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CONDITIONAL OPTIMIZATION OF VESSEL CONTROLS WITH WIND ADDITIONAL PROPULSION SYSTEM

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The maritime industry is facing significant challenges due to increasingly stringent legislative requirements for reducing emissions of harmful substances into the atmosphere and mitigating climate change. Among the wide range of technologies and fuel solutions considered in this context, one of the most promising is wind additional propulsion systems (WAPS), which can significantly reduce fuel consumption by ships and, as a result, reduce emissions of greenhouse gases and other harmful substances into the atmosphere. At present, wind propulsion systems such as WindWings, Wind Challenger, CWS are already in operation on ships including Pyxis Ocean, Berge Olympus, Shofu Maru, Windcoop and others. The WindWings system does not require auxiliary power for operation and has a built-in feathering function to manage sail performance in different weather conditions. The Wind Challenger system uses advanced patented technologies that allow the determination of wind direction and speed in real time, providing fully automatic control of extending, retracting, compressing and rotating sails. These and other wind turbines operate autonomously, independently of the vessel motion control system. The object of the research is the process of finding optimal controls for the combined structure of the vessel's actuators, which includes traditional actuators (propeller, rudder) and additional wind turbines. A method for controlling the movement of a vessel with additional wind turbines has been developed, which allows for further reduction in fuel consumption. This is achieved by finding optimal controls for the combined structure of the vessel's actuators by solving the problem of conditional optimization with equalities and inequalities in the on-board computer of the automatic control system. Equalities ensure the creation of the forces and moments necessary to maintain the given motion, and inequalities take into account the permissible ranges of control changes. The results obtained can be used in the development of mathematical support for autonomous vessel control systems or mathematical support for automatic control modules in automated systems.

***Key words**: WAPS; automatic control; conditional optimization; energy efficiency; additional wind turbines; on-board computer.*

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Introduction. The International Maritime Organization (IMO) has been working consistently for many years to develop and improve international conventions and codes aimed at preventing air pollution from ships. In 2017 IMO adopted the Initial Strategy for Reducing Air Emissions from Ships, which set the scale of the industry's tasks to reduce the carbon footprint of international shipping by 2030, as well as to reduce absolute emissions from ships in the coming decades, with the goal of full decarbonization. In accordance with the IMO Initial Strategy, technical and operational measures to reduce emissions were developed, which were adopted in 2021 by amendments to Annex VI of the MARPOL Convention. A review of the Initial Strategy for Reducing Greenhouse Gas Emissions was planned for 2023. The task of the review is to record the current goals, objectives, conditions for decarbonizing the industry in the coming decades, and the expected nature of specific measures. As a result of the negotiations, the text of the Revised Strategy did not include a hard deadline for achieving net zero emissions from international shipping. Instead, the deadline was specified more flexibly – around 2050, taking into account the national characteristics of the states and with intermediate stages of emission reduction by 2030 and 2040. In addition, the Revised Strategy included the expected level of use of fuels with minimal or zero greenhouse gas content and relevant technologies by 2030. One of the directions for reducing emissions of harmful substances from shipping is the use of ships with additional wind power plants (WAPS). Such plants allow using wind energy for propulsion, which reduces the load on the main engines and saves fuel. Although the total number of ships equipped with WAPS is still relatively low, there is a steady trend towards their growth. Figure 1 shows the number of ships that are/will be equipped with WAPS.

