UDC 004.942:656.61.052

INFLUENCE OF HULL AND CARGO CONTOURS ON LATERAL FORCE AND YAW TORQUE IN REAL-TIME VESSEL CONTROL SYSTEMS

Zinchenko S., *Sc.D., Professor of the Ship Handling Department, Kherson State Maritime Academy, Kherson, Ukraine, e-mail: srz56@ukr.net, ORCID: 0000-0001-5012-5029;*
Kalinichenko Ye., *Ph.D., Associate Professor, Head of the Department of Navigation and Control of the Ship, Odesa National Maritime University, Odesa, Ukraine, e-mail: kalinichenko.yevgeniy1964@gmail.com, ORCID: 0000-0003-2898-7313;*
Kozachok Yu., *Graduate student, Software development Company N-IX LTD, Ukraine, e-mail: kozak9995@gmail.com, ORCID: 0009-0005-6430-3961;*
Mateichuk V., *Ph.D., Associate Professor of the Ship Handling Department, Kherson State Maritime Academy, Kherson, Ukraine, e-mail: mateichykv@gmail.com, ORCID: 0000-0001-9328-0651.*

The purpose of the research is to increase the accuracy of control calculations, the efficiency of the control system and the safety of navigation in general, by using a mathematical model in the control system to determine the parameters of external influences in real time. The mathematical model of the vessel is an important element of the mathematical support of the control system, the use of which allows to significantly improve the quality of the control system. Mathematical models are used to predict the movement of the control object, monitor the parameters of the state vector of the control object that are inaccessible to direct measurement, including in noise, determine the failures of command and executive devices, solve optimization problems, etc. In the work, integral functions for determining the resulting lateral force, the resulting yaw torque and the arm of the resulting lateral force, depending on the angle of attack of the flow and the shape of the hull contours, are obtained. The values of integral functions for simple hull contours are calculated. Compared with known approaches to determining the hydrodynamic and aerodynamic interaction of the ship's hull with the environment, the obtained results allow: in comparison with simple models, to estimate external forces and yaw torque much more accurately; in comparison with complex models, to carry out their estimation in real-time control systems. The obtained results are explained by finding and using integral functions for determining the resultant lateral force, resultant yaw torque and resultant lateral force arm, which for simple hull shapes are reduced to analytical solutions. The results are reproducible and can be used in the mathematical support of automated/automatic control systems in real time.

Key words: *intelligent transport control systems; navigational safety; mathematical model; on-board computer; lateral force arm; energy efficiency.*

DOI: 10.33815/2313-4763.2024.2.29.024-034

Introduction. The quality of the automated / automatic vessel movement control system as a whole is determined by the quality of the mathematical support of the on-board computer, the quality of the input information coming from the measuring instruments and the quality of processing command signals from the on-board computer by the executive devices.

Automated control systems used on all transport vessels and specialized vessels with a dynamic positioning system have distributed computing power located in specialized units: Automatic Radar Plotting Aid (ARPA) – for processing radar information, Electronic Chart Display and Information System (ECDIS) – for processing cartographic information, AUTOPILOT – for automatic course / trajectory maintenance, power plant automation – for automatic control of propeller speed or propeller blade pitch. In dynamic positioning systems, additional computing power is used to maintain a given position or move along a given trajectory and the related tasks of evaluating external influences, splitting controls into redundant structures, etc. By the term "on-board computer" used in the article, the authors mean the computing power of such specialized units.

An important element of the mathematical support of the on-board computer is the mathematical model of the vessel, the use of which allows you to significantly improve the quality of the control system. Mathematical models are used to predict the movement of a controlled object, monitor the parameters of the system state vector that are inaccessible to direct measurement [1–3], using a neural network model of a ship for control tasks [4, 5], optimal control [6, 7], solving multi-objective divergence problems [8], etc. Automation of control processes allows to maximally eliminate the human factor, which is the cause of a large number of accidents and disasters and significantly reduce the human influence on the processes of controlling moving objects. The use of mathematical models of objects and processes in the on-board computer allows to significantly increase the operational efficiency of automated / automatic control systems. Therefore, the development of such models is an urgent scientific and technical task.

Problem statement. Find the resulting lateral hydrodynamic (aerodynamic) force, the arm of the resulting lateral hydrodynamic (aerodynamic) force, and the resulting yaw torque depending on the shape of the hull and cargo contours $f(x, y) = 0$ and the angle of attack of the flow.

Analysis of recent research and publications. Many works of the authors are devoted to the issue of using mathematical models in the control system and studying the influence of the shape of the body on the hydrodynamic and aerodynamic characteristics.

The aim of the research [9] is to study the applicability of the SQCM (Source Quasi-Continuous Vortex Method) to predict the hydrodynamic forces acting on the Wigley hull. Two types of free vortex models are considered. The predicted results are compared with the results of model tests to verify the effectiveness of the free vortex model.

