This study investigates processes related to automatic optimal control over additional wind propulsion systems, propeller, and rudder as a single structure of vessel's actuators.

The maritime industry faces significant challenges because of increasingly stringent legislative requirements for reducing emissions of harmful substances into the atmosphere and improving the climate. Among the wide range of technologies and fuel solutions considered in this context, one of the most promising ones are wind propulsion systems, which can significantly reduce fuel consumption by vessels and, as a result, decrease emissions of greenhouse gases and other harmful substances into the atmosphere. In known solutions, each sail of a wind propulsion system is equipped with a system of automatic optimal guidance to the wind, which allows for maximum utilization of wind energy.

This work considers the issues of additional reduction of fuel consumption by a single-propeller conventional vessel with a wind propulsion system when moving along the route, in comparison with known solutions. The results are attributed to the use on-board controller in the vessel movement control system; to the calculation, at each step of the on-board controller, of optimal controls for the wind propulsion system, propeller, and rudder as a single structure of vessel's actuators. Optimal controls are found by solving the problem of conditional optimization of the objective function with constraints on equalities and inequalities type in the on-board controller. This allows for an additional 11% reduction in fuel consumption compared to the prototype and, at the same time, providing the necessary steering forces and torque to maintain a vessel's desired movement along the route. Results can only be achieved if the on-board computer control system has sufficient power

Keywords: additional wind propulsion systems, energy efficiency, conditional optimization, unified structure of actuators

DEVELOPMENT OF A METHOD OF AUTOMATIC CONTROL OF ADDITIONAL WIND PROPULSION SYSTEM, PROPELLER AND STERN AS A SINGLE STRUCTURE OF SHIP ACTUATORS

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1. Introduction

The maritime industry faces significant challenges because of increasingly stringent legislative requirements for reducing emissions of harmful substances into the atmosphere and improving the climate. This is facilitated by the improvement of power plants, structural [1, 2] and hydrodynamic solutions [3], the introduction of large-scale energy storage systems [4], and the use of modern mathematical tools in the mathematical support to control systems to solve various problems. In particular dumping kinetic energy in the event of an imminent collision [5], preventing parametric resonance [6], reconfiguring redundant structures of actuators [7, 8], rotation around the pole of rotation [9], etc.

Among the wide range of technologies and fuel solutions considered in this context, one most promising option is

wind-assisted propulsion systems (WAPSs). They can significantly reduce fuel consumption by ships and, as a result, reduce emissions of greenhouse gases and other harmful substances into the atmosphere. Several types of WAPS have been designed for the maritime industry [10]. Although the total number of ships equipped with WAPSs is still relatively low, there is a steady trend towards their growth.

Examples of ships equipped with rigid sails are the Pyxis Ocean, Berge Olympus, Shofu Maru, Windcoop. Pyxis Ocean is a 229 m long Kamsarmax class dry cargo ship equipped with two WindWing sails. Berge Olympus [11] is a 300 m long cargo ship equipped with four WindWing sails. The WindWing system does not require auxiliary power to operate and has a built-in feathering function to control the sail performance under different weather conditions. Shofu Maru is a 235 m long bulk carrier equipped with a rigid Wind Challenger sail [12]

as an auxiliary propulsion. This innovative solution uses the most modern and patented technologies that allow real-time determination of wind direction and speed. Windcoop is the world's first container ship, 91.3 m long, equipped with three rigid sails with an area of 350 m^2, designed by CWS. On the Windcoop vessel, the company solves a serious technical and logistical task – enabling efficient container handling with integrated sails.

As can be seen from the above, the latest trend in terms of fuel economy and reducing carbon emissions into the atmosphere is to equip ships with wind-assisted propulsion systems; therefore, this scientific issue is relevant. Thus, research on devising methods for controlling a ship with WAPS is a timely task.

2. Literature review and problem statement

The task of reducing fuel consumption by ships and their greenhouse gas emissions is multifaceted and can be solved by various methods. Thus, in work [13], based on the analysis of wind energy density in different navigation areas, fuel consumption and carbon emissions on ships with WAPS were studied. The results showed that fuel consumption and CO_2 emissions by ships with WAPS in areas with wind energy density over 1000 W/m^2 are approximately 29.7% lower than in areas with wind energy density below 500 W/m^2. The findings indicate that in order to reduce fuel consumption and carbon emissions on ships with WAPS, it is necessary to choose routes with high wind energy. At the same time, the question of applying the devised method on routes with low wind energy density remained unresolved. A likely reason is the limitation of the route planning method itself in areas with high wind energy density. An option to overcome the difficulties is to develop shipping services for vessels powered by wind engines. This method is considered in [14]. The problem is formulated as a two-stage stochastic model of mixed integer programming. The solutions at the first stage determine the optimal sequence of calls to ports, while the solutions at the second stage adapt the ship's schedule to a set of wind scenarios. The method devised makes it possible to minimize the expected total costs of the voyage by solving a logistics problem. At the same time, the method does not take into account the possibility of reducing fuel consumption through the use of mathematical models.

Another approach is considered in [15] and involves using an accurate fuel consumption forecasting model. The proposed model combines the ship model, its equipment, and the control system model. The genetic algorithm GA (Genetic algorithm), convolutional neural network CNN (Convolutional Neural Networks), recurrent neural network LSTM (long short-term memory), and white box models WBM (White Box Models) were used to build the models. However, the study does not show how the resulting model could be used in the ship motion control system with WAPS and what reduction in fuel consumption would be achieved. An option to overcome the difficulties may be to study the influence of the sail profile geometry on the maximum lift coefficient, given in [16]. A genetic algorithm and a surrogate Kriging model were used to optimize the geometry. It is shown that with this approach, the increase in the maximum lift coefficient is 13.17%, compared to the basic one. The study is important from the point of view of improving the profile quality but the issues of practical use of the research results in reducing fuel consumption, accumulating or saving energy on the ship remain unresolved. An option to overcome

the difficulties is to optimize the combined collection of wind and solar energy, considered in [17]. It involves optimizing the sail angle and the deck area where the wind and solar energy collection systems are located. The results showed that optimizing the sail angle and deck area allowed for increased renewable energy collection and reduced carbon dioxide emissions by 36%, compared to the same vessel without innovative technologies.