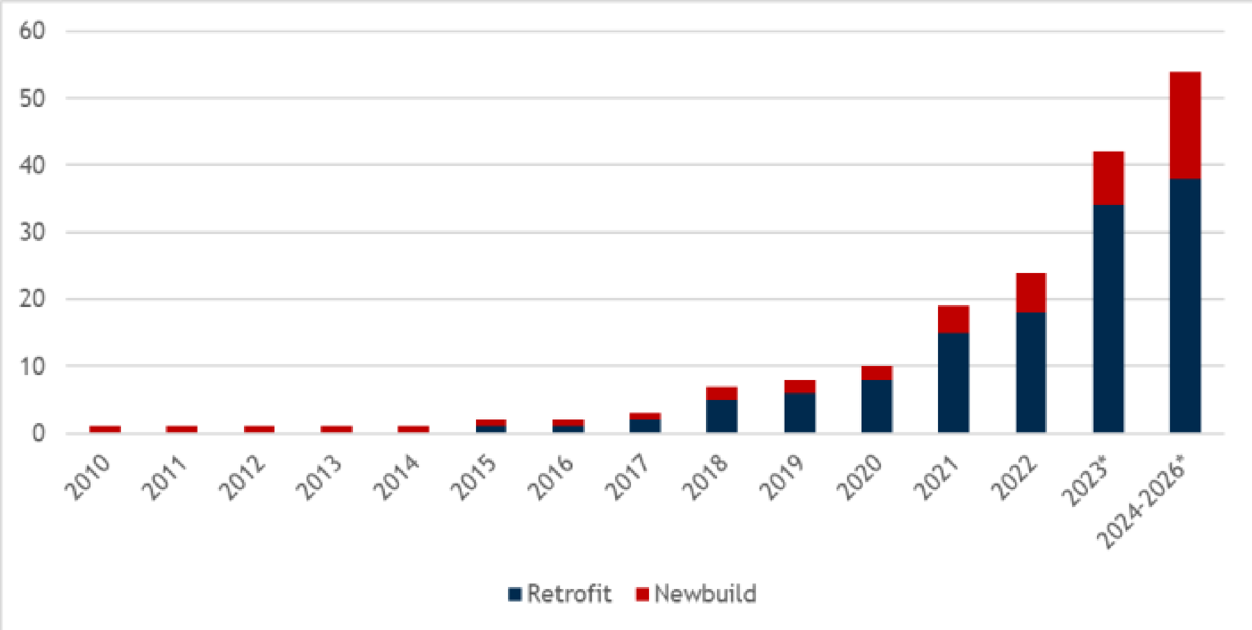

Figure 1 – Number of vessels that are/will be equipped with WAPS [1]

There are six categories of WAPS: rotary sails [2], rigid sails [3], suction wings [3], kites [4], soft sails [5] and hull technologies [6]. In addition to these systems, wind turbines [7] are also being developed for the production of electricity on board the ship. The paper considers an additional wind turbine installed on the ship from rigid sails as an additional wind energy source for the movement of the ship. Today, the WindWings, Wind Challenger, CWS wind turbines are already operated on the ships Pyxis Ocean [8], Berge Olympus [9], Shofu Maru [10], Windcoop [11], etc. The WindWing system [12] does not require auxiliary power for operation and has a built-in feathering function to control the performance of the sail in different weather conditions. The Wind Challenger system [13] is an innovative solution for reducing greenhouse gas emissions. It uses the most modern and patented technologies that allow determining the direction and speed of the wind in real time, provide fully automatic control of the extension, removal, compression and rotation of the sails. These and other wind turbines operate autonomously, regardless of the ship's motion control system. According to the authors of this article, the use of wind turbines as additional executive devices of the ship's motion control system will allow more efficient use of wind energy and achieve further reduction in fuel consumption. Of course, such tasks can be solved using a specialized on-board computer with automatic modules of the ship's motion control system. Some other automatic control problems were considered by the authors of the article earlier, for example, the problem of automatic discharge of kinetic energy in the event of an inevitable collision of vessels [14], the problem of optimal control of the vessel’s movement with boundary conditions [15], the use of a neural network model for evaluating the maneuvering characteristics of the vessel [16] and solving automatic control problems [17], the use of a simulation bench for developing and testing automatic control modules for vessel movement [18]. The problem of controlling the movement of a vessel with additional wind turbines along a route involves finding at each step of the on-board computer of the automatic control module optimal controls for the combined structure of the vessel’s actuators (propeller, rudder and sails).

The object of the research is the process of finding optimal controls for the combined structure of the vessel's actuators during its movement along the route.

The subject of the research is models and methods for finding optimal controls for the combined structure of the vessel's actuators during its movement along the route.

Problem statement. The problem of optimizing the energy consumption of the power plant (PP) of a ship with additional wind turbines when moving along a route can be written in the form:

$$\begin{cases} E\left[P_x(\Theta)\right] = P_x^2(\Theta) \to \min; \\ V_x = V_x^*, \Delta Y = \Delta Y^*, K = K^*; \\ |\Theta| \le \Theta_{\max}, |\delta| \le \delta_{\max}, |\gamma_j| \le \gamma_{\max}, \end{cases} \quad (1)$$

