Application of the conditional optimization method in the problem of vessel stormy sailing

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Abstract

Stormy sailing conditions are among the most extreme and dangerous. The rocking of the ship in the roll and trim channels greatly exhausts the crew, which leads to an increase in the number of errors when making management decisions. The situation worsens also due to the fact that during a storm such dangerous phenomena as harmonic and parametric resonances, a decrease in stability on passing waves, broaching, impacts of group waves in the stern, which can lead to the ship's capsizing, hull destruction, overloads of the power plant and occurrence of blackouts. The most radical way to combat such dangers is the automation of control processes. The authors have developed a method of automatic and optimal control of the ship's movement in storm conditions, which allows to avoid the occurrence and development of dangerous phenomena that lead to the capsize of the ship. The obtained result is explained by: the use of an on-board computer in the ship's motion control system; constant measurement of ship movement parameters and waves; finding, at each step of the on-board computer, safe and optimal values of the ship's course and speed by solving the optimization problem; taking into account when solving the optimization problem linear and non-linear constraints of the type of inequalities that define dangerous areas; maintaining safe and optimal movement parameters using the automatic control system. The theoretical significance of the obtained result lies in the development of a method of automatic and optimal control of the ship's movement in conditions of stormy sailing. The practical significance of the obtained results consists in: verification of the developed method by mathematical modeling; the possibility of using the method in the automatic control system, which allows to automate and optimize the processes of controlling a ship in a storm, reduce the influence of the human factor on control processes, crew fatigue, risks of losing the ship and cargo, and generally increase the safety of shipping.

Keywords

Navigation safety, human factor, intelligent transport systems, automated system, resonance zone, stormy sailing

1. Introduction

Steering in a storm is an important stage in sailing a ship. During a storm, there are dangers of ship's capsizing caused by harmonic resonance, parametric resonance of the first and second type, loss of stability in following seas, broaching and impacts of group waves in the stern of the ship. Also, during a storm, the ship is subjected to large loads, which can significantly increase with improper control and lead to the destruction of the hull.

To facilitate the task of steering a ship in a storm, a number of scientists have suggested using storm diagrams. The universal Remes diagram allows to determine dangerous areas of harmonic resonance and choose safe parameters of storming (course and speed of the vessel). At various times, the International Maritime Organization has also developed guidelines for safe sailing in storms. This is "Resolution A.562(14), adopted on 20 November 1985, 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, MSC/Circ.707 from 19 October 1995. Guidance to the master for avoiding dangerous situations in following and quartering seas (MSC/Circ.707 from 19 October 1995), MSC.1/Circ.1228 from 11 January 2007. Revised guidance to the master for avoiding dangerous situations in adverse weather and sea conditions. Storm diagrams and IMO guidelines involve visual

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determination of wave parameters and subsequent manual calculations, using formulas and graphs, which gives low accuracy and contains an element of human factors. To reduce sway, stabilizers of sway built on various physical principles, vane thrusters, special forms of the ship's hull, etc. are also used.

Recently, automated navigation control systems have been developed: HULLMOS navigation parameters monitoring system, OCTOPUS-DSS decision support system, IMDSS integrated marine decision support system, VOSS navigation optimization assessment system, fiber optic system "SENSFIB" and others, which automatically measure the parameters of the own vessel's movement and disturbances, perform the necessary calculations for assessing the seaworthiness of the vessel. At the same time, automated navigation control systems involve the presence of a person in the control circuit and associated decision-making delays and the human factor.

The authors of this article believe that the best solution in this case is the use of automatic storming modules in automated systems. An example of automatic module in automated systems is autopilot, which was introduced in the last century and is successfully used on modern vessels. The captain only needs to make a decision to use the automatic module, and then observe its operation. The use of automatic control modules to solve various problems was considered by us earlier, in particular: automatic optimal control of the vessel's rotation around the pivot point [18], automatic reset of kinetic energy in case of an inevitable collision [19], automatic control of redundant structures of executive devices [20], automatic prevention of the vessel's parametric rolling on the wave [21], devising an approach to safety management of vessel control through the identification of navigator's state [22] and other. Based on the above, a very important issue is the development of the automatic control methods, which would ensure safe sailing in stormy conditions, the implementation of these methods in the automatic control modules of the ship's control system.

