Control of the Pivot Point Position of a Conventional Single-Screw Vessel

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Abstract

The issues of using the pivot point concept for the control of a conventional single-screw vessel are considered. The relevance of the task lies in the need for a more accurate assessment of the vessel's trajectory and the necessary area for maneuvering, since conventional single-screw vessels have low maneuverability, and their share in the total number of vessels exceeds 85%. For manual maneuvering of the vessel, using the pivot point, it is important to know the position of the pivot point relative to a fixed point of the vessel's hull. Traditionally, this point was the gravity center/middle frame of the vessel. The disadvantage of the existing approaches to the calculation of the pivot point position was the use of a simplified calculation scheme "gravity center – pivot point", which did not take into account the dependence of the pivot point position on the rotation center position. In previous works, the authors of this article proposed the "gravity center – rotation center – pivot point" calculation scheme, which made it possible to more accurately estimate the pivot point position, taking into account the position of the rotation center. In the refined scheme proposed by the author, the pivot point position was determined relative to the moving rotation center, which is not convenient for manual control. In this article, for a single-screw conventional vessel, a formula and graphs of pivot point position relative to a fixed point on the vessel's hull (gravity center/middle frame) are obtained, for the refined calculation scheme "gravity center – rotation center – pivot point". The obtained formulas and graphs of the pivot point position relative to a fix point (gravity center/middle frame) allow us to use them both for automatic and manual control of the vessel's movement. Mathematical modeling of a single-screw conventional vessel movement in the closed circuit "Control object – Control system" was carried out for the two considered calculation schemes. The simulation results showed that the use of the refined calculation schem allows for a 23% more accurate assessment of the vessel's trajectory and the required maneuvering area.

Keywords

Navigation safety, human factor, pivot point, center of rotation, maneuvering area, automated system

1. Introduction

Over the past decades, the number and dimensions of vessels have grown at a much faster rate than the size of ports, as a result of which ports have become "crowded". There was an urgent need to create methods of managing ships in ports, narrows and other limited waters, which would allow reducing the area of maneuvering. One of the effective directions for solving this problem is the use of the concept of the pivot point – an alternative view of the processes of controlling the vessel's rotation. A simple

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deflection of the stern leads to the appearance of a lateral force and a moment from the stern. Under the action of this force and moment, the vessel receives simultaneously the lateral speed V_y and the angular speed of rotation ω_z in the yawing channel. It is obvious that there is always a point on the longitudinal axis OX1 of the vessel, at a distance R from the rotation center, at which the sum of the lateral velocity V_y of the rotation center and the tangential velocity $V_\tau = \omega_z R$ from the rotation of the vessel is zero

$$V_y + \omega_z R = 0. \tag{1}$$

This special point at a distance R from the rotation center is called the pivot point (PP). The use of pivot point allows two movements of the vessel, lateral and rotational around the rotation center to be replaced by one rotational movement around the PP. This replacement significantly simplifies the representation of the vessel's movement and allows to optimize the processes of controlling the vessel's rotation.

In article [5] author proposed to use a vector equation instead of the scalar equation (1)

$$V + \omega \mathrm{x} R = 0, \tag{2}$$

where $\boldsymbol{V}$ is the linear velocity vector of the vessel, $\boldsymbol{\omega}$ is the angular velocity vector of the vessel, $\boldsymbol{R}$ is the position vector of the PP in the linked coordinate system (LCS).

After opening the vector equation (2), the author obtained the projections of the vector $\boldsymbol{R} = (R_x, R_y, R_z)$ on the LCS axis. For practical maneuvering, the vessel's longitudinal speed V_x, lateral speed V_y, and yawing angular speed ω_z are of greatest importance. In this case, the applicate $R_z = 0$, and the abscissa R_x and the ordinates R_y of the vector $\boldsymbol{R}$ are determined by the following equations

$$\begin{cases} R_x = -\dfrac{V_y}{\omega_z} \\ R_y = \dfrac{V_x}{\omega_z} \end{cases} \tag{3}$$

Figure 1 shows the geometric interpretation of the abscissa R_x and the ordinate R_y of the PP

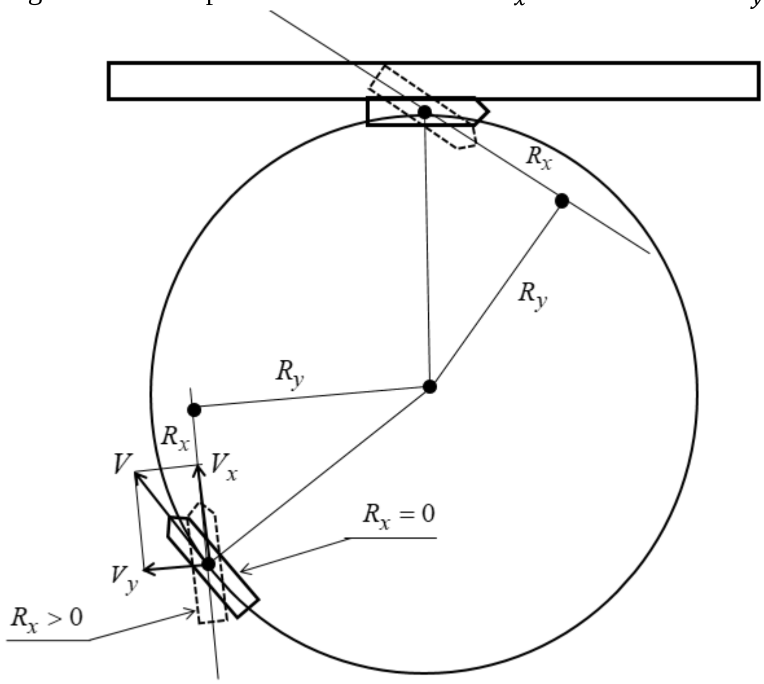

Figure 1: The abscissa and ordinate of the pivot point

As can be seen from Figure 1, the abscissa and ordinate of PP in LCS determine the position of turning circle center and the radius of turning circle