where the first equation of the system (1) determines the objective function of the minimum fuel energy consumption of the PP, the second equation of the system (1) determines the required movement along the route with a given speed $V_x = V_x^*$, a given lateral deviation $\Delta Y = \Delta Y^*$ and a given course $K = K^*$. This problem can be considered as a problem of conditional optimization of the objective function $E[P_x(\Theta)] = P_x^2(\Theta) \to \min$ (minimization of fuel consumption of the PP) with nonlinear constraints of the equalities type $V_x = V_x^*, \Delta Y = \Delta Y^*, K = K^*$ and linear constraints of the inequalities type $|\Theta| \le \Theta_{\max}, |\delta| \le \delta_{\max}, |\gamma_j| \le \gamma_{\max}$, $j = 1..n$. Nonlinear constraints of the equalities type determine the required movement along the route with a given speed $V_x = V_x^*$, a given lateral deviation $\Delta Y = \Delta Y^*$ and a given course $K = K^*$. Linear constraints of the inequalities type determine the permissible ranges of deviations of the PP telegraph $|\Theta| \le \Theta_{\max}$, rudder deviations $|\delta| \le \delta_{\max}$ and sail angles $|\gamma_j| \le \gamma_{\max}$, $j = 1..n$.

Analysis of recent research and publications. Conditional optimization problems have previously been considered by many authors. Thus, in [19], the practical problem of optimizing the planning of vessel traffic on the Kiel Canal, which is the most visited artificial waterway in the world, was considered. The aim of the study was to minimize the total waiting time of all vessels. The algorithmic ideas of collision-free routing of automatically controlled vehicles were generalized, which provides a single view of planning and dynamic routing, which can serve as a prototype for planning bidirectional traffic with conflicts. The developed method allows creating schedules that are significantly better than manual planning, and which were approved by expert planners. Due to a significant increase in the number and size of vessels, the canal was planned to be expanded. The developed tool was also used to select the best option for expansion.

In [20], the issues of creating a safe and efficient vessel placement scheme in a busy Ro-Ro passenger terminal with a limited port basin were investigated. A multi-objective mathematical model is formulated for the integrated optimization of fairway and turn basin planning, with minimum total planning time and total waiting time as objective functions. An adaptive ant colony optimization algorithm is applied to the proposed model, where minimizing the total waiting time is the objective function. Numerical experiments at Xuwen Terminal, the largest Ro-Ro passenger terminal in the world, show that the model has shorter total planning time and total waiting time, compared with actual operational data. The effective solutions obtained by the proposed model and algorithm not only significantly improve safety and efficiency, but also improve the availability of the turn basin and fairway.

Optimization of ship energy efficiency is attracting increasing attention to meet the requirements of energy conservation and emission reduction. Factors such as speed, wind direction, current speed, and depth significantly affect the energy efficiency of ships. Due to the inherent temporal variability and uncertainty associated with these various factors, it is very difficult to accurately determine the optimal sailing speed for different sections of the route using traditional static optimization methods, especially when weather conditions change frequently. In [21], a dynamic optimization method using predictive model control is proposed. A dynamic ship energy efficiency optimization model, taking into account time-varying factors, and a nonlinear system model of ship energy efficiency are developed. Based on these models, a control algorithm and controller are developed for dynamic ship energy efficiency optimization. A study is conducted to demonstrate the validity of the developed optimization method. The results show that the optimal sailing speed for different time intervals can be determined using the dynamic optimization method. This method can improve the ship energy efficiency and effectively reduce CO_2 emissions.

In the article [22], the issues of safe crew transfer to an offshore wind turbine are considered. An optimal control scheme based on a neural network observer is proposed to identify dynamics and disturbances, nonlinear effects and asymmetric saturation constraints of input control signals. The structure of the neural network takes into account the Hamilton-Jacobi-Bellman equation and forms an optimal control signal that remains within the saturation limits. Lyapunov theory guarantees a uniformly limited system of all closed-loop signals. The high performance of the presented method is demonstrated on regular waves with high frequency, compared to previous studies.

In the paper [23], the issues of optimal control of the movement of a vessel with additional wind turbines along the route are considered. A method for determining the recommended average vessel speed per trip – a constant value present in the optimality criteria, and the distribution law of the optimal speed per trip that would satisfy the given optimality criterion, in particular, minimum fuel consumption, are developed. The problem of determining the optimal current speed of a ship is formulated as a variational isoparametric problem under constraints in the class of piecewise-smooth functions, and a method for its solution is proposed. The results obtained allowed us to determine, for a specific voyage, the dependence of the optimal ship speed and specific fuel consumption on the speed and direction of the true wind. The dependence of the recommended average ship speed per voyage of the specific hourly fuel consumption and the specific total consumption per voyage for different types of wind turbines was also determined. The calculations confirm that the use of wind turbines significantly increases the economic efficiency of ship operation and leads to a reduction in environmental pollution.