A similar method of using a sailing-hybrid power supply scheme on ships as an environmentally friendly solution for reducing greenhouse gas emissions is considered in study [18]. To effectively use the advantages of several energy sources, the task of their optimal distribution is relevant. The study proposes a probabilistic optimization method that integrates several energy sources and takes into account correlated uncertainties between wave direction, wave height, wave period, wind direction and wind speed. Decision-making according to several criteria is performed using a multi-objective particle swarm optimization algorithm. The considered optimization schemes for combined wind and solar energy collection, as well as the sailing-hybrid power supply scheme, make it possible to optimize energy storage on the ship and reduce greenhouse gas emissions but require additional areas for placing wind and solar energy collection systems. An option to overcome the shortcomings is the optimization of WAPS control processes, described in [19]. It is noted that optimizing only the sail angle of attack in the WAPS system, without taking into account related effects, limits the potential for energy efficiency. A multidimensional optimization method is proposed that optimizes the ship motion parameters (route, speed, trim) and the sail angle of attack in a related manner. A mathematical model of WAPS is built that provides an accurate representation of the system dynamics, the fuel consumption minimization problem is stated, and a particle swarm optimization method with an improved optimization algorithm that integrates sea state recognition, and a maximum sail drag coefficient strategy is selected. The effectiveness of the method is confirmed by experiments on a large oil tanker. The results showed that fuel consumption and greenhouse gas emissions were reduced by 8.6%. The disadvantages of the method include a slight reduction in fuel consumption compared to the additional computational load for solving the multidimensional optimization problem.

Our review of the literature [13–19] demonstrates that the reduction of fuel consumption and greenhouse gas emissions on ships can be achieved by planning routes with denser wind energy, forecasting fuel consumption, optimizing the sail profile, combined collection of wind and solar energy, optimal distribution of energy sources, using multidimensional optimization (sail angle of attack, speed and trim). The closest in technical essence is the multidimensional optimization method, which involves the simultaneous optimization of several parameters (sail angle of attack, route, speed and trim). At the same time, the multidimensional optimization method makes it possible to reduce fuel consumption by only 8.6%. All this gives grounds to argue that it is advisable to conduct further research aimed at reducing fuel consumption and carbon emissions into the atmosphere by optimizing WAPS control processes.

3. The aim and objectives of the study

The purpose of our research is to devise a method for automatic optimal control over additional wind turbines, a propeller, and a rudder, as a single structure of the actuators at a con-

ventional single-propeller vessel. This will provide additional opportunities for more efficient use of wind energy and further reduction of fuel consumption.

The goal can be achieved by performing the following tasks:
– to formalize the set problem;
– to design a control scheme of and mathematical support to the control system for a single structure of a vessel's actuators;
– to conduct mathematical modeling of control processes in a closed circuit "Control object – Control system".

4. Materials and methods

The object of our study is the processes of automatic optimal control over additional wind turbines, a propeller, and a rudder as a single structure of the vessel's actuators.

The principal hypothesis assumes the possibility of reducing fuel consumption by a conventional single-propeller vessel with additional wind turbines by using wind energy, forming optimal controls of wind turbines, a propeller, and a rudder as a single structure of a vessel's actuators.

When conducting the study, a number of assumptions were adopted, the main ones of which are constant draft and mass of the vessel; no interaction of the sails with each other and the vessel's hull; no flow on the sails, no backlash in the actuators of the control system, etc.

The following simplifications were also accepted in the study. The mathematical support to the on-board computer of the control system used a model of plane-parallel motion of the vessel, analytical models for calculating external and control forces and moments. When simulating the ship's motion, full mathematical models were used, which are simplified in relation to the real ship, or simulator models.

The study used a systems approach, analysis, and synthesis, mathematical analysis, methods of aerodynamics and hydrodynamics, methods from the theory of automatic and optimal control, methods of numerical modeling. The following equipment was used: a personal computer with the Windows 10 operating system (HP Inc., USA) with the MS Office 2016 application package (Microsoft Corporation, USA) and the MATLAB environment (MathWorks, Inc., USA).

The source of input data for modeling is the main characteristics of the ship and WAPS, given in Table 1.

When conducting the study, we built on earlier results reported in [20].

Table 1

Basic characteristics of vessel and WAPS

ID	Value
Mass m, t	4514
Length L, m	119.2
Width B, m	13.4
Max. Speed V_{max}, kn	10.3
Max. Power W, kW	2×640
Actuators	Propeller, rudder
Name	Value
Number of sails	4
Sail shape	rectangular
Max. quality $k_{max} = (C_y / C_x)_{max}$	8
Optimal attack angle $\alpha(k_{max})$, dg	5
Sail area S_a, m^2	120
Sail height H_s, m	20

5. Results of investigating the processes of automatic optimal control over additional wind turbines, propeller, and rudder, as a single structure of actuators at a conventional single-propeller vessel

5. 1. Formalization of the problem

The problem of optimal control over the movement of a conventional single-propeller vessel with additional wind turbines along the route takes the following form:

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

The first equation in system (1) determines the minimization of the telegraph movement (fuel consumption) at each step of the on-board computer. The second equation in system (1) determines the movement of the vessel along the route with a given speed $V_x = V_x^*$, a given lateral displacement $\Delta Y = \Delta Y^*$ and a given course $K = K^*$. The third equation in system (1) determines the given ranges of permissible movements of control: telegraph $|\Theta| \le \Theta_{max}$, rudder $\|\delta| \le \delta_{max}$ and sails $|\gamma_j| \le \gamma_{max}, j = 1..n$.