Taking into account hydrodynamic forces and torques is of great importance in describing any maneuvers of a vessel, such as braking, acceleration, circulation, Kempf zigzag, dynamic positioning, and others. In [10], based on known experimental data, using multifactor quasilinear (linear in coefficients) regression analysis, expressions for the constants of hydrodynamic polynomial models of hydrodynamic forces and torques on the vessel hull were obtained. Various dimensionless ratios of the geometric parameters of the vessel, such as length, width, draft, and fullness coefficient, were taken as factors (regressors). When selecting regression models, the values of the normalized R-square and standard errors were estimated.

In [11], the reference hull model KCS (KRISO Container Ship, KRISO – Korea Research Institute for Ships and Ocean Engineering) is used to analyze the maneuverability characteristics in shallow water. The PMM (Planar Motion Mechanism) test, based on the RANS (Reynolds-averaged Navier–Stokes) equations, was carried out to obtain the maneuverability coefficient for different drift angles, using the overload method. The computational hydrodynamics results are compared with experimental data from the literature and show good agreement.

In the article [12], the problem of static positioning of a vessel with non-rectilinear hull contours on a wave is considered. The dependences of bending torques and shearing forces on the frequency and amplitude of the oncoming wave are obtained. The influence of the non-rectilinearity of the hull contours on the values of bending torques and shearing forces is analyzed.

Designing and optimizing the shape of a ship's hull to minimize drag and meet other design requirements is a well-known problem in ship theory and design. The hull shape design and optimization method proposed in [13] uses CFD (Computational Fluid Dynamics) analysis to estimate drag under systematic transformations of the hull surface. Each individual transformation corresponds to a new hull shape variant with a transformed surface area. All variants prepared on the basis of the initial hull shape belong to the first step of the optimization process. They are used in CFD calculations to estimate resistance changes in calm water. As a result, an optimal shape along the frames can be obtained, which expresses the optimal longitudinal distribution of the constant hull volume and corresponds to the optimized hull surface shape. This method was applied to the bows of two ships, including the well-known KCS hull shape. The obtained optimization results in calm water conditions were additionally evaluated in waves.

In the article [14], a reasonable choice of the dimensions of a fishing vessel with a large block coefficient is considered. To solve the problem, a mathematical instrument was developed, which included design equations, including equations of buoyancy, mass, capacity, waterplane area coefficient, stability, power, relative elongation, prismatic coefficient, as well as boundary conditions and calculation of economic indicators. The key indicator of the economic profitability of the project was determined to be the efficiency of capital investments. To find the most efficient vessel, a variational calculation was performed – solving a system of equations with a variation of some initial data. According to the results of the variational calculation, the most successful combination of the main characteristics of the vessel was determined, which provide the best economic indicators.

In the article [15], the assessment of maneuverability of high-speed vessels at the early stages of their design was studied. Previously, experimental, analytical and empirical methods were used for this. Nowadays, numerical methods are also used, given their accuracy and short calculation time. The paper presents a hybrid numerical-theoretical method for calculating hydrodynamic coefficients using CFD modeling based on RANS equations. Linear and nonlinear hydrodynamic coefficients of the vessel hull were calculated using the combined method. The simulation results were compared with those calculated by the semi-empirical Levandowski method. The comparison results show that the proposed hybrid model can predict the maneuverability of a marine vehicle at the preliminary design stage.

The textbook [16] contains formulas for determining the lateral aerodynamic force $R_{ay} = C_{ay} \frac{\rho_a}{2} S_{ay} \Delta W_a^2$, where C_{ay} is the coefficient of lateral aerodynamic force, ρ_a is the air density, S_{ay} is the area of the above-water part of the vessel perpendicular to the incident flow, ΔW_a is the relative velocity of the oncoming aerodynamic flow; $R_{gy} = C_{gy} \frac{\rho_g}{2} S_{gy} \Delta W_g^2$ is the lateral hydrodynamic force, where C_{gy} is the coefficient of lateral hydrodynamic force, ρ_g is the water density, S_{gy} is the area of the underwater part of the vessel hull perpendicular to the oncoming flow, ΔW_g is the relative velocity of the oncoming hydrodynamic flow; relative arm of lateral aerodynamic force $\vec{l}_a = 0{,}25 + \frac{l_{sc}}{L} - \frac{q_w^\circ}{360^\circ}$, where l_{sc} is the center of sail, L is the length of the vessel, q_w° is the angle of the oncoming aerodynamic flow; relative arm of lateral hydrodynamic force $\vec{l}_g = 0{,}5 + \frac{l_{colr}}{L} - \frac{\alpha_w^\circ}{180^\circ}$, where l_{colr} is the center of lateral resistance, α_w° is the angle of the oncoming hydrodynamic flow; aerodynamic yaw torque $M_a = R_{ay} l_a$ and hydrodynamic yaw torque $M_g = R_{gy} l_g$.