In [24], the feasibility and advantages of hybrid propulsion systems for tankers that combine diesel engines with sails to reduce fuel consumption and emissions were investigated. The aim of the study is to develop and evaluate a hybrid propulsion system that integrates a diesel engine with a sail system to improve the overall performance of the propulsion system, reduce greenhouse gas emissions, and improve fuel efficiency. The performance of the hybrid system is compared with the traditional diesel engine scheme. The results of the study showed that the integration of sails with diesel engines can improve the overall performance of the propulsion system, reduce greenhouse gas emissions, and improve fuel efficiency. The comparative analysis showed that the applied methods (empirical formulas, CFD modeling, and model testing) give similar results with a maximum deviation of 7%.

In the study [25], an optimal energy-saving control system is proposed for coordinating sail thrust and propeller thrust, which is achieved by adjusting the sail azimuth and propeller speed. A coordination control algorithm based on the predictive control-adaptive Pontryagin minimum principle (MPC-APMP) is proposed. This algorithm transforms the optimal control problem for improving the energy efficiency of the sail and propeller into a rolling optimization problem. Taking into account the delay of the control system relative to time-varying environmental conditions, a model for predicting the wind direction and speed, and the direction and speed of the vessel based on a neural network with a long short-term memory is developed. According to the aerodynamics of the sail and the hydrodynamics of the propeller, a dynamic model of the combined "sail-propeller" propulsion system is created, which is used to estimate the potential wind energy and the total thrust demand. The PMP (Pontryagin minimum principle) algorithm is used to obtain the optimal control sequence. The energy-saving efficiency and stability of the proposed method are confirmed by simulation.

The purpose and objectives of the study. The purpose of the study is to develop a method for calculating optimal controls for a combined structure of ship actuators, which includes traditional controls (propeller, rudder) and wind turbine controls. The objectives of the study are: analysis of literature sources devoted to methods for optimizing controls and optimal wind turbine controls; development of a block of optimal controls for a combined structure of ship actuators;

development of models of external influences and controls for the conditional optimization block; analysis of the optimal controls formation results.

Main part. Fig. 2 shows a block of calculating optimal controls for the movement of a ship with additional wind sails.

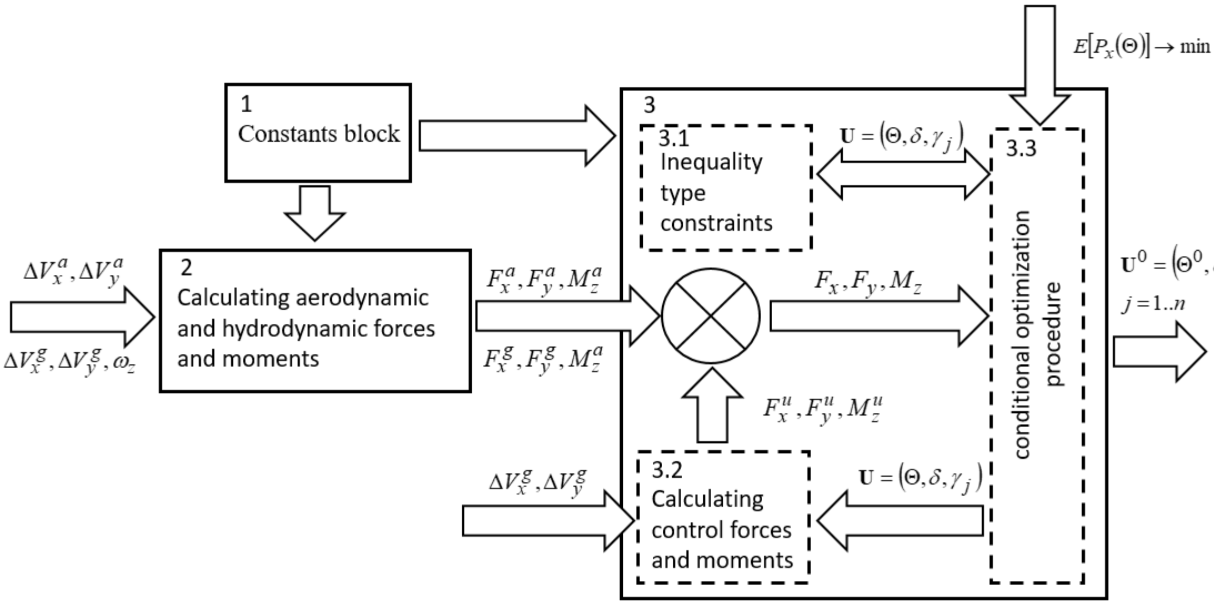

Figure 2 – Optimal control calculation block

The optimal control calculation block includes a constant setter 1, a block 2 for calculating aerodynamic and hydrodynamic forces and moments, and a block 3 for optimization. The optimization block 3 contains a subblock 3.1 for linear constraints on control such as inequalities, a subblock 3.2 for calculating control forces and moments, and a subblock 3.3 for conditional optimization.

