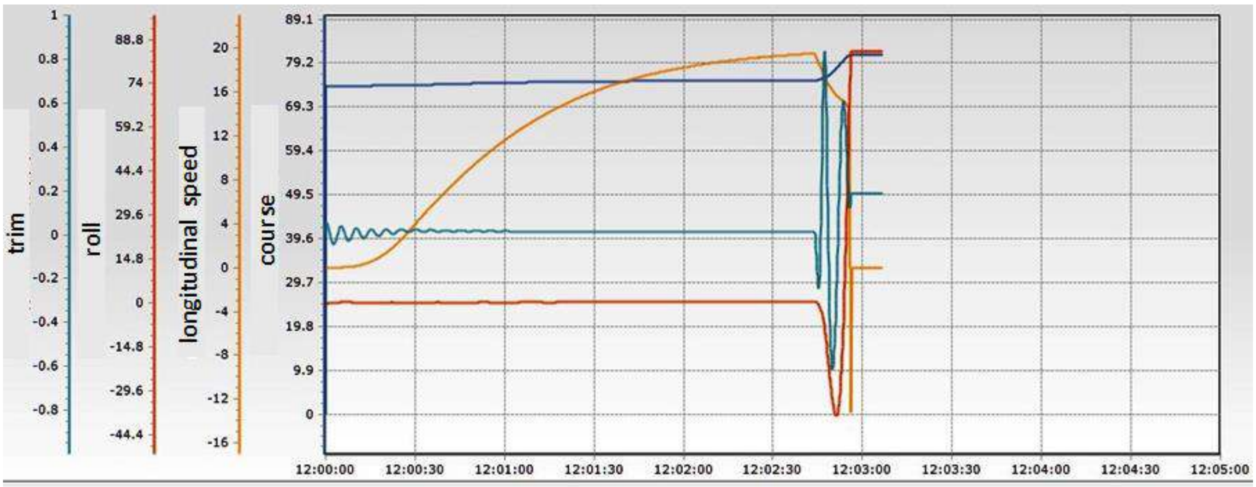

Figure 4 – Parameters of the Ro-Ro passenger ferry 13 movement by course $K(n)=75^{\circ}$

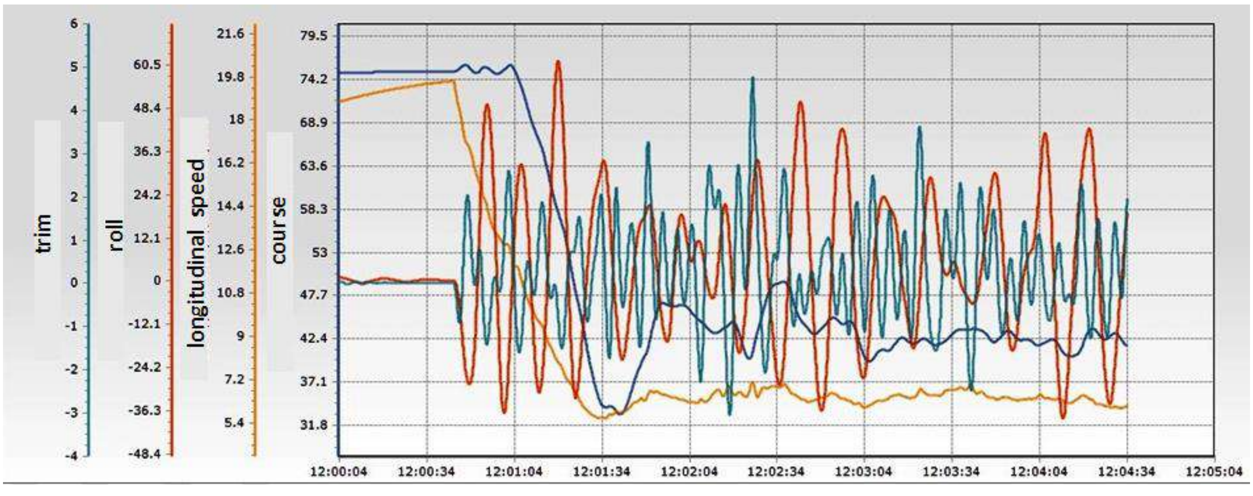

Figure 5 – Automatic control of the vessel Ro-Ro passenger ferry 13 in a storm

Main results and their discussion. The method, algorithmic and software of the automatic ship control module in a storm have been developed, which allows forming safe and optimal parameters of the movement of the ship. The obtained results are explained by the use of an on-board computer, solving, at each step of the on-board computer, an optimization problem with nonlinear constraints. Taking nonlinear constraints into account allows you to optimize the objective function, taking into account the dangers of stormy synchronous and parametric resonance, loss of stability in following seas, impacts of group waves on the stern of the ship, exceeding permissible loads on the ship's hull structure, etc. The obtained results differ from known solutions in that for the first time the problem of automatic optimal control of a ship in a storm is solved, which allows to significantly reduce the influence of human factor on storm processes and increase the safety of navigation.