5. 2. Control scheme and mathematical support to the control system for a single structure of vessel's actuators

Statement (1) can be considered as a problem of conditional optimization of the objective function $E[P_{x-}(\Theta)] = |\Theta| \to$ min with constraints on the type of equalities and inequalities. Constraints on the type of equalities provide, when searching for optimal controls, the force and yaw moment necessary to maintain a given motion. For a conventional single-propeller vessel, these constraints take the following form:

$$\begin{cases} \sum_{j=1}^{N} F_{xj} = P_x - R_x^r + \\ + \sum_{j=1}^{n} \left(Y_j^a \sin \beta_a - X_j^a \cos \beta_a \right) - R_x^a - R_x^g = F_x^*, \\ \sum_{j=1}^{N} F_{yj} = P_y + R_y^r + \\ + \sum_{j=1}^{n} \left(Y_j^a \cos \beta_a + X_j^a \sin \beta_a \right) + R_y^a + R_y^g = F_y^*, \\ \sum_{j=1}^{N} M_{zj} = -P_y l_p - R_y^r l_r + \\ + \sum_{j=1}^{n} -\left(Y_j^a \sin \beta_a - X_j^a \cos \beta_a \right) Y_{ÖÒj} + \\ + \sum_{j=1}^{n} \left(Y_j^a \cos \beta_a + X_j^a \sin \beta_a \right) X_{ÖÒj} + M_z^a + M_z^g = M_z^*, \end{cases} \quad (2)$$

where P_x – propeller thrust force, P_y – lateral force from propeller rotation, R_x^r – rudder drag force, R_y^r – rudder lateral force, R_x^a – hull aerodynamic drag force, R_y^a – hull lateral aerodynamic drag force, R_x^g – hull hydrodynamic drag force, R_y^g – hull lateral hydrodynamic drag force, M_z^a – hull and superstructure aerodynamic moment, M_z^g – hull hydrodynamic moment, l_p – lateral force arm from propeller rotation to the vessel's center of rotation, l_r – lateral force arm from the rudder center to the vessel's center of rotation X_j^a, $j = 1..n$ – drag force of the j-th sail Y_j^a, $j = 1..n$ – lift force of the j-th sail, β_a – angle of

incidence of the aerodynamic flow on the vessel's diametrical plane X_{PCj}, Y_{PCj}, $j = 1..n$ – coordinates of the pressure center of the j-th sail , F_x^*, F_y^*, M_z^* – forces and moments necessary to maintain the given vessel motion (formed by the PID controller).

Inequality-type constraints enable the search for optimal controls within the permissible control ranges:

$$\begin{cases} |\Theta| \le \Theta_{max}, \\ |\delta| \le \delta_{max}, \\ |\gamma_j| \le \gamma_{max}, j = 1..n. \end{cases} \quad (3)$$

These constraints are used in the conditional optimization module of the control system for the unified structure of vessel's actuators.

Fig. 1 shows control scheme for the unified structure of vessel's actuators.

The scheme works as follows. Sensor 1 measures parameters of the vessel's velocity vector in projections onto the ZSK axis $V = (V_x, V_y)$. Sensor 2 measures the vessel's course K. Sensor 3 measures the projections of the wind velocity vector onto the ZSK axis $Wd = (Wd_x, Wd_y)$. Sensor 4 measures the projections of the current velocity vector onto the ZSK axis $Sm = (Sm_x, Sm_y)$. Sensor 5 measures the lateral displacement of the vessel relative to the trajectory ΔY. Sensor 6 measures the angular yaw rate ω_z. Module 7 calculates the relative velocity of the aerodynamic flow ΔV_a, the relative velocity of the hydrodynamic flow ΔV_g, the angle of incidence of the aerodynamic flow on the diametrical plane of the vessel β_a and the angle of

$$\begin{cases} \Delta V_{ax} = V_x - Wd_x, \Delta V_{ay} = V_y - Wd_y, \Delta V_a = \sqrt{(\Delta V_{ax})^2 + (\Delta V_{ay})^2}, \\ \Delta V_{gx} = V_x - Sm_x, \Delta V_{gy} = V_y - Sm_y, \Delta V_g = \sqrt{(\Delta V_{gx})^2 + (\Delta V_{gy})^2}, \\ \beta_a = -\text{arctg}\left(\dfrac{\Delta V_{ay}}{\Delta V_{ax}}\right), \beta_g = -\text{arctg}\left(\dfrac{\Delta V_{gy}}{\Delta V_{gx}}\right). \end{cases} \quad (4)$$

incidence of the hydrodynamic flow on the diametrical plane (drift angle) β_g:

Modules 8–10 calculate the forces and yaw moment required to maintain the given motion of the vessel:

$$\begin{cases} F_x^* = k_1(V_x - V_x^*) + k_2 \int (V_x - V_x^*) dt, \\ F_y^* = k_3(Y - Y^*) + k_4 V_y + k_5 \int (Y - Y^*) dt, \\ M_z^* = k_6(K - K^*) + k_7 \omega_z + k_8 \int (K - K^*) K dt, \end{cases} \quad (5)$$

where $k_j, j = 1..8$ are the coefficients of the PID controller. Module 11 calculates the forces and moments of external influences that do not depend on the controls, as well as the control forces and the yaw control moment. The control forces and the control moment are calculated at each step of the iterative process of finding optimal controls, and the forces and moments of external influences, to reduce the load on the computer, are calculated once at each step of the on-board computer. The necessary constants for calculating the forces and moments are supplied from constants module 13. Module 12 solves the conditional optimization problem with constraints such as equalities and inequalities. Namely, at each step of the on-board computer it finds optimal controls $U^* = (\Theta^*, \delta^*, \gamma_j^*)$, $j = 1..n$ that minimize the objective function (fuel consumption) and satisfy constraints (2) and (3). In the first step of the calculation, the starting control vector $U^0 = (\Theta^0, \delta^0, \gamma_j^0)$, $j = 1..n$ for the conditional optimization procedure is supplied from constants module 13. In the following steps of the calculation, the starting vector is assigned the value of the optimal control vector from the previous step of the calculation $U^0(n) = U^*(n-1)$, which makes it possible to reduce the time for searching for optimal control.