2. Related works

Many works are devoted to the study of the processes of controlling a ship in a storm. In particular, work [1] considered the optimization of route planning in order to reduce the probability of the ship encountering severe weather conditions and to minimize the accumulation of fatigue in the ship's structure. Storm profiles were defined as a set of waves, the parameters of which were obtained on the basis of full-scale measurements for two years of flights. The advantages of using route optimization are considered on the example of a container ship.

The work [2] describes a method that allows you to prepare polar maps for various assumed sea states and load conditions in a relatively short time, without long-term modeling of irregular wave conditions. If ships are equipped with a wave radar and have access to a weather service, the polar charts will correspond to the actual sea state, allowing them to be used in practice to form a route taking into account the weather, including the dangers of parametric rolling.

The work [3] investigated the dynamics, controllability, and stability of oscillations in a roll channel on a regular wave. The vessel was modeled as a classical Helmholtz-Duffing oscillator with highly nonlinear asymmetric recovery moment characteristics. The method of incremental harmonic balance was used to obtain frequency characteristics. The effect of gain and time delay in the control circuit of the fundamental and subharmonic responses is investigated. Steady, periodic, and stationary solutions obtained by the incremental harmonic balance method are verified by numerical simulations. The solutions are supplemented with phase portrait, Poincaré map, time chronology and Fourier spectrum for better understanding.

In work [4] the issue of calculating the damping moment in the roll channel was studied. An accurate calculation of the damping moment improves the prediction of oscillations. There are several methods for calculating the damping moment, but most of them do not take into account the effects of viscosity. In the study, the authors used the method of computational hydrodynamics to determine the characteristics of oscillation and damping coefficients in the roll channel for various conditions. The influence of scale effects on vibration characteristics and damping coefficients was studied.

At various times, the International Maritime Organization has also developed guidelines for safe sailing in storms. In the latest document MSC.1/Circ.1228, the requirements for avoiding the dangers associated with capsizing of the vessel from: synchronous resonance, parametric resonance, reduction of stability in following seas, broaching and encounter wave grouping phenomena. In addition to these dangers, there are also dangers associated with the destruction of the vessel's hull.

Works [5-7] are devoted to the study of issues of hull strength. Storm diagrams and IMO guidelines involve visual determination of wave parameters and subsequent manual calculations, using formulas and graphs, which gives low accuracy and contains an element of human factors. To reduce wobble, sway stabilizers [8], hydrodynamic stabilizers [9], gravity stabilizers [10, 11], gyroscopic stabilizers, vane thrusters, special forms of the vessel's hull [12], etc. are also used.

Work [13] gives recommendations to shipmasters when preparing a ship for stormy sailing in terms of preparing the steering system, engine room, water tight doors and other important systems.

In the work [14], chapter 7 "Ship Handling in Rough Sea", the author describes the dangers of sailing in counter and following seas. In counter seas is this propeller racing; speed reduction and the torque rich effect on the engine; shipping seas; slamming phenomenon; countermeasures for rough weather in countering seas. In following seas it are encounter wave grouping phenomena; parametric rolling phenomena; reduction of stability; surf-riding (broaching-to) phenomena; countermeasures for rough weather in following seas. The given material is accompanied by illustrations, tables and graphs.

In doctoral thesis [15], in the storm sailing section, the author investigates the forces and moments acting on the ship's hull, conducts mathematical modeling of the processes of the ship's angular motion in the roll channel and the stability of the ship during waves. The author suggested using different models, depending on the navigation task to be solved. The linear 6-degree model of the ship's angular motion in the roll channel, which can be used to calculate the amplitude-frequency characteristics, is advisable to use for evaluating the roll amplitude, optimizing the ship's route in channels and narrows, and planning operations at shallow depths. It is advisable to use the nonlinear 6-degree model of the ship in studies of stability, parametric resonance, broaching, etc.