The aim and objectives of the research. The aim of the study is to obtain a refined mathematical model in terms of integral equations for determining the resultant lateral force and torque, as well as the resultant lateral force arm, depending on the angle of attack of the flow and the shape of the hull, to increase the accuracy of control calculations using the refined mathematical model, to increase the efficiency of the control system and navigation safety in general. The aim is achieved by taking into account the hull contours when determining the resultant lateral force and torque, as well as the resultant lateral force arm. The objectives of the study are to obtain, for a given hull contour: the integral equation of the resultant lateral force; the integral equation of the resultant torque; the resultant lateral force arm; the values of these parameters for individual simplified forms of hull contours; to compare the results obtained with those known from literary sources.

Main part. Fig. 1 shows a diagram of the interaction of the ship's hull with the oncoming flow.

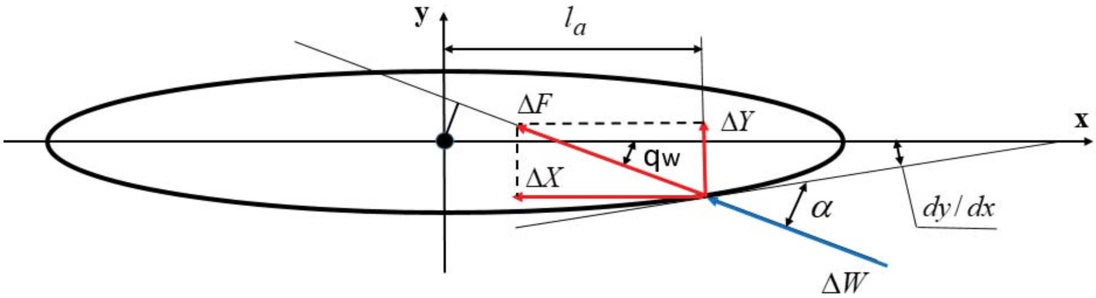

Figure 1 – Diagram of the interaction of the ship's hull with the oncoming flow

A body element of length Δl is subjected to lateral force ΔY and drag force ΔX from an oncoming flow with a relative velocity ΔW at an angle α.

$$\alpha = q_w + arctg\left(\frac{dy}{dx}\right), \tag{1}$$

where $(y, x) = 0$ is the function describing the contours of a ship's hull, $\frac{dy}{dx}$ is the derivative of the function $(y, x) = 0$ at the point of the element Δl, q_w is the angle of incidence of the flow on the diametrical plane of the vessel.

For a constant q_w, only the angle $arctg\left(\frac{dy}{dx}\right)$ along the length of the body changes.

The lateral force dY generated by a hull element dl can be written as

$$dY = C_y^{\alpha}\left(q_w + arctg\left(\frac{dy}{dx}\right)\right)\rho\frac{\Delta W^2}{2}dl, \tag{2}$$

where C_y^{α} – is the coefficient of lateral force, ρ is the density of the medium.

We write the element dl in the form

$$dl = \sqrt{d^2x + d^2y} = \sqrt{d^2x + \left(\frac{dy}{dx}\right)^2 d^2x} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\,dx \tag{3}$$

After substituting equation (3) into equation (2), we obtain

$$dY = C_y^{\alpha}\left(q_w + arctg\left(\frac{dy}{dx}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1 + \left(\frac{dy}{dx}\right)^2}\,dx \tag{4}$$

The resulting lateral force of the hull is equal to

$$Y(q_w) = \int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha}\left(q_w + arctg\left(\frac{dy}{dx}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1 + \left(\frac{dy}{dx}\right)^2}\,dx, \tag{5}$$

where L is the length of the ship's hull.

The torque from the lateral force element dY is equal to

$$dM_z = -C_y^{\alpha}\left(q_w + arctg\left(\frac{dy}{dx}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1 + \left(\frac{dy}{dx}\right)^2}\,xdx, \tag{6}$$

and the resultant torque from the oncoming flow

$$M_z(q_w)=\int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha}\left(q_w+arctg\left(\frac{dy}{dx}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1+\left(\frac{dy}{dx}\right)^2}\,xdx. \quad (7)$$

Using equations (5) and (7), we find the resultant lateral force arm

$$l_a(q_w)=\frac{M_z}{Y}=\frac{\int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha}\left(q_w+arctg\left(\frac{dy}{dx}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1+\left(\frac{dy}{dx}\right)^2}\,xdx}{\int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha}\left(q_w+arctg\left(\frac{dy}{dx}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1+\left(\frac{dy}{dx}\right)^2}\,dx}. \quad (8)$$

Formulas (5), (7) and (8) allow us to determine the resultant lateral force of the hull, the resultant hull torque and the resultant lateral force arm, depending on the angle q_w of the incident flow, for an arbitrary hull contour $(y,x)=0$.