The optimal sail positions γ_j^*, $j = 1..n$, from the output of the conditional optimization unit 12, are fed to sail automation unit 14 and then to sail drives 17. The sail automation unit 14 and sail drives 17 ensure the sails are turned to the optimal position γ_j^*, $j = 1..n$, or the sails are folded. The optimal control Θ^* of SEU, from the output of conditional optimization unit 12, is fed to the SEU automation unit 15, where the SEU drive limitations are taken into account, and then to the SEU drive 18. The optimal rudder control δ^*, from the output of the conditional optimization unit 12, is fed to the rudder automation unit 16, where the rudder
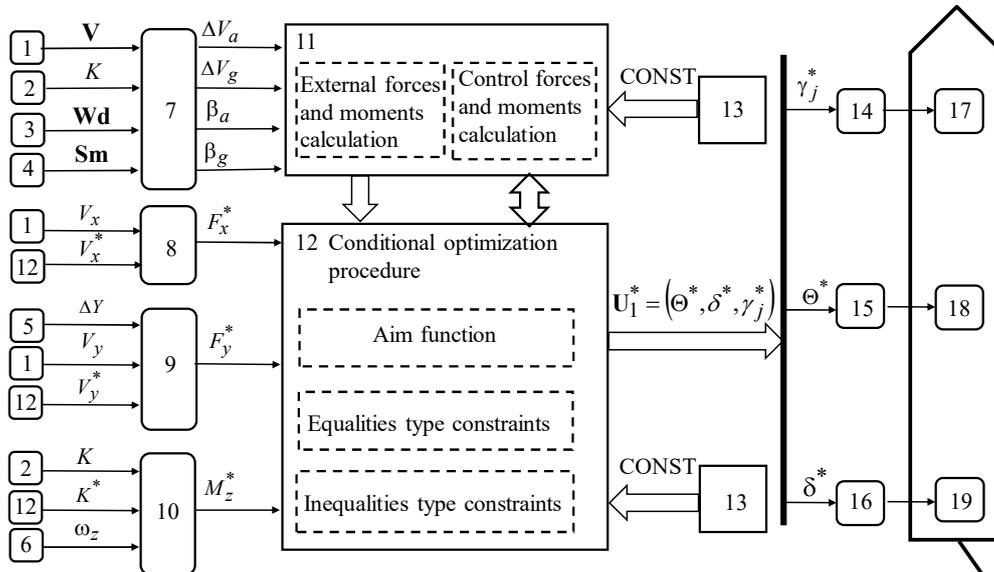

Fig. 1. Control scheme of a single structure of ship's actuators

drive limitations are taken into account, and then to the rudder drive 19.

Under the influence of the generated controls, the vessel changes its motion parameters, which are again measured by sensors and processed by the control system units, as described above, at each subsequent step of the on-board computer.

Fig. 2 shows a fragment of the control system software in the MATLAB environment.

Lines 53–58 specify the coefficients of the PID controller. Line 59 calculates the integral of the deviation of the longitudinal velocity from the set value. Lines 60–62 represent the PID controller, which calculates the control signals in the longitudinal, lateral, and angular motion channels based on the deviations of the current motion parameters from their program values. Lines 63–65 calculate the necessary forces and torques to work out the deviations. Lines 70–73 specify the matrices and vectors of the right-hand sides of the system of linear constraints of the equalities and inequalities type. In this case, they are empty, since linear constraints of the equalities type are absent in the problem under consideration, and linear constraints of the inequalities type are specified below in lines 74–75. Line 76 con-

tains the objective function. Line 77 specifies an array of initial control values for the optimization procedure. In line 78, the optimization procedure is called. The reference @nonlcon in the optimization procedure points to the file nonlcon.m of the function procedure for nonlinear constraints of the equality type.

```
    disp12.m  ×   meteo.m  ×   sysctr12.m*  ×   ship12.m  ×   sensor.m  ×   runge12.m  ×   nonlcon.m  ×   GR
51 -      end
52 -      if flg==2
53 -      k(1)=100;
54 -      k(2)=1;
55 -      k(3)=0.0;
56 -      k(4)=50;
57 -      k(5)=1;
58 -      k(6)=0.0;
59 -      intDVx=intDVx+DVx;
60 -      sig1=0.5*DVx+0.001*intDVx;
61 -      sig2=k(4)*vnyg+k(5)*Dy+k(6)*intDy;
62 -      sig3=500*(k(1)*x(6)+k(2)*Dpsi+k(3)*intDpsi); %500
63 -      Pxz=-3000*sig1;
64 -      Pyz=-3000*sig2;
65 -      Mzz=-5000*(sig2+sig3);
66 -      glPxz=Pxz;
67 -      glPyz=Pyz;
68 -      glMzz=Mzz;
69 -      betawd=glbetawd;
70 -      A = [];
71 -      b = [];
72 -      Aeq = [];
73 -      beq = [];
74 -      lb = [-pi/2,-pi/6,-pi/2,-pi/2,-pi/2,-pi/2];
75 -      ub = [pi/2,pi/6,pi/2,pi/2,pi/2,pi/2];
76 -      fun = @(u)u(1)^2;
77 -      u0=u;
78 -      u = fmincon(fun,u0,A,b,Aeq,beq,lb,ub,@nonlcon);
79 -      end
```