The article [16] discusses the issue of parametric resonance in a roll channel on a regular wave. The research was carried out experimentally on a typical Norwegian fishing vessel with a blunt hull and a small ratio of length to width, as well as numerical simulation. Nonlinearities in Froude-Krylov loads and recoverable loads were taken into account by integrating the pressure over the instantaneous wetted surface of the hull. It was found that near the instability limit of the Mathieu diagram, experimental and numerical predictions regarding the appearance of parametric roll differ from each other. The instability limits in the experiment also differed from the instability limits of the Mathieu diagram. The region of instability for the 6-DOF experiments and simulations spans a wider range of frequency ratios, and the amplitude threshold of the metacentric height is found to be lower than that of the Mathieu diagram. The results also showed that the region of instability, in the presence of speed, shifts towards smaller ratios of natural and forced oscillation frequencies.

The most common and most dangerous phenomenon on container ships is parametric rocking in countering and following seas, which occurs as a result of dynamic instability of the vessel. The causes of parametric roll are periodic (with a period that is twice the period of the wave) changes in the metacentric height during the movement of the ship across the waves. Parametric roll is also facilitated by special hull shapes (use of extended sides in the front of the hull, etc.). The authors of the article [17], by means of mathematical modeling in the MATLAB environment, investigated the influence of wave height, wavelength and ship speed on the parametric resonance of a container ship. The enveloping stability curve for countering and following excitation is determined. Damping effects were taken into account when estimating the range of metacentric height changes.

As can be seen from the above review of literary sources, the issue of automatically controlling the movement of a ship in a storm has not been considered before, so their solution remains an urgent scientific and technical task.

In this article, the authors developed a storming method that allows to automatically find safe and optimal parameters of the ship's movement (speed and course) by solving at each step of the on-board computer an optimization problem with linear and nonlinear constraints of the inequalities type, which determine the danger areas of vessel's capsizing and navigational hazards.

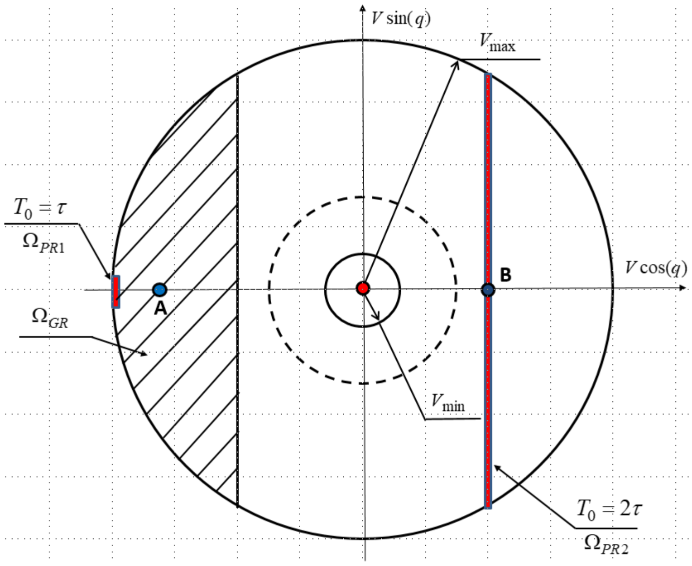
3. Materials and Methods

The object of research is the processes of the vessel's automatic stormy sailing. The subject of research is methods and models of automatic stormy sailing. The purpose of research is to develop a method of ship's automatic storming for use in on-board computer of automatic control system, which would allow automating processes of storm sailing, reduce influence of the human factor on the control processes, reduce crew fatigue, reduce the risks of losing the ship and cargo, and generally increase navigation safety. To solve the problem, authors used numerical methods of conditional optimization to find safe and optimal parameters of the ship's movement in a storm at each step of the on-board computer; recommendations of the IMO, theoretical work and practical experience of other authors, for the formation of inequalities that define the dangerous areas of storm sailing, and are used as constraints when solving the problem of conditional optimization; methods of automatic control theory, mathematical modeling.

4. Results

During stormy sailing, there is a danger of the vessel capsizing caused by synchronous resonance, parametric resonance, reduction of stability in following seas, broaching, impacts of encounter group waves in the stern of the vessel, and the danger of destruction of the vessel's hull due to exceeding the maximum permissible forces and moments. In fig. 1 shows areas of synchronous resonance Ω_{GR}, parametric resonance of the first type Ω_{PR1} and parametric resonance of the second type Ω_{PR2} for the wavelength $\lambda = 90m$ and the period of the vessel's own oscillations $T_C = 12{,}5\,s$.