Resultant lateral force, resultant torque and resultant lateral force arm for an elliptical hull contour. In this case, the hull contour function $(y,x)=0$ has the form

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1. \quad (9)$$

Let’s find the derivative $\frac{dy}{dx}$ of equation (9)

$$\frac{2x}{a^2}+\frac{2y}{b^2}\frac{dy}{dx}=0 \;\rightarrow\; \frac{dy}{dx}=-\frac{x}{y}\frac{b^2}{a^2}. \quad (10)$$

Also, from equation (9) we find

$$y^2=b^2\left(1-\frac{x^2}{a^2}\right) \;\rightarrow\; y=\frac{b}{a}\sqrt{a^2-x^2} \;\rightarrow\; \frac{x}{y}=\frac{xa}{b\sqrt{a^2-x^2}} \quad (11)$$

After substituting equation (11) into equation (10), we obtain

$$\frac{dy}{dx}=-\frac{x}{y}\frac{b^2}{a^2}=-\frac{xa}{b\sqrt{a^2-x^2}}\frac{b^2}{a^2}=-\frac{xb}{a\sqrt{a^2-x^2}} \quad (12)$$

Substitute the values $\frac{dy}{dx}$ from (12) into equations (5), (7) and (8)

$$Y=\int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha}\left(q_w+arctg\left(-\frac{xb}{a\sqrt{a^2-x^2}}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1+\left(-\frac{xb}{a\sqrt{a^2-x^2}}\right)^2}\,dx \quad (11)$$

$$M_z=\int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha}\left(q_w+arctg\left(-\frac{xb}{a\sqrt{a^2-x^2}}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1+\left(-\frac{xb}{a\sqrt{a^2-x^2}}\right)^2}\,xdx \quad (12)$$

$$l_a(q_w) = \frac{M_z}{Y} = \frac{\int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha}\left(q_w + arctg\left(-\frac{xb}{a\sqrt{a^2-x^2}}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1+\left(-\frac{xb}{a\sqrt{a^2-x^2}}\right)^2}\,xdx}{\int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha}\left(q_w + arctg\left(-\frac{xb}{a\sqrt{a^2-x^2}}\right)\right)\rho\frac{\Delta W^2}{2}\sqrt{1+\left(-\frac{xb}{a\sqrt{a^2-x^2}}\right)^2}\,dx} \quad (13)$$

The obtained integrals (11), (12) and (13) are quite complex to find an analytical solution (or do not have one at all). Therefore, calculations according to formulas (11), (12), (13) are better performed numerically.

Resultant lateral force, resultant torque and resultant lateral force arm for a rectangular hull. For a hull having a rectangular shape, $\frac{dy}{dx} = 0$ along the entire length of the vessel. Then, from formulas (5), (7), (8) we obtain

$$Y = \int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha} q_w \rho\frac{\Delta W^2}{2}dx = C_y^{\alpha} q_w \rho\frac{\Delta W^2}{2} x\,|_{-L/2}^{+L/2} = C_y^{\alpha} q_w \rho\frac{\Delta W^2}{2}\left(\frac{L}{2}+\frac{L}{2}\right) = C_y^{\alpha} q_w \rho\frac{\Delta W^2}{2}L \quad (14)$$

$$M_z = \int_{-\frac{L}{2}}^{+\frac{L}{2}} C_y^{\alpha} q_w \rho\frac{\Delta W^2}{2}xdx = \frac{1}{2}C_y^{\alpha} q_w \rho\frac{\Delta W^2}{2}x^2\,|_{-L/2}^{+L/2} = \frac{1}{2}C_y^{\alpha} q_w \rho\frac{\Delta W^2}{2}\left(\left(\frac{L}{2}\right)^2 - \left(-\frac{L}{2}\right)^2\right) = 0 \quad (15)$$

$$l_a(q_w) = \frac{M_z}{Y} = 0 \quad (16)$$

Resultant lateral force, resultant torque and resultant lateral force arm for the wedge-shaped part of the hull. The diagram of the interaction of the wedge-shaped part of the hull with the oncoming flow is shown in Fig. 2.

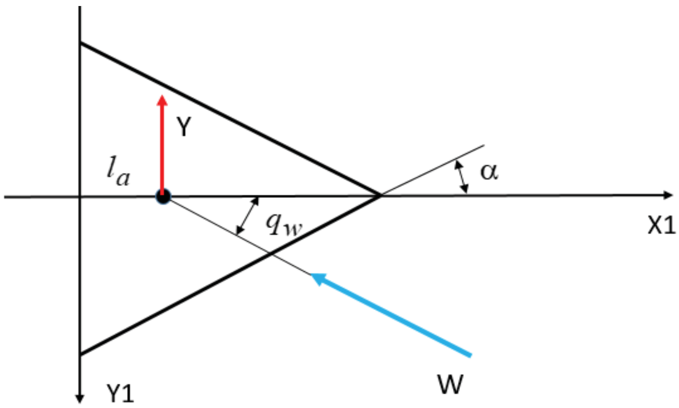

Figure 2 – Diagram of the interaction of the wedge-shaped part of the body with the oncoming flow