Fig. 2. Fragment of the control system software

```
    disp12.m  ×   meteo.m  ×   sysctr12.m  ×   ship12.m  ×   sensor.m  ×   runge12.m  ×   nonlcon.m  ×   GR_3D.m  ×   +
74 -      FT2=Xa2*cbetawd+Ya2*sbetawd;
75 -      FD2=-Xa2*sbetawd+Ya2*cbetawd;
76        %third sail
77 -      Cxs3=-1.22*sin(abs(alfa3));
78 -      Cys3=5.1*sin(2*alfa3);
79 -      Xa3=Cxs3*Pa;
80 -      Ya3=Cys3*Pa;
81 -      FT3=Xa3*cbetawd+Ya3*sbetawd;
82 -      FD3=-Xa3*sbetawd+Ya3*cbetawd;
83        %fourth sail
84 -      Cxs4=-1.22*sin(abs(alfa4));
85 -      Cys4=5.1*sin(2*alfa4);
86 -      Xa4=Cxs4*Pa;
87 -      Ya4=Cys4*Pa;
88 -      FT4=Xa4*cbetawd+Ya4*sbetawd;
89 -      FD4=-Xa4*sbetawd+Ya4*cbetawd;
90        %total forces and moments from the sails
91 -      FTs=FT1+FT2+FT3+FT4;
92 -      FDs=FD1+FD2+FD3+FD4;
93 -      Mzs=(-FT1*Ycp1+FD1*Xcp1)+(-FT2*Ycp2+FD2*Xcp2)+(-FT3*Ycp3+FD3*Xcp3)+(-FT4*Ycp4+FD4*Xcp4);
94        %nonlinear equality type constraints
95 -      ceq=[Fxp+Fxr+FTs+glFxksm+glFxkwd-glPxz;
96             %Fyp+Fyr+FDs+glFyksm+glFykwd-glPyz;
97           Mzp+Mzr+Mzs+glMzksm+glMzkwd-glMzz];
98 -      c=[];
99 -      end
```

Fig. 3. Fragment of the function procedure for nonlinear constraints of the equality type

Fig. 3 shows a fragment of the function procedure for nonlinear constraints of the equality type.

Lines 77–82 calculate the drag coefficient and the lateral force coefficient of the third sail (from the sail polar data), the drag force and lateral force of the third sail in the speed coordinate system, the thrust force and drift force of the third sail in ZSK. Lines 84–89 calculate the drag coefficient and the lateral force coefficient of the fourth sail, the drag force and lateral force of the fourth sail in the speed coordinate system, the thrust force and drift force of the fourth sail in ZSK. Lines 91–93 calculate the total thrust force, total drift force and total yaw moment of the four sails. Lines 95–97 record vector ceq of the total forces and yaw moment in projections onto the ZSK axis (nonlinear constraints of the type of equality for the channels of longitudinal, lateral, and angular motion).

5. 3. Mathematical modeling of the processes of automatic optimal control over the movement of a vessel with additional wind engines

The performance and efficiency of the method were verified by mathematical modeling in the MATLAB environment.

The characteristics of the vessel and WAPS are given in Table 1.

The purpose of the experiment is to compare fuel consumption for the following schemes:

1) a vessel without sails;

2) a vessel with sails, each of which independently orients itself to the wind with an optimal angle of attack (prototype scheme);

3) a vessel with sails, the control of which is considered in a single control scheme with a propeller and rudder (proposed method).

For all experiments, the vessel set speed is $V_x^* = 5.3$ m/s, the vessel set course is $K^* = 0$ dg, the wind speed $W = 7$ m/s, the wind course $K_W = 90$ dg.

Experiment No. 1. Mathematical modeling of the movement of a vessel without WAPS along the route.

The modeling results are shown in Fig. 4.

From the plots shown in Fig. 4, it is clear that the control system supports the accuracy of movement along the route: in lateral displacement $|Y_g| \leq 4.1$ m, in heading $Yaw| \leq 0.3$ dg. Fuel consumption for time $t = 1000$ s of movement along the route with a maximum speed $V_x = 5.3$ m/s is $En = 62$ kg.
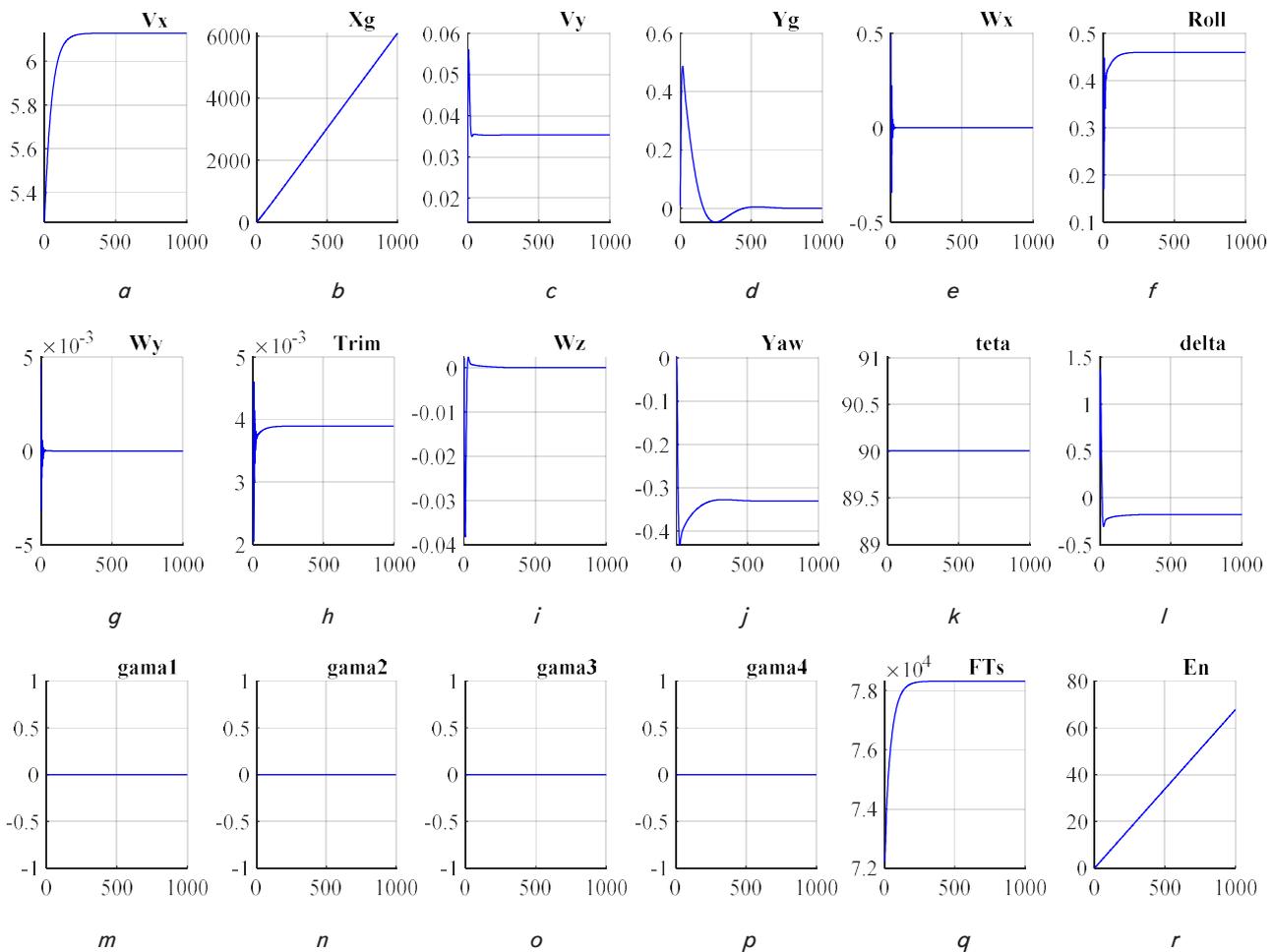