Figure 1: Areas of synchronous and parametric resonance



The task of storm sailing is to choose safe parameters of the vessel's movement - speed V^* and course φ^*, which would not belong to dangerous zones. Taking into account that in addition to the indicated areas, there are other areas, the impact of which can lead to the capsizing of the vessel or the destruction of the hull, it becomes clear that it is quite difficult to take into account all the existing dangers when manually controlling the vessel, and even in the presence of difficult sailing conditions. The authors believe the most radical way to solve this problem is the use of automatic storming modules in automated systems, the algorithms of which can find not only safe, but also optimal storming parameters.

The task of the automatic storming module is constantly, with on-board computer's circle, measure the vessel's movement parameters and waves, find safe and optimal movement parameters, taking into account the permissible range of storming speeds and all areas dangerous for capsizing the vessel and destroying the hull, supporting the automatic control system of safe and optimal movement parameters. In the most general form, the task of finding safe and optimal storm parameters can be formulated as follows

$$F(V^*, q^*, \lambda, T_C) = \min_{V,q} F(V, q, \lambda, T_C), \tag{1}$$

$$\begin{cases} f_1(V,q,\lambda,T_C) \le 0 \\ f_2(V,q,\lambda,T_C) \le 0 \\ \dots \\ f_n(V,q,\lambda,T_C) \le 0 \end{cases}, \tag{2}$$

where $F(V,q,\lambda,T_C)$ is the aim function to be optimized, $f_j(V,q,\lambda,T_C) \le 0,\ j = 1..n$ is the linear and non-linear constraints of inequalities type. The objective function (1) and constraints (2) depend on the vessel's speed V and the heading angle q of the wave, as well as on the wavelength λ and the period of the vessel's own oscillations T_C. Of the named parameters, only two are available for control - the vessel's speed V and the heading angle of the wave $q = \varphi - K_W + 180dg$ (due to the course of the vessel), which we will use for conditional optimization. Other parameters on which we have no influence (wave parameters, maximum and minimum vessel speeds, period of natural oscillations of the vessel, etc.) are used as external data when solving the optimization problem. As the first limitation, we will accept a linear limitation on the vessel's speed. To maintain controllability, the vessel's speed must be greater than minimum speed $V_{\min}$ and less than maximum speed $V_{\max}^{st}$ in storm conditions, i.e. the condition must be fulfilled

$$V_{\min} \le V \le V_{\max}^{st} \tag{3}$$

As the second limitation, we will accept the condition of finding the vessel's movement parameters (speed and course) outside the limits of synchronous resonance. It is known [1] that synchronous resonance occurs under the condition when the ratio of the vessel's own oscillations period T_C to the imaginary period of the waves τ rocking the vessel is within

$$0{,}7 \le \frac{T_C}{\tau} \le 1{,}3, \tag{4}$$

where the imaginary period τ of the waves is determined by the formula

$$\tau = \frac{\lambda}{1{,}25\sqrt{\lambda} + V\cos q}. \tag{5}$$

From the inequalities (4), we determine the area of the storm that is safe from synchronous resonance

$$\begin{cases} \dfrac{T_C}{\tau} > 1{,}3 \\ \dfrac{T_C}{\tau} < 0{,}7 \end{cases} \tag{6}$$

As the third and fourth constraints, we accept the condition of finding the vessel's motion parameters outside the parametric resonance of the 1st and 2nd types. It is known that the most dangerous is parametric resonance of the 2nd type, when the period of the natural oscillations of the vessel is twice as long as the imaginary period of the wave.

$$\left| \frac{T_C}{2} - \tau \right| \ge \Delta T, \tag{7}$$

where ΔT is the difference between the imaginary periods of the waves and the half-period of the vessel's own oscillations. Also, parametric resonance can occur when the period of the vessel's own oscillations coincides with the period of the waves.