Block 2 for calculating aerodynamic and hydrodynamic forces and moments acting on the ship's hull and superstructure. In order to reduce the calculation time, block 2 is removed from the optimization block 3 as one that does not use control. The projections of the resulting aerodynamic force R_x^a, R_y^a and moment M_z^a on the linked coordinate system (LCS) axis are determined by the formulas

$$\begin{cases} R_x^a = c_x^a \rho_a \dfrac{\left(\Delta V_x^a\right)^2}{2} S_x^a; \\ R_y^a = c_y^a \rho_a \dfrac{\left(\Delta V_x^a\right)^2}{2} S_y^a; \\ M_z^a = m_z^a \rho_a \dfrac{\left(\Delta V_x^a\right)^2}{2} S_x^a L; \end{cases} \quad (2)$$

$$\begin{cases} c_x^a = -(0,03 + 0,08\cos\beta_a); \\ c_y^a = -(1,1 - 1,2)\sin\beta_a; \\ m_z^a = c_y^a \left(0,25 + \dfrac{x_n}{L} - \dfrac{\beta_a}{2\pi}\right), \end{cases} \quad (3)$$

where c_x^a, c_y^a, m_z^a are the coefficients of longitudinal, lateral aerodynamic force and aerodynamic moment, ρ_a is air density, $\Delta V_x^a, \Delta V_y^a$ are the relative longitudinal and lateral velocity of the aerodynamic flow, S_x^a, S_y^a are the projections of the above-water part of the ship's hull and superstructures onto the plane perpendicular to the axis OX_1 of the LCS and onto the plane perpendicular to the axis OY_1 of the LCS, L is the ship length, $\beta_a = -\arctan\left(\frac{\Delta V_y^a}{\Delta V_x^a}\right)$ is the angle of incidence of the aerodynamic flow onto the diametrical plane.

The projections R_x^g, R_y^g of the resulting hydrodynamic force and moment M_z^g on the axis of the LCS are determined by the formulas

$$\begin{cases} R_x^g = c_x^g \rho_g \frac{\left(\Delta V_x^g\right)^2}{2} F_\partial; \\ R_y^g = c_y^g \rho_g \frac{\left(\Delta V_x^g\right)^2}{2} F_\partial; \\ M_z^g = m_z^g \rho_g \frac{\left(\Delta V_x^g\right)^2}{2} F_\partial L; \end{cases} \quad (4) \qquad \begin{cases} c_x^g = -[c_{x0}^g + 0,25(\frac{L}{B} - 2)\beta_g^3]; \\ c_y^g = -(\frac{\partial c_y^g}{\partial \beta}\beta_g + \frac{\partial c_y^g}{\partial \omega_z}\omega_z); \\ m_z^g = -(\frac{\partial m_z^g}{\partial \beta}\beta_g + \frac{\partial m_z^g}{\partial \omega_z}\omega_z), \end{cases} \quad (5)$$

where c_x^g, c_y^g, m_z^g are the coefficients of longitudinal, lateral hydrodynamic force and hydrodynamic moment, ρ_g is the water density, $\Delta V_x^g, \Delta V_y^g$ are the relative longitudinal and lateral velocity of hydrodynamic flow, F_∂ is the area of diametrical buttocks, B is the width of the vessel, $\beta_g = -\arctan\left(\frac{\Delta V_y^g}{\Delta V_x^g}\right)$ is the drift angle, ω_z is the yaw angular rate, $\frac{\partial c_y^g}{\partial \beta}, \frac{\partial c_y^g}{\partial \omega_z}, \frac{\partial m_z^g}{\partial \beta}, \frac{\partial m_z^g}{\partial \omega_z}$ are the hydrodynamic coefficients.

Control forces and moments calculation block.