Fig. 4. Modeling the motion of a vessel without wind turbines: a — longitudinal speed V_x, m/s; b — longitudinal displacement X_g, m; c — lateral speed V_y, m/s; d — lateral displacement Y_g, m; e — angular rate of roll ω_x, dg/s; f — roll angle *Roll*, dg; g — trim angular rate ω_y, dg/s; h — trim angle Trim, dg; i — yaw angular rate ω_z, dg/s; j — yaw angle *Yaw*, dg; k — telegraph deflection angle Θ, dg; l — rudder deflection angle δ, dg; m — angle of rotation of the 1st sail gama1; n — angle of rotation of the 2nd sail gama2; o — angle of rotation of the 3rd sail gama3; p — angle of rotation of the 4th sail gama4; q — total thrust of the sails FTS, N; r — fuel consumption *En*, kg

Experiment No. 2. Mathematical modeling of the movement of a vessel with sails, each of which independently orients itself to the wind with an optimal angle of attack (prototype diagram).

The modeling results are shown in Fig. 5.

The plots show that the control system supports the accuracy of movement along the route: in lateral displacement $Y_g| \leq 6.0$ m, in heading $Yaw| \leq 0.35$ dg. Fuel consumption for time $t = 1000$ s of movement along the route with a maximum speed $V_x = 5.3$ m/s is $En = 42$ kg.

Experiment No. 3. Mathematical modeling of the movement of a vessel with sails, the control of which is considered in a single control scheme with a propeller and a rudder. The modeling results are shown in Fig. 6.

From the plots above it is clear that the control system supports the accuracy of movement along the route: in lateral displacement $|Y_g| \leq 4.0$ m, in heading $|Yaw| \leq 0.35$ dg. Fuel consumption for time $t = 1000$ s of movement along the route with a maximum speed $V_x = 5.3$ m/s is $En = 40$ kg.

Summarizing our results, it should be noted that the devised control method makes it possible to obtain fuel savings for 1000 s of movement along the route, in comparison with the control scheme without sails, $\Delta E_n = 62 - 40 = 22$ kg, or $\delta F_n = (22 : 62) * 100\% = 35.5\%$. Compared to the control scheme with sails, each of which independently orients itself to the wind with the optimal angle of attack (prototype scheme), $\Delta E_n = 45 - 40 = 5$ kg, or $\delta F_n = (5 : 45) * 100\% = 11.1\%$.
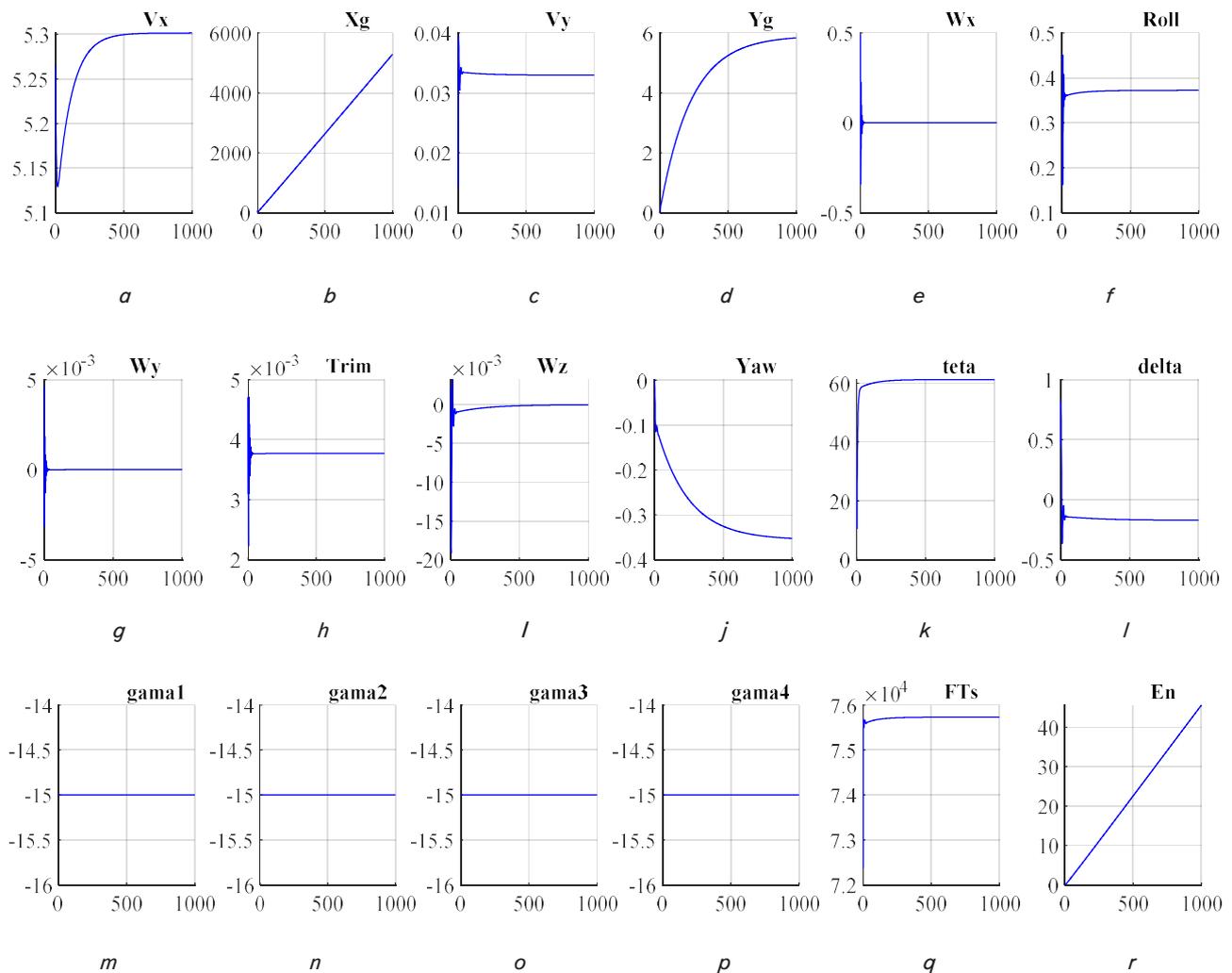