$$|T_C - \tau| \ge \Delta T \tag{8}$$

As the fifth limitation, we accept the condition of finding the parameters of the vessel's movement outside the region of stability reduction in following seas. The vessel loses its stability in following seas under the condition [5]

$$\begin{cases} \lambda = L \\ V = C \\ q = \pm 180dg \end{cases}, \tag{9}$$

where L is the vessel's length, $C = 1{,}25\sqrt{\lambda}$ is the wave speed. From the system (9), we find the region safe from the reduction of stability in following seas

$$\begin{cases} |\lambda - L| > \Delta L_{LS} \ .or. |V - C| > \Delta V_{LS} \\ \left| q - 180^\circ \right| > \Delta q_{LS} \end{cases}, \quad (10)$$

where ΔL_{LS}, ΔV_{LS}, Δq_{LS} are the dimensions of the region of loss of stability in following seas.

As the sixth limitation, we accept the condition of finding the parameters of the vessel's motion outside the broaching limits. Broaching often results in loss of control during accelerated sliding along the steep leading edge of a high wave. Broaching occurs under the condition [5]

$$\begin{cases} \frac{V\cos(180^\circ - q)}{\sqrt{L}} \ge 1{,}4 \\ 135^\circ \le q \le 225^\circ \end{cases} \quad (11)$$

From system (11), we find the area of storming that is safe from broaching

$$\begin{cases} V\cos q > -1{,}4\sqrt{L} \\ q > 225dg.or.\ q \le 135dg \end{cases} \quad (12)$$

As the seventh limitation, we accept the condition of finding the vessel's movement parameters outside the area of dangerous impacts of encounter group waves in the stern. As the seventh limitation, we accept the condition of finding the vessel's movement parameters outside the area of dangerous impacts of encounter group waves in the stern. In the accompanying disturbance, when the speed of the waves slightly exceeds the speed of the vessel, then the handling of the vessel becomes uncontrollable. Also, the action of such waves can damage the hull and the steering device. The dangerous area is determined by the V/T diagram [5], based on which we write down the system of inequalities that define the boundaries of this dangerous area.

The dangerous area is determined by the V/T diagram [5], based on which we write down the system of inequalities that define the boundaries of this dangerous area.

$$\begin{cases} 1{,}3 \le \frac{V\cos(180 - q)}{T_W} \le 2 \\ 135dg \le q \le 225dg \end{cases} \quad (13)$$

From system (13), we find the area safe from the impact of group waves in the stern of the vessel.

$$\begin{cases} V\cos q < -2T_W \ .or. V\cos q > -1{,}3T_W \\ q < 135dg \ .or. q > 225dg \end{cases}, \quad (14)$$

where T_W is the wave period.

Restrictions can be extended further to determine areas of navigational hazards, damage to the vessel's hull, etc.

As aim function we can select a function

$$F = (\varphi^* - \varphi_{SET})^2 \to \min, \quad (15)$$

which minimizes the deviation of the safe course φ^* from the given φ_{SET}, or function

$$F = (V^* - V_{SET})^2 \to \min, \quad (16)$$

which minimizes the deviation of the safe speed V^* from the given V_{SET}, or any other target function that will provide the desired control quality.

To find the parameters V^*, φ^*, which optimize the objective function (15), (16), or another and are within the safe regions (3), (6), (7), (8), (10), (12), (14), we apply the procedure of nonlinear optimization of the type $f\min con(\bullet)$ MATLAB

$$f\min con\left(@\,fun, \mathbf{x}0, \mathbf{A}, \mathbf{b}, \mathbf{A}eq, \mathbf{b}eq, \mathbf{l}b, \mathbf{u}b, @\,nonlcon\right) \quad (17)$$

where $@\,fun$ is a link to the target function file, $\mathbf{x}0 = (V(0), q(0))$ is the initial vector of parameters to be optimized, $\mathbf{A}$ is a matrix of the linear inequalities system, absent, $\mathbf{b}$ is a vector of the right part linear inequalities system, absent, $\mathbf{A}eq$ is a matrix of the linear equalities system, absent, $\mathbf{b}eq$ is a vector of the right part linear equalities system, absent, $\mathbf{l}b = [-V_{\min}, -\pi]$ is a vector of the lower limit of the parameter area, $\mathbf{u}b = [V_{max}, \pi]$ is a vector of the upper limit of the parameter area, $@nonlcon$ is a link to a nonlinear constraint system file.