Forces and moments from propeller rotation. Projections of forces and moments from propeller rotation on the LCS axis are calculated by the formulas

$$\begin{cases} P_x(\Theta) = (1-t)\frac{1}{2}\sigma_p \rho_g \Delta V_x^g S_{\partial в}; \\ P_y(\Theta) = P_{y1} + P_{y2} + P_{y3}; \\ M_z(\Theta) = M_{z2} + M_{z3}, \end{cases} \quad (6)$$

where $P_{y1} = \psi \rho_g n^2 D_{\partial в}^4 K_{m0} \frac{\Lambda_p}{\sqrt{1-\Lambda_p^2}} \left(\frac{\sqrt{1-\Lambda_{p0}^2}}{\Lambda_{p0}}\right)$ is the component of the lateral force from the rotation of the propeller, caused by the unevenness of the speeds of the flow incident on the propeller disk along the height,

$P_{y2} = 2{,}14 \rho_g n D_{\partial в}^3 \beta_g K_{m0} \left[1 - \frac{1}{2}\frac{\Lambda_p}{\sqrt{1-\Lambda_p^2}} \left(\frac{\sqrt{1-\Lambda_{p0}^2}}{\Lambda_{p0}}\right)\right]$ is the component of the lateral force from the rotation of the propeller, caused by the oblique flow incident on the propeller disk at the drift angle β_g,

$P_{y3} = \rho_g n_{зх}^2 D_{дв}^4 \left(-\dfrac{0{,}05}{(1-10\lambda_p)^2} - 0{,}13\sin^2 \pi\lambda_p \right)$ is the component of the lateral force from the rotation of the propeller, caused by the splashing of water on the ship's hull in the propeller reverse mode,

$M_{z2} = 0{,}16\rho_g n D_{дв}^4 \left(K_p - \dfrac{\Lambda_p}{2}\dfrac{dK_p}{d\Lambda_p} \right) V_z$ is the component of the yaw moment from the rotation of the propeller, caused by the oblique flow incident on the propeller disk at the drift angle β_g,

$M_{z3} = \rho_g n_{зх}^2 D_{дв}^5 \left(\dfrac{0{,}8}{(1+100\lambda_p)^2} + 1{,}2\sin^4 \pi\lambda_p \right)$ is the component of the yaw moment from the rotation of the propeller, caused by the splashing of water on the ship's hull in the propeller reverse mode,

ψ is the co-current flow coefficient, $\psi = 0{,}165\, C_b \sqrt{\dfrac{\sqrt[3]{\Delta}}{D_{дв}}} - \Delta\psi$,

Δ is the displacement of the vessel,
$\Delta\psi$ is the correction for the Froude number,
$t = (0{,}15 - 0{,}17)$ is the propeller suction coefficient,
$\sigma_p = \dfrac{8K_p}{\pi\Lambda_p}$ is the propeller load coefficient at the stop,
$\Lambda_p = \dfrac{\Delta V_g}{\sqrt{\Delta V_g^{\,2} + n^2 D_{дв}^{\,2}}}$ is the universal propeller pitch,
K_p, K_m are the universal stop coefficient screw and universal torque coefficient, are determined from the graphs as functions Λ_p,
Λ_{p0} is the universal screw pitch, for which the universal torque coefficient is $K_m = 0$,
K_{m0} is the value of the universal torque coefficient for $\Lambda_p = 0$,
n is the screw revolutions,
$D_{дв}$ is the diameter of the screw disk,
$S_{дв}$ is the area of the screw disk.

Forces and moments from the rudder. Projections R_x^r, R_y^r of the control force and moment M_z^r on the LCS axis from the rudder deflection are calculated by the formulas

$$\begin{cases} R_x^r(\delta) = c_x^r \rho_g \dfrac{\left(\Delta V_x^g\right)^2}{2} S_r; \\ R_y^r(\delta) = c_y^r \rho_g \dfrac{\left(\Delta V_x^g\right)^2}{2} S_r; \\ M_z^r(\delta) = m_z^r \rho_g \dfrac{\left(\Delta V_x^g\right)^2}{2} S_r b_r; \end{cases} \quad (7) \qquad \begin{cases} c_x^r = 1{,}46\delta^2; \\ c_y^r = \dfrac{2\pi\lambda}{2+\lambda}\delta; \\ m_z^r = -c_y^r l_r, \end{cases} \quad (8)$$

where c_x^r, c_y^r, m_z^r are the coefficients of longitudinal, lateral hydrodynamic force of the rudder and hydrodynamic moment of the rudder, S_r, b_r are the area and width of the rudder, δ is the rudder's deflection angle, λ is the elongation of the rudder, l_r is the rudder arm (distance from the middle of the rudder to the center of the vessel's rotation).