Fig. 5. Modeling the motion of a ship with sails, each of which is independently oriented to the wind with an optimal angle of attack (prototype diagram):
a — longitudinal speed V_x, m/s; *b* — longitudinal displacement X_g, m;
c — lateral speed V_y, m/s; *d* — lateral displacement Y_g, m;
e — angular roll velocity ω_x, dg/s; *f* — roll angle *Roll*, dg;
g — trim angular velocity ω_y, dg/s; *h* — trim angle *Trim*, dg;
i — yaw angular velocity ω_z, dg/s; *j* — yaw angle *Yaw*, dg;
k — telegraph deflection angle Θ, dg; *l* — rudder deflection angle δ, dg;
m — 1st sail yaw angle gama1; *n* — 2nd sail yaw angle gama2;
o — 3rd sail yaw angle gama3; *p* — 4th sail yaw angle gama4;
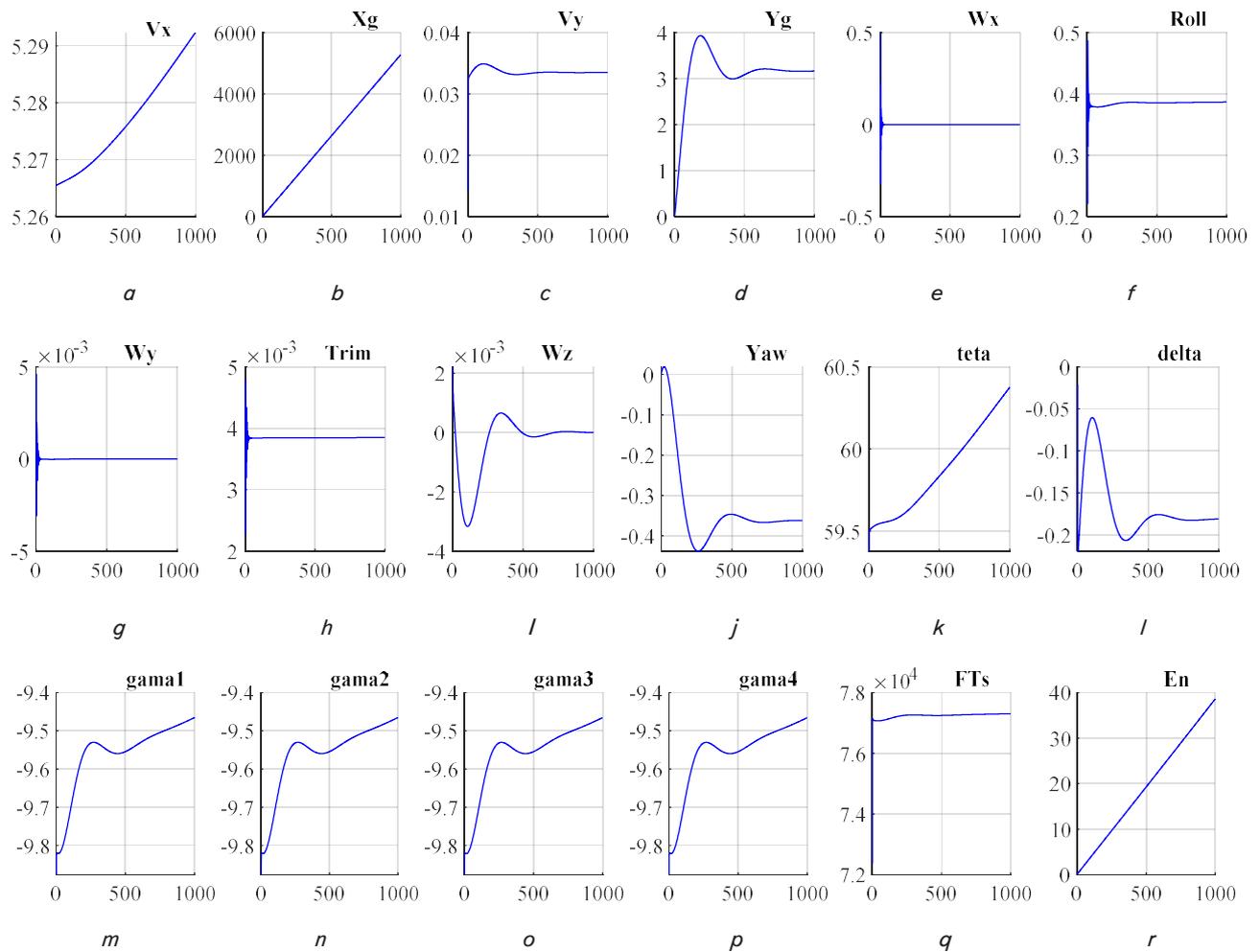*q* — total sail thrust FTS, N; *r* — fuel consumption *En*, kg