For the wedge-shaped part of the body

$$\frac{dy}{dx} = -tg\alpha \quad (17)$$

After substituting equation (17) into equations (5), (7), (8), we obtain

$$Y(q_w)=\int_0^{\Delta} C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}dx=C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}x\,|_0^{\Delta}= \\ =C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}(\Delta-0)=C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}\Delta \tag{18}$$

$$M_z(q_w)=\int_0^{\Delta} C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}xdx=\frac{1}{2}C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}x^2\,|_0^{\Delta}= \\ =\frac{1}{2}C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}\left(\Delta^2-0\right)=\frac{1}{2}C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}\Delta^2 \tag{19}$$

$$l_a(q_w)=\frac{M_z(q_w)}{Y(q_w)}=\frac{\frac{1}{2}C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}\,\Delta^2}{C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}\,\Delta}=\frac{1}{2}\Delta \tag{20}$$

Resultant lateral force, resultant torque and resultant lateral force arm for a rectangular hull with a wedge-shaped nose. The resultant lateral force is found as the sum of the resultant forces of the rectangular and wedge-shaped hull parts, taking into account the change in the limits of integration

$$Y=C_y^{\alpha}q_w\rho\frac{\Delta W^2}{2}(L-\Delta)+C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}\,\Delta \tag{21}$$

The resultant torque is found as the sum of the resultant torque of the rectangular and wedge-shaped parts of the body, taking into account the change in the limits of integration.

$$M_z=\frac{1}{2}C_y^{\alpha}q_w\rho\frac{\Delta W^2}{2}\left(\left(\frac{L}{2}-\Delta\right)^2-\left(\frac{L}{2}\right)^2\right)+\frac{1}{2}C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}\Delta^2 \tag{22}$$

From equations (21), (22) we find the shoulder of the resulting lateral force

$$l_a(q_w)=\frac{M_z(q_w)}{Y(q_w)}=\frac{\frac{1}{2}C_y^{\alpha}q_w\rho\frac{\Delta W^2}{2}\left(\left(\frac{L}{2}-\Delta\right)^2-\left(\frac{L}{2}\right)^2\right)+\frac{1}{2}C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}\Delta^2}{C_y^{\alpha}q_w\rho\frac{\Delta W^2}{2}(L-\Delta)+C_y^{\alpha}(q_w+\alpha)\rho\frac{\Delta W^2}{2}\sqrt{1+tg^2\alpha}\,\Delta} \tag{23}$$

Fig. 3 shows a container ship with a rectangular cargo shape in the aerodynamic flow, a rectangular and wedge-shaped hull shape in the aerodynamic and hydrodynamic flow.

Figure 3 – Shapes of the hull and cargo contours of a container ship

Conducting the experiment. The above-obtained integral equations (11)–(13) for determining the resultant lateral force, the resultant torque and the resultant lateral force arm for the elliptical contour of the hull, Fig. 1, which do not have analytical solutions, or the solutions are quite complex, so we will apply numerical methods. A fragment of the program for numerical integration of equations (11)–(13) is shown in Fig. 4.

```
Editor - C:\Program Files\Polyspace\Наработка\ПРАКТИЧНІ ЗАНЯТТЯ\Article4.m*
disp12.m | sensor.m | runge12.m | ship12.m | meteo.m | sysctr12.m | Article.m | Arti

%Початкові умови
x=-a+dx;
Y=0;                      %результуюча бокова сила
Mz=0;                     %результуючий момент

dV=10;                    %відносна швидкість набігаючого потоку
qw=180/57.3;              %кут набігання потоку
jp=1;
while x<=a-dx
dydx=-b*x/(a*sqrt(a^2-x^2)+0.0000001);
calfa=(cos(qw)+dydx*sin(qw))/sqrt(1+dydx^2);
salfa=(dydx*cos(qw)-sin(qw))/sqrt(1+dydx^2);
alfa=asin(salfa);
if alfa>0
alfa=0;                   %бокова сила і момент не створюються
end
dY=0.5*cyalfa*alfa*ro*dV^2*sqrt(1+dydx^2)*dx;
Y=Y+dY;
dMz=0.5*cyalfa*alfa*ro*dV^2*sqrt(1+dydx^2)*x*dx;
Mz=Mz+dMz;
la=Mz/Y;
x=x+dx;
xp(1,jp)=Y;
xp(2,jp)=Mz;
xp(3,jp)=la;
jp=jp+1;
end
subplot(1,3,1);                     %матриця 1х3, перший графік
```

Figure 4 – A fragment of the program in the MATLAB environment

Fig. 5–7 show graphs of the dependence of the resulting lateral force Y, the resulting torque M_z and the resulting lateral force arm l_a on the angle q_W of attack of the flow for an elliptical body contour.