Forces and moments from the wind turbine. The thrust force F_T, drift force F_D and moment M_z of the wind turbine in projections on the LCS axis are determined by the formulas

$$\begin{cases} F_T = \sum_{j=1}^{n} \left[Y^a(\gamma_j)\sin\beta_a - X^a(\gamma_j)\cos\beta_a \right]; \\ F_D = \sum_{j=1}^{n} \left[Y^a(\gamma_j)\cos\beta_a + X^a(\gamma_j)\sin\beta_a \right]; \\ M_z = \sum_{j=1}^{n} \left(-F_{T\,j} Y_{PC\,j} + F_{D\,j} X_{PC\,j} \right); \end{cases} \quad (9)$$

$$\begin{cases} X^a(\gamma_j) = C_x^a(\alpha_j)\rho_a \dfrac{\left(\Delta V_x^a\right)^2}{2} S; \\ Y^a(\gamma_j) = C_y^a(\alpha_j)\rho_a \dfrac{\left(\Delta V_x^a\right)^2}{2} S, \end{cases} \quad (10)$$

where $X^a(\gamma_j), Y^a(\gamma_j)$ are the drag force and lift force of the *j*-th sail, β_a is the angle of incidence of the aerodynamic flow on the diametrical plane, $X_{PC\,j}, Y_{PC\,j}$ are the coordinates of the *j*-th sail pressure center, $C_x^a(\alpha_j), C_y^a(\alpha_j)$ are the drag and lift coefficient of the *j*-th sail, α_j is the angle of attack of the *j*-th sail, S is the sail area.

The sum of aerodynamic (2), hydrodynamic (4) and control (6)–(9) forces and moments in projections on the LCS axis has the form

$$\begin{cases} P_x = P_x(\Theta) - R_x^r + \sum_{j=1}^{n} \left(Y^a(\gamma_j)\sin\beta_a - X^a(\gamma_j)\cos\beta_a \right) - R_x^a - R_x^g; \\ P_y = P_y(\Theta) + R_y^r + \sum_{j=1}^{n} \left(Y^a(\gamma_j)\cos\beta_a + X^a(\gamma_j)\sin\beta_a \right) + R_y^a + R_y^g; \\ M_z = -P_y(\Theta) l_p - R_y^r l_r + \sum_{j=1}^{n} -\left(Y^a(\gamma_j)\sin\beta_a - X^a(\gamma_j)\cos\beta_a \right) Y_{PC\,j} + \\ + \sum_{j=1}^{n} \left(Y^a(\gamma_j)\cos\beta_a + X^a(\gamma_j)\sin\beta_a \right) X_{PC\,j} + M_z^a + M_z^g. \end{cases} \quad (11)$$

To ensure the given motion of the vessel, the sum of all forces and moments (11) must be equal to the forces and moments F_x^*, F_y^*, M_z^* necessary to maintain the given motion, which are determined by the PID controller

$$\begin{cases} P_x(\Theta) - R_x^r + \sum_{j=1}^{n} \left(Y^a(\gamma_j)\sin\beta_a - X^a(\gamma_j)\cos\beta_a \right) - R_x^a - R_x^g = P_x^*; \\ P_y(\Theta) + R_y^r + \sum_{j=1}^{n} \left(Y^a(\gamma_j)\cos\beta_a + X^a(\gamma_j)\sin\beta_a \right) + R_y^a + R_y^g = P_y^*; \\ -P_y(\Theta) l_p - R_y^r l_r + \sum_{j=1}^{n} -\left(Y^a(\gamma_j)\sin\beta_a - X^a(\gamma_j)\cos\beta_a \right) Y_{PC\,j} + \\ + \sum_{j=1}^{n} \left(Y^a(\gamma_j)\cos\beta_a + X^a(\gamma_j)\sin\beta_a \right) X_{PC\,j} + M_z^a + M_z^g = M_z^*. \end{cases} \quad (12)$$

System (12) can be considered as a system of the equalities type constraints on control.

Subblock 3.1 of linear constraints on control of the inequalities type. Serves to take into account constraints of the inequalities type on control (allowable control ranges)

$$|\Theta| \le \Theta_{\max}, |\delta| \le \delta_{\max}, |\gamma_j| \le \gamma_{\max}, \; j = 1..n. \tag{13}$$

Subblock 3.3 of conditional optimization. Serves to search for the global extremum of the objective function and optimal controls. Uses one of the known methods of searching for the global extremum (global search method, modified gradient, heuristic, etc.). At each iteration of the search for optimal controls, block 3.1 checks whether the current iteration of controls belongs to the allowable range, and block 2 calculates the control forces and moments for the current iteration of controls. The sum of the control, aerodynamic and hydrodynamic forces and moments is again fed to the inputs of subblock 3.3 of conditional optimization for the next iteration. Subblocks 3.3 of conditional optimization complete their work at the current cycle of the on-board computer after the specified criterion for completing the search process is met (depends on the selected method). The found optimal controls $\mathbf{U}^0 = \left(\Theta^0, \delta^0, \gamma_j^0\right), \; j = 1..n$ are fed to the automation of the corresponding drives (PP, rudder, sails) for processing.