Fig. 6. Modeling the motion of a vessel with sails, the control of which is considered in a single control scheme with a propeller and rudder (proposed method): *a* — longitudinal speed V_x, m/s; *b* — longitudinal displacement X_g, m; *c* — lateral speed V_y, m/s; *d* — lateral displacement Y_g, m; *e* — angular roll velocity ω_x, dg/s; *f* — roll angle *Roll*, dg; *g* — trim angular velocity ω_y, dg/s; *h* — trim angle *Trim*, dg; *i* — yaw angular velocity ω_z, dg/s; *j* — yaw angle *Yaw*, dg; *k* — telegraph deflection angle Θ, dg; *l* — rudder deflection angle δ, dg; *m* — 1st sail yaw angle gama1; *n* — 2nd sail yaw angle gama2; *o* — 3rd sail yaw angle gama3; *p* — 4th sail yaw angle gama4; *q* — total sail thrust *FTS*, N; *r* — fuel consumption *En*, kg

6. Discussion of results based on investigating the processes of automatic control over a single structure of ship's actuators

A method of automatic optimal control over additional wind turbines, a propeller, and a rudder, as a single structure of ship's actuators, has been devised. This allowed us to achieve additional reduction in fuel consumption, in comparison with known solutions. Our results are attributed to the following:

– formalization of the set task (system 1). A feature of the result is the use of the objective function of minimizing fuel consumption, and not generating maximum sail thrust, as in the prototype. Maximizing sail thrust in a nonlinear system is not equivalent to minimizing fuel consumption;

– design of a control scheme and mathematical support to the system of controlling a single structure of ship's actuators (systems (2)–(5), Fig. 1). A feature of the control scheme is that the wind turbines, propeller, and rudder are considered as a single structure of ship's actuators, which makes

it possible, unlike the prototype, to optimize the interaction between them. The mathematical support to the control system, unlike the prototype, calculates optimal controls for the wind turbines, propeller, and rudder as a single structure of vessel's actuators, by solving a conditional optimization problem, which makes it possible to find optimal controls for the entire structure of actuators, not just the wind turbines, and thereby achieve further reductions in fuel consumption;

– mathematical modeling (Fig. 4–6). A feature of the problem being solved is the confirmation of the operability and efficiency of the method by mathematical modeling in the MATLAB environment. The simulation results showed that the fuel consumption for a vessel without wind turbines is $En = 62$ kg for time $t = 1000$ s of movement along the route with a maximum speed $V_x = 5.3$ m/s (Fig. 4, *r*). Under the same conditions, the fuel consumption of a vessel with sails that are automatically oriented to the relative wind is 45 kg. Under the same conditions, the application of the devised method for orienting the vessel by wind turbines, a propeller, and a rudder as a single structure of vessel's actuators

In known solutions [13–17], the reduction of fuel consumption is achieved due to route planning in areas with a high density of wind energy; forecasting fuel consumption; optimization of the sail profile; combined collection of wind and solar energy; optimization of the distribution of energy sources. Unlike these methods, in our method, fuel consumption reduction is achieved through multidimensional optimization of controls. The reduction of fuel consumption in study [18] involves multidimensional optimization of the vessel's motion parameters (route, speed, trim) and the angle of attack of the sails. In contrast, in the devised method, fuel consumption reduction is achieved through multidimensional optimization of controls (sails, propeller, and rudder). The sails, propeller, and rudder are considered as a single structure of actuators. For this structure, optimal controls are calculated by solving the problem of conditional optimization with constraints such as equalities and inequalities at each step of the on-board computer.

The performance and efficiency of the method were verified by mathematical modeling in the MATLAB environment. The modeling results showed that the devised method makes it possible to reduce fuel consumption, compared to the scheme without sails, by 35.5% and, compared to the prototype, by 11.1%.

The limitations of the method include the presence of an on-board computer with sufficient power to solve the conditional optimization problem in real time. The disadvantages of the method include the impossibility of its application for acute angles of attack of the aerodynamic flow, which is typical for all wind turbine systems.

Further studies may involve applying the devised method for acute angles of attack of the aerodynamic flow.

7. Conclusions

1. The problem of automatic optimal control over wind turbines, propeller, and rudder as a single structure of ship's actuators has been formalized. A feature of the result is the use of the objective function of minimizing fuel consumption, and not generating maximum sail thrust, as in the prototype. This is explained by the fact that maximizing sail thrust in a nonlinear system is not equivalent to minimizing fuel consumption.

2. A control scheme and mathematical support for the system for controlling a single structure of ship's actuators have been developed. The control scheme differs from the prototype in that wind turbines, propeller, and rudder are considered as a single structure of ship's actuators, which makes it possible to optimize the interaction among them. The mathematical support to the control system, unlike known solutions, calculates optimal control over a single structure of actuators and is placed in the on-board computer of the ship's motion control system, and not in the controllers of individual sails. This makes it possible, when controlling the sails, to also take into account the current propeller and rudder controls and obtain a further reduction in fuel consumption.

3. The efficiency and effectiveness of our method were verified by mathematical modeling of the motion control processes at a conventional single-propeller vessel for the following schemes:

1) a scheme without sails;

2) a scheme with sails that are automatically and optimally oriented to the wind (prototype scheme);

3) a scheme with sails that are considered as a component of a single structure of the vessel's actuators (proposed method).

The modeling results confirm the efficiency and effectiveness, showing that the use of the devised method makes it possible to reduce fuel consumption by 35.5% compared to the scheme without sails, and by 11.1% compared to the scheme with sails that are independently oriented to the wind.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Serhii Zinchenko: Supervision, Methodology, Conceptualization, Software; **Kostyantyn Tovstokoryy:** Validation, Formal Analysis; **Kostiantyn Tymofeiev:** Investigation, Data curation; **Dmytro Onyshko:** Writing – review & editing, Writing – original draft; **Vadym Polishchuk:** Project administration, Visualization.

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