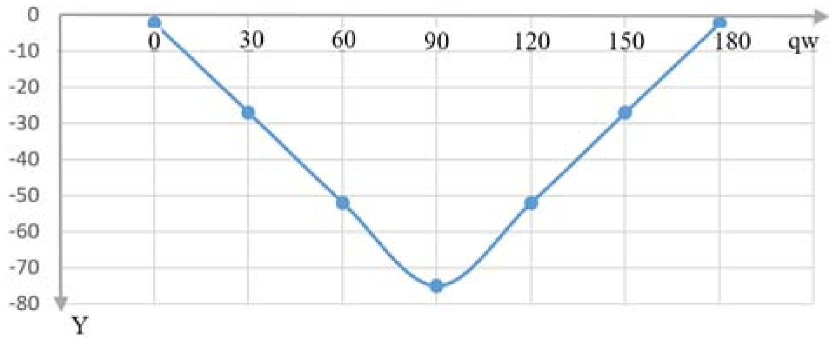

Figure 5 – Graph of the dependence of the resulting lateral force Y on the angle q_W of attack of the flow for an elliptical body contour

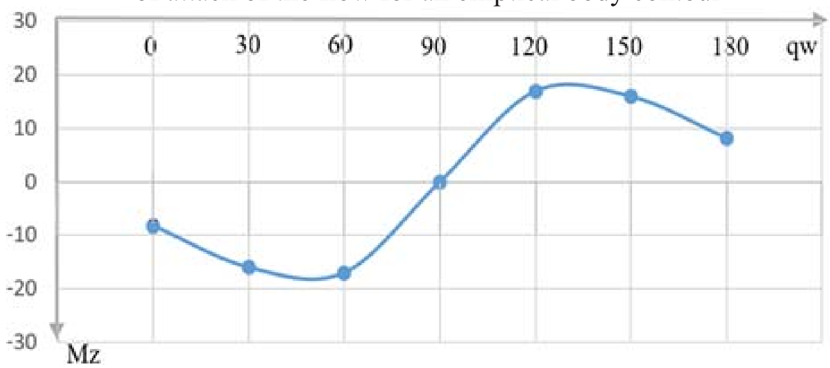

Figure 6 – Graph of the dependence of the resulting torque M_z on the angle q_W

of attack of the flow for an elliptical body contour

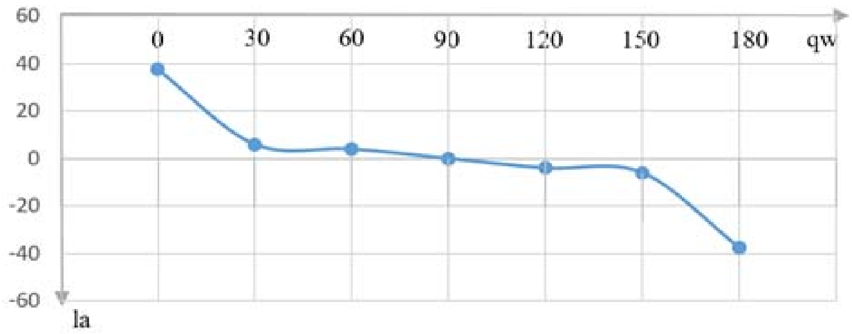

Figure 7 – Graph of the dependence of the resultant lateral force arm l_a on the angle q_w of attack of the flow for an elliptical body contour

As can be seen from the results obtained, for the elliptical shape of the hull contours, the resultant torque M_z and the resulting lateral force arm significantly depend on the angle of attack of the flow, Fig. 6–7. For the rectangular shape of the hull contours, the resultant torque M_z and the resulting lateral force arm are equal to zero, regardless of the angle of attack of the flow, formulas (15), (16). For the wedge-shaped shape of the hull contours, the resultant torque M_z and the resulting lateral force arm are constant values and also do not depend on the angle of attack of the flow, formulas (19), (20). Therefore, the resultant torque and the resulting lateral force arm do not depend on the angle of attack of the flow, if the derivative of the hull contour function is constant along the length of the vessel. The resultant torque and the resultant lateral force arm do not depend on the angle of the incident flow, and are equal to zero if the derivative of the hull contour function is equal to zero along the entire length of the vessel hull.