The safe parameters of the vessel's movement V^*, φ^*, which are found at each step of the on-board controller by solving a conditional optimization problem with linear and nonlinear constraints of the inequalities type, are fed to the inputs of the units for determining the control of the power plant and the rudder.

$$\begin{cases} \Theta = \dfrac{V^*}{V_{max}} \Theta_{max} \\ \delta = k_\varphi(\varphi - \varphi^*) + k_\omega \omega_z + k_\int \int (\varphi - \varphi^*) dt \end{cases}, \tag{18}$$

where Θ is a deviation angle of the power plant telegraph, Θ_{max} is a maximum deviation angle of the power plant telegraph, K is a current course, ω_z is a yaw angular rate, k_φ, k_ω, $k_\int$ are the gain coefficients of the PID - regulator.

4.1. Experiment

To confirm the efficiency and effectiveness of the developed methods of automatic stormy sailing, mathematical modeling of stormy sailing processes in the MATLAB environment was carried out.

4.1.1. Simulation of automatic control with synchronous resonance

Simulation of automatic control with synchronous resonance. The initial parameters of the vessel's movement and waves correspond to point A (synchronous resonance area), Fig. 1: the specified course of the vessel is $\varphi(0) = 180dg$, the specified speed of the vessel is $V(0) = 4{,}1 m/s$; wave course is $K_W = 0dg$ wave speed is $C = 13{,}7 m/s$, wave length is $\lambda = 120m$.

Fig. 2 shows graphs of changes in time of longitudinal speed $V_x[m/s]$, longitudinal displacement $X_g[m]$, roll angular rate $\omega_x[dg/s]$, roll angle $\theta[dg]$, yaw angular rate $\omega_z[dg/s]$ and yaw angle $\varphi[dg]$.

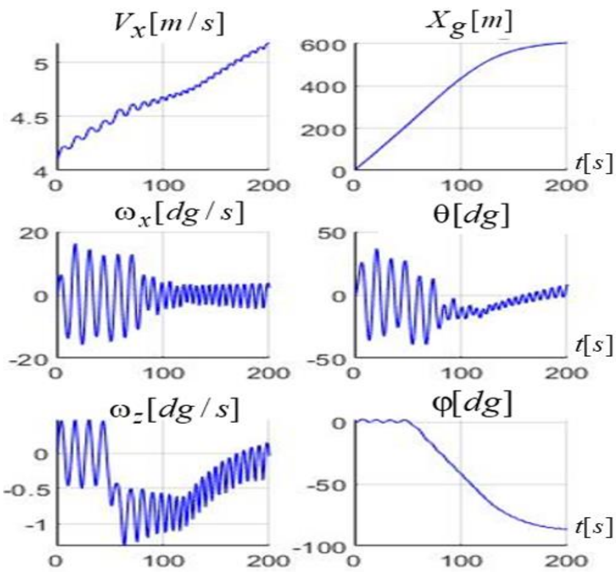


Figure 2: Longitudinal and angular movement parameters change in roll and yaw channel in experiment with synchronous resonance

Fig. 3 shows graphs of changes in time of lateral speed $V_y[m/s]$, lateral movement $Y_g[m]$, trim rate $\omega_y[dg/s]$, trim angle $\psi[dg]$, telegraph deflection $teta[dg]$ and stern deflection $delta[dg]$. The control system supports the set course of the vessel $\varphi(t) = 0dg$ for up to $t = 50s$. In this area, a significant amplitude of oscillations $\theta(t) = \pm 50dg$ is observed in the roll channel. For $t = 50s$, the automatic storming module is turned on, which calculates the safe course and speed of the vessel. To change the course and speed, the rudder $delta(t)$ and the telegraph $teta(t)$ are deflected. After that, a change in course and speed is observed. As can be seen from the graph $\varphi(t)$, the course of the vessel begins to change from $\varphi(t) = 0dg$ to $\varphi(t) = -77dg$, the speed of the vessel increases from $V_X(t) = 4.1 m/s$ to $V_X(t) = 5.2 m/s$. Starting with $t = 80s$ amplitude of oscillations in the roll channel sharply decreases to $\theta(t) = \pm 5dg$, which corresponds to the amplitude of forced oscillations. The change in lateral speed $V_y(t)$ and lateral displacement $Y_g(t)$ is caused by a change in the ship's course $\varphi(t)$. The trim angular rate $\omega_y(t)$ and the trim angle $\psi(t)$ change with the frequency of the forced oscillations and are within the limits $\omega_y(t) = \pm 0.5dg$ and $\psi(t) = \pm 0.2dg$.