An experiment was conducted using a Imitation Modeling Stand [18]. The result of the experiment was compared with the data during the training sessions with manual control by the cadets (10 passing of each exercise).

Table 1 shows comparable data which include average rolling amplitude, average duration of being in dangerous zone. Also, it is important to point out that automatic mode allows to calculate the parameters of safe movement faster than the manual mode.

Table 1 – Compared data of the experiments and data during the training sessions with manual control by the cadets

Exercise	***Manual mode by navigator***		***Automatic mode***		***Relative deviation***	
	Average rolling amplitude, °	Average duration of being in the danger zone, min	Average rolling amplitude, °	Average duration of being in the danger zone, min	Average rolling amplitude, %	Average duration of being in the danger zone, %
№1	20,3	2,10	8,2	1,1	-59,6	-47,6
№2	26,7	3,15	11,3	1,2	-57,7	-61,9
№3	43,4	2,05	25,1	0,9	-42,1	-56,1

The developed methods can be used only in the on-board computer of the automatic ship motion control module. The results obtained are reproducible and scalable. Extensibility is explained by taking into account other hazards in the form of restrictions on optimization parameters.

Conclusions The method, algorithmic and software of the automatic ship control module in a storm have been developed. The obtained results are explained by the use of an on-board computer, by finding in the on-board computer the optimal and safe parameters of the ship's movement in a storm by solving the conditional optimization problem with restrictions on the optimization parameters. Limitations on optimization parameters take into account the dangers of stormy sailing. The theoretical significance of the obtained results lies in the application of the nonlinear optimization method with linear and nonlinear constraints of the type of inequalities to find optimal and safe storm parameters. The practical significance of the obtained results lies in the possibility of applying the developed methods in the automatic ship control module in a storm, which allows to reduce the influence of human factor on the storming processes, reduce fatigue of the crew, and increase the safety of navigation. Compared data of the experiments show, that using the automatic ship control module in a storm can reduce average rolling amplitude and duration of being in the danger zone by more than 40 percent.

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Матейчук В. М., Зінченко С. М., Товстокорий О. М. АВТОМАТИЧНЕ КЕРУВАННЯ СУДНОМ У ШТОРМ

Штормові умови плавання є одними із найбільш складних при плаванні на маршруті. Тривала хитавиця, необхідність постійної концентрації уваги дуже виснажує екіпаж та призводить до прийняття помилкових рішень. Існуючі методи штормування мало ефективні, так як мають низьку точність, значні затримки у часі між отриманням даних для розрахунку і визначенням безпечних параметрів руху, відсутність можливості постійного визначення безпечних параметрів руху, складність виявлення домінуючого фактору із системи небезпечних факторів, інтуїтивне оцінювання рівня небезпеки. Метою дослідження є розробка методу автоматичного штормування, який забезпечить безпечне плавання в шторм. Розроблено метод, алгоритмічне та програмне забезпечення модуля автоматичного штормування, які дозволяють формувати безпечні та оптимальні параметри руху *судна. Отримані результати пояснюються використанням бортового обчислювача, вирішенням, на кожному кроці бортового обчислювача, оптимізаційної задачі з нелінійними обмеженнями. Використання нелінійних обмежень дозволяє оптимізувати цільову функцію із врахуванням небезпек штормового плавання: гармонійного та параметричного резонансу, втрати остійності на попутному хвилюванні, ударів групових хвиль у корму судна, перевищення допустимих навантажень на конструкцію корпуса судна, тощо. Отримані результати відрізняються від відомих рішень тим, що вперше вирішена задача автоматичного оптимального керування судном у шторм, що дозволяє суттєво зменшити вплив людського чинника на процеси штормування та підвищити безпеку судноплавства. Отримані результати є відтворюваними та розширюваними. Розширюваність пояснюється врахуванням інших небезпек у вигляді обмежень на оптимізаційні параметри. Теоретичне значення отриманих результатів полягає у застосуванні методу нелінійної оптимізації з лінійними та нелінійними обмеженнями типу нерівностей для знаходження оптимальних і безпечних параметрів штормування. Практичне значення отриманих результатів полягає у можливості застосування розроблених методів у модулях автоматичного штормування судна, що дозволяє зменшити вплив людського чинника на процеси штормування, зменшити втомлюваність екіпажу, підвищити безпеку судноплавства.*

Ключові слова: *навігаційна безпека; людський чинник; інтелектуальні системи транспорту; автоматичне керування; штормові діаграми; оптимізація з обмеженнями; небезпечні зони.*

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