Discussion. The issues of the influence of hull and cargo contours on hydrodynamic and aerodynamic forces and torques are considered, which is important to know when using a mathematical model in a control system. A search and analysis of literary sources devoted to the issues of hydrodynamic and aerodynamic interaction of the ship's hull with the environment and the use of mathematical models in control systems are carried out. Integral functions for determining the resulting lateral force, the resulting yaw torque and the resulting lateral force arm are obtained, depending on the angle of incidence of the flow and the shape of the hull contours. The values of the integral functions are calculated for simple hull contours, and a numerical calculation is performed for an elliptical hull contour. In comparison with known solutions [16], it was found that the arm of lateral force and the resulting yaw torque do not depend on the angle of incidence of the flow for hulls in which the derivative of the contour is constant along the length of the hull, for example, for a rectangular and wedge-shaped hull. For other hull contours, these dependencies are purely nonlinear. The obtained results allow: to estimate the resulting lateral force, arm of lateral force and the resulting yaw torque much more accurately. In comparison with other known approaches to determining external influences by mathematical modeling of a system of partial differential equations, for example, by CFD methods, the developed model allows estimating the specified parameters in real time and can be used in the on-board computer of automated / automatic control systems. The obtained results are explained by finding and using the integral functions of the given forces and torque, which for simple hull shapes are reduced to analytical solutions. The results are reproducible and can be used in the development of mathematical support for the on-board computer of automated / automatic vessel motion control systems. Further research may be related to the use of neural networks for evaluating hydrodynamic interaction.

Conclusions. The issues of the influence of the hull and cargo contours on the hydrodynamic and aerodynamic forces and torques are considered. Integral functions for determining the resulting lateral force, the resulting yaw torque and the arm of the resulting lateral force are obtained, depending on the angle of incidence of the flow and the shape of the hull contours. The values of the integral functions are calculated for simple hull contours and a numerical calculation is performed for an elliptical hull contour. It is established that the resulting torque and the arm of the resulting lateral force do not depend on the angle of incidence of the flow for hull contours in which the derivative of the contour is constant along the length of the hull. Compared with known approaches to determining the hydrodynamic and aerodynamic interaction of the vessel hull with the environment, the obtained results allow: to calculate the resulting lateral force, arm of resulting lateral force and resulting yaw torque more accurately using simple mathematical models that can be used in the automated / automatic control system.

The theoretical significance of the results obtained is: obtaining integral functions for determining the resultant lateral force, the resultant yaw torque and the resultant lateral force arm, depending on the angle of attack of the flow and the shape of the hull contours; calculating the value of integral functions for simple hull contours.

The practical significance of the results obtained is the possibility of their use for calculating the resultant lateral force, the arm of resultant lateral force and the resultant torque in the mathematical model of the on-board computer automated / automatic vessel motion control system in real time.

REFERENCES

1. Zhang, X., Ding, F. (2020). Adaptive parameter estimation for a general dynamical system with unknown states, International Journal of Robust and Nonlinear Control. https://doi.org/10.1002/rnc.4819.

2. Kliuiev, O., Sadovoi, O., Serhiienko, S., Sokhina, Yu. (2022). Vykorystannia filtra Kalmana yak sposterihacha stanu u vektornii systemi keruvannia asynkhronnoiu mashynoiu, Elektroenerhetyka, elektrotekhnika ta elektromekhanika. https://doi.org/10.32782/1995-0519.2022.5.

3. Ivaniuk, M. A., Pyskunov, S. O. (2021). Kontroler tysku dlia pnevmatychnoho halma na osnovi filtra Kalmana, Innovatsii molodi v mashynobuduvanni, Vol. 3. https://doi.org/10.20535/2708-3926.2021.3.229206.

4. Zinchenko, S. N., Lyashenko, V. G. (2017). Ispol'zovanie nejrosetevoj modeli sudna dlya resheniya zadach upravleniya, Naukovij visnik HDMA №2 (17), c. 231–237. http://journals.ksma.ks.ua/nvksma/article/view/587/524.

5. Zinchenko, S. N., Lyashenko, V. G., Shalaeva, A. A. (2017). Ocenka manevrennyh vozmozhnostej sudna s pomoshch'yu nejrosetevoj modeli, sinteziruemoj v processe ego shtatnoj ekspluatacii, Materiali IV MNPK «Bezpeka zhittediyal'nosti na transporti a virobnictvi: osvita, nauka, praktika», Herson, 14–16 veresnya 2017 r., s. 236–240.

6. Zinchenko, S. N., Lyashenko, V. G., Grosheva, O. A. (2018). Sintez optimal'nogo upravleniya sudnom s granichnymi usloviyami, Naukovij visnik HDMA №1(18). http://journals.ksma.ks.ua/nvksma/article/view/502/440.

7. Kulikov, D. O., Kupina, O. A., Loriia, M. H., Tselishchev, O. B (2022). Vykorystannia matematychnoi modeli dlia optymizatsii dynamichnykh parametriv protsesiv vyrobnytstva amiaku, Visnyk skhidnoukrainskoho natsionalnoho universytetu im. V. Dalia. https://doi.org/10.33216/1998-7927-2022-275-5-49-54.

8. Zinchenko, S. N., Lyashenko, V. G., Shalaeva, A. A. (2017). Raschet i realizaciya manevra raskhozhdeniya s sudami celyami v bortovoj CVM, Materiali IV MNPK «Bezpeka zhittediyal'nosti na transporti ta virobnictvi: Osvita, nauka, praktika», Herson, 14–16 veresnya 2017 r., s. 230–235.