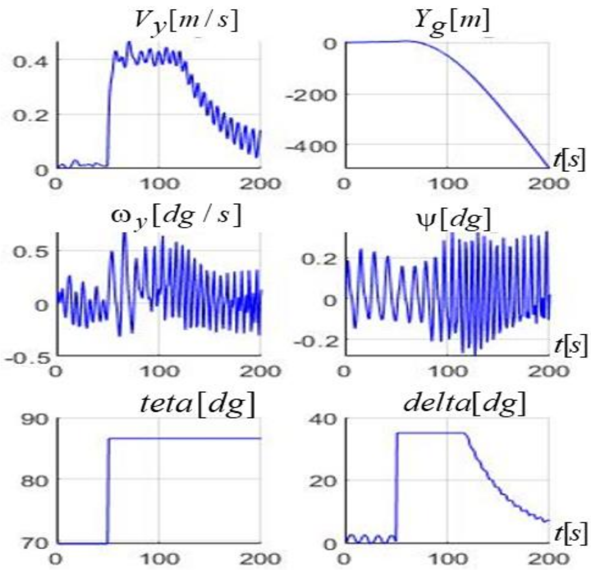


Figure 3: Lateral and trim movement parameters, telegraph's and rudder's deflection in experiment with synchronous resonance

4.1.2. Simulation of automatic control with parametric resonance

The initial parameters of the vessel's movement and the wave correspond to point B, which is in the area of parametric resonance Ω_{PR2}, fig. 1: the vessel's course is $\varphi(0) = 0dg$, the vessel's speed is $V(0) = 2{,}5 m/s$; wave course is $K_W = 180dg$, wave speed is $C = 11{,}9 m/s$.

Fig. 4 shows graphs of changes in time of longitudinal speed $V_X[m/s]$, longitudinal displacement $X_g[m]$, roll angular rate $\omega_X[dg/s]$, roll angle $\theta[dg]$, yaw angular rate $\omega_Z[dg/s]$ and yaw angle $\varphi[dg]$. Fig. 5 shows graphs of changes in time of lateral speed $V_y[m/s]$, lateral movement $Y_g[m]$, trim rate $\omega_y[dg/s]$, trim angle $\psi[dg]$, telegraph deflection $teta[dg]$ and stern deflection $delta[dg]$. The automatic storming module continuously calculates and maintains the optimal and safe parameters of the vessel's movement. For optimization, the aim function (15) was used, which ensured the minimum deviation of safe course, calculated at each step on-board controller, from set course. The calculated optimal and safe storming parameters are $V^* = 2.1 m/s,\ \varphi^* = 0dg$. It can be seen from the graphs $V(t),\ \varphi(t)$ that the control system maintains a safe course with precision $|\varphi(t)| \le 2dg$ and at the same time reduces the vessel's speed to a safe one. After reaching a safe speed for about $t = 100s$, the amplitude of oscillations in the roll channel sharply decreases to the value of forced oscillations. As for the channel of lateral movement, it can be seen from the graphs that the lateral speed during the entire experiment did not exceed $|V_y(t)| \leq 0.2 m/s$, and the lateral deviation did not exceed $|Y_g(t)| \leq 6.0 m$. In the trim channel, the angular speed does not exceed $|\omega_y(t)| \leq 0.5 dg/s$, and the trim angle does not exceed $|\psi(t)| \leq 0.2 dg$.