Main results and discussion. A method for automatic control of the vessel's movement along a route with additional wind sails has been developed, which allows for additional reduction of fuel consumption. The achieved result is explained by the finding in the on-board computer of the automatic movement control module of optimal controls for a combined structure of actuators, which includes traditional controls (propeller, rudder) and control of the wind sails installation, by solving a conditional optimization problem with equalities and inequalities type constraints. Equalities type constraints provide simultaneous formation of the controls necessary to maintain a given movement along the route, and inequalities type constraints take into account the permissible ranges of control changes. The developed method differs from known solutions in that: it determines optimal controls not only for wind sails, but for the combined structure of the vessel's actuators; optimal controls are calculated by solving a conditional optimization problem with equalities and inequalities type constraints. The results obtained are reproducible and can be used in the development of mathematical support for autonomous systems, or in automated systems with automatic motion control modules.

Conclusions. A method for calculating optimal controls of the combined structure of the vessel's actuators, which includes traditional controls (propeller, rudder) and wind sails control, has been developed. The developed method allows for a further reduction in fuel consumption. This is explained by finding optimal controls not only for the sails, but for the entire combined structure of the actuators, which includes traditional controls (propeller and rudder), as well as sail control, by solving the problem of conditional optimization with constraints such as equalities and inequalities. The theoretical significance of the results obtained lies in the development of a method for automatic optimal control of the combined structure of actuators. The practical significance of the results obtained lies in the further reduction of fuel consumption, due to more efficient use of wind energy, the possibility of applying the method in the development of mathematical support for automatic modules for controlling the movement of vessels with additional wind sails.

Prospects for further research. Further research may be related to the development of methods for controlling the motion of a vessel with additional wind sails for sharp angles of the flow incidence on the diametrical plane $|\beta| \le 30dg$. As is known, at such angles of the flow incidence, the thrust force of the sails is not sufficient for movement against the flow, therefore, the tacks method of movement is used on sailboats. Development of the optimal control methods for combined structure of actuators, which includes traditional controls and a wind turbine, remains an urgent scientific and technical problem.

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Зінченко С. М., Товстокорий К. О. УМОВНА ОПТИМІЗАЦІЯ КЕРУВАНЬ СУДНА З ДОДАТКОВОЮ ВІТРОРУШІЙНОЮ СИСТЕМОЮ

Морська галузь стикається зі значними викликами через дедалі жорсткіші законодавчі вимоги щодо скорочення викидів шкідливих речовин в атмосферу та покращення клімату. Серед широкого спектра технологій та паливних рішень, що розглядаються в цьому контексті, одними з найперспективніших є додаткові вітрові рушійні системи (WAPS), які можуть суттєво зменшити споживання палива суднами та, як наслідок, зменшити викиди парникових газів та інших шкідливих речовин в атмосферу. Відомі рішення дозволяють зменшити витрати палива за рахунок використання енергії вітру, які полягають у розрахунку оптимальних керувань лише для віторушіїв. Об’єктом дослідження є процеси пошуку оптимальних керувань для об’єднаної структури виконавчих пристроїв судна, яка включає традиційні керування (гвинт, стерно) та додаткові віторушії. Розроблено метод керування рухом судна з додатковими віторушіями, який дозволяє ще більше зменшити витрати палива. Це досягається шляхом знаходження оптимальних керувань для об’єднаної структури виконавчих пристроїв судна шляхом вирішення у бортовому обчислювачі автоматичної системи керування задачі умовної оптимізації з обмеженнями типу рівностей та нерівностей. Обмеження типу рівностей забезпечують створення необхідних для підтримування заданого руху сил і моментів, а обмеження типу нерівностей враховують допустимі діапазони зміни керувань. Отримані результати можуть бути використані при розробці математичного забезпечення систем керування автономними суднами, або математичного забезпечення модулів автоматичного керування в автоматизованих системах.

Ключові слова: *WAPS; автоматичне керування; умовна оптимізація; енергоефективність; додаткові віторушії; бортовий обчислювач.*

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