9. Ayub, F. A, Furukawa, Y. (2020). Prediction of Hydrodynamic Forces Acting on Wigley Hull based on SQCM, IOP Conference Series Earth and Environmental Science, 557(1):012015, September 2020. https://doi.org/10.1088/1755-1315/557/1/012015.

10. Kryvyi, O., Miyusov, M. (2019). The Creation of Polynomial Models of Hydrodynamic Forces on the Hull of the Ship with the help of Multi- factor Regression Analysis, 8-th International Maritime Science Conference (IMSC), Budva, Montenegro.

11. Gokulakrishnan, M., Jebin, S., Kumar, A., Vijayakumar, R. (2022). Numerical prediction of hydrodynamic forces and moments of KCS in shallow water, Conference: OCEANS 2022 – Chennai. https://doi.org/10.1109/OCEANSChennai45887.2022.9775441.

12. Bitiukov, M. A., Herasymov, K. D., Kyrylov, P. A., Chystiakov, R. S. (2022). Zastosuvannia chyselnykh metodyk dlia otsinky vplyvu nepriamostinnosti korpusu sudna na velychynu khvylovykh navantazhen, Pratsi Krylovskoho derzhavnoho naukovoho tsentru S-I (1), 98–101 https://doi.org/10.24937/2542-2324-2022-1-S-I-98-101.

13. Davydov, I., Pecheniuk, A. (2023). Doslidzhennia vplyvu formy nosovoi chastyny sudna na yoho opir v umovakh tykhoi vodi ta khvyliuvannia, Visnyk Odeskoho natsionalnoho morskoho universytetu. https://doi.org/10.47049/2226-1893-2023-3-7-20.

14. Chureev, E. A., Romanyuta, D. A., Belousov, V. A., Nikolaev, I. I. (2022). Obosnovanie i vybor osnovnyh harakteristik malogo rybolovnogo sudna s bol'shoj polnotoj korpusa, Izvestiya KGTU. https://doi.org/10.46845/1997-3071-2022-67-71-86.

15. Begovic, E., Panahi, S., Rinauro, B., Rosano, G. (2023). Determination of Hydrodynamic Maneuvering Coefficients of a Planing Hull Using CFD with the Aid of SDT, Progress in Marine Science and Technology, Vol. 7, 65–77. https://doi.org/10.3233/PMST230010.

16. D'omin, S. I., Zhukov Ye. I., Kubachov M. O. ta in. (1991). Keruvannya sudnom: Navchal'nyy posibnyk dlya VNZ. Pid redaktsiyeyu Snopkova V. I., 359 s.

Зінченко С., Калініченко Є., Козачок Ю., Матейчук В. ВПЛИВ КОНТУРІВ КОРПУСУ ТА ВАНТАЖУ НА БІЧНУ СИЛУ І МОМЕНТ РИСКАННЯ В СИСТЕМАХ КЕРУВАННЯ СУДНОМ У РЕАЛЬНОМУ ЧАСІ

Важливим елементом математичного забезпечення бортового обчислювача є математична модель судна, використання якої дозволяє суттєво підвищити якість системи керування. Математичні моделі використовуються для прогнозування руху об'єкта керування, спостереження за параметрами вектора стану системи, недоступних прямому вимірюванню, у тому числі в шумах, визначення відмов командних та виконавчих пристроїв, вирішення оптимізаційних задач тощо. Метою дослідження є визначення результуючої бокової сили і моменту, а також плеча результуючої бокової сили, залежно від кута набігання потоку та форми корпусу, підвищення точності розрахунків керувань із використанням уточненої математичної моделі, підвищення ефективності системи керування та безпеки судноплавства в цілому. Отримані інтегральні функції визначення результуючої бокової сили, результуючого моменту рискання та плеча результуючої бокової сили, залежно від кута набігання потоку та форми обводів корпусу. Розраховані значення інтегральних функцій для простих обводів корпусу. У порівнянні із відомими підходами до визначення гідродинамічної та аеродинамічної взаємодії корпусу судна з оточуючим середовищем, отримані результати дозволяють: значно точніше оцінювати зовнішні впливи із використанням простих математичних моделей, які можна застосовувати у бортовому обчислювачі системи керування у реальному часі. Отримані результати пояснюються знаходженням та використанням інтегральних функцій визначення результуючої бокової сили, результуючого моменту та плеча результуючої бокової сили, які для простих форм корпусу зводяться до аналітичних рішень. Результати є відтворюваними і можуть використовуватися в математичній моделі автоматизованої системи керування рухом судна в реальному часі.

Ключові слова: *інтелектуальні системи керування транспортом; людський чинник; навігаційна безпека; математична модель; плече бокової сили; енергоефективність.*

Статтю прийнято до редакції 06.12.2024