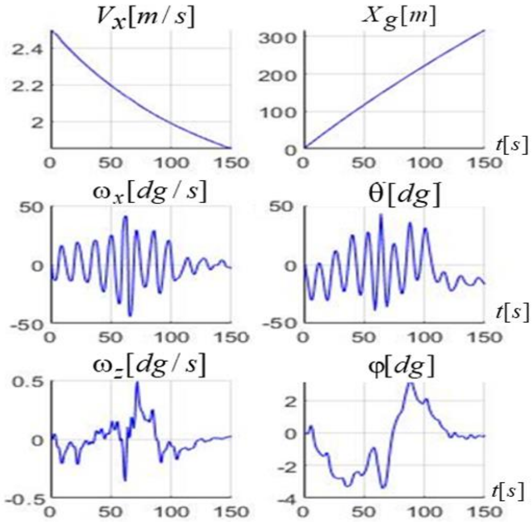


Figure 4: Longitudinal and angular movement parameters change in roll and yaw channel in experiment with parametric resonance

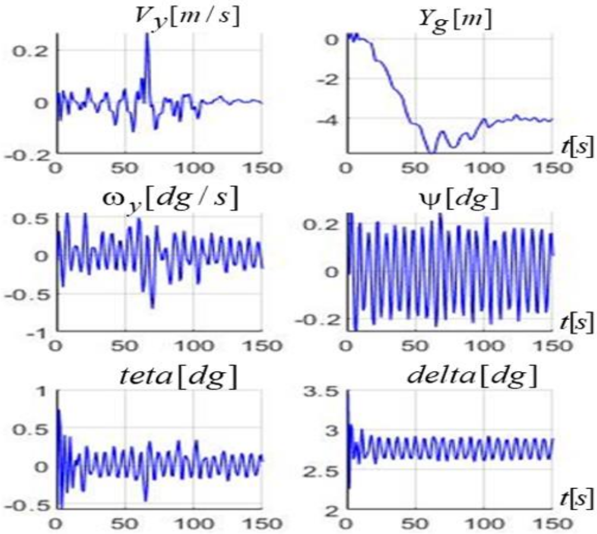


Figure 5: Lateral and trim movement parameters, telegraph's and rudder's deflection in experiment with parametric resonance

The analysis of the simulation results shows that the automatic storming module allows to effectively calculate the optimal and safe parameters of the vessel's movement and maintain them during stormy sailing.

Further research may be related to the extension of the conditional optimization method to other hazardous areas to avoid hull damage, bypass navigational hazards, etc.

5. Discussion

A method of automatic and optimal control of the ship's movement in a storm has been developed, which allows to avoid the occurrence and development of dangerous phenomena, such as harmonic and parametric resonances, loss of stability in the following seas, broaching, impacts of the group waves in the stern, which can lead to ship's capsizing.

The obtained result is explained by: the use of on-board controller in the ship's motion control system; constant measurement of ship movement and wave parameters; finding at each step of the on-board controller safe and optimal values of the ship's course and speed by solving the optimization problem; taking into account, when solving the optimization problem, linear and non-linear constraints of the inequalities type, which define dangerous areas; maintaining safe and optimal movement parameters by means of the automatic control system.

The obtained results differ from the known solutions in that they allow to automate and optimize the control processes a ship in a storm, reduce the influence of the human factor on the, reduce the risks of capsizing the ship, save cargo and human life.

The method of determining the safe and optimal parameters of the ship's movement in a storm is designed only for use in the on-board computer of the automated ship movement control system and cannot be used for manual control.

The obtained results are reproducible and can be used in the development of automated systems with automatic storming modules. Further research may be related to expanding the range of possible applications of the developed method.

6. Conclusion

A method of automatic stormy sailing has been developed, which allows to automatically find safe and optimal stormy sailing parameters and maintain them.

The obtained results are explained by the solution at each step of the on-board controller of the optimization problem with constraints of the inequalities type, which describe the dangerous areas.

The scientific novelty of the obtained results lies in the fact that, for the first time, a method of automatically avoiding the dangers of capsizing a ship during stormy sailing has been developed, unlike existing solutions, it allows to automate and optimize the processes of ship control in a storm.

The practical significance of the obtained results is that: the workability and effectiveness of the method are verified by mathematical modeling in the MATLAB environment. The method can be used for the development of automatic modules for controlling the movement of a ship in stormy conditions, which will allow automating the control processes in a storm, reducing the influence of the human factor on the control processes, reducing the fatigue of the crew, reducing the risks of losing the ship and cargo, and generally increasing the safety of shipping.

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