$$R_{cir} = \sqrt{R_x^2 + R_y^2}. \tag{4}$$

It can be seen from equation (4) that the turning circle of the vessel with the same radius of turning circle R_{cir} can be carried out for different sets of values R_x and R_y. The abscissa R_x and the ordinate R_y of the PP determine the position of the vessel in turning circle. Since the vessel's speed vector is always tangential to the turning circle (see Figure 1), for the abscissa of the pivot point $R_x > 0, V_y < 0$ and the vessel's nose is turned inside the turning circle. For the abscissa of the pivot point $R_x < 0, V_y > 0$ and the nose of the vessel is turned outside the turning circle. In these cases, the vessel moves with a drift angle, which increases the width of the traffic lane and the maneuvering area. Of practical interest is the case $R_x = 0$, when the diametrical plane of the vessel is oriented tangentially to the turning circle and the vessel moves without a drift angle. This motion can also be used to moor without the bow or stern hitting the mooring wall. Controlling the position of the vessel in turning circle is possible only in the presence of sufficient or excess control [12-15]. Vessels with a number of controls less than 3, which include conventional single-screw vessels, are always oriented with the nose into the turning circle and move with a drift angle. This is explained by the fact that the lateral force from the rotation of the propeller and the deflection of the rudder in such vessels are always applied in the stern and abscissa of pivot point $R_x > 0$. For such vessels, we can only talk about the minimization of the drift angle, the lane of the vessel and the maneuvering area, provided that the restrictions on the longitudinal movement speed are met.

The purpose of the research is to develop a method, algorithm and software for the automatic control module of a single-screw conventional vessel in compressed waters, which will allow to reduce deviation errors from the predicted trajectory of movement and the area of maneuvering of the vessel, to reduce the influence of the human factor on control processes and to increase the safety of navigation.

The task of the research is: analysis of literary sources dedicated to the problem of reducing the maneuvering area in compressed waters; development of the maneuvering method taking into account the refined scheme for calculating the pivot point position "Gravity center – Rotation center – Pivot point"; obtaining a linearized model of the steady motion of a single-screw conventional vessel in the control channels, taking into account the refined scheme for calculating the pivot point position; calculation of the pivot point position relative to a fixed point on the vessel's hull, for use during manual maneuvering; confirmation of the workability and effectiveness of the developed method, algorithmic and software by mathematical modeling in the MATLAB environment.

2. Related works

Many works by various authors are devoted to the study of automation issues and the use of a pivot point to optimize control processes.

In particular, in the book by Henry H. Hooyer [1], chapter 1, is devoted to the use of the pivot point for maneuvering the vessel. The author writes that for a vessel standing in the water, the pivot point is always on the opposite side from the middle frame of the vessel, relative to the applied lateral force of the rudder or other lateral force. For a vessel moving in water, the rotation center is additionally shifted in the direction of the vessel's movement. The author supports this conclusion with the example of two tugboats pushing the vessel with a log. The author also analyzes the influence of wind, trim, lateral force from the rotation of the propeller and the deflection of the rudder on the position of the pivot point.

In the article [2], the author considered an approximation method for calculating the position of the pivot point, which is based on the equations of steady motion of the linearized vessel model in the channels of lateral and angular motion (sway-yaw equations). According to the author, the position of the pivot point depends on the ratio of the sensitivity coefficients of the lateral force and moment to the deflection of the rudder, which can be calculated using six coefficients of the linearized model. Numerical simulation results confirmed that the estimation of the pivot point position using the linearized model correlates well with the estimations obtained for the full mathematical model of the channels of lateral and angular movements. The existence of similarity between the lateral speed and the angular speed of movement, known as the reduction effect in the turning maneuver (in the formula for determining the position of the pivot point, the applied lateral force is reduced), significantly expands the possibilities of applying the proposed approach using the assumption of steady motion. In other words, the ratio of lateral velocity to angular velocity, which determines the position of the pivot point, reaches a constant value long before the steady motion of the vessel itself begins.

In the article [3] the author describes experiments being carried out for shipmasters at the training center in Port Revel, France, to study the behavior of a vessel's pivot point. Bow and stern thrusters are used to simulate tugboats, which push the vessel bodily. As soon as the vessel acquires even an insignificant longitudinal speed, it begins to rotate, which is explained by the author by the change of shoulders from the thrusters to the rotation center. The author notes that this effect can be used in practice, namely, to turn around the center of gravity, the vessel needs to be stopped, to increase the steering moment, the vessel needs to accelerate, and to reduce the steering moment, the vessel needs to be braked, or even reversed. The author also extends the experience gained in the port of Revel to sailing vessels.

Article [4] is one of the most important works in the theory of the pivot point. Using the example of a vessel backing out of a dock, the author explains that the traditional theory of the pivot point is incorrect. According to this theory, the vessel, after deflecting the rudder, should rotate around the pivot point, which is shifted to the stern, and safely leave the dock. But in practice, the vessel leans against the wall of the dock. The author explains this by the fact that after the rudder deflection, in addition to the moment, a lateral force is also created, which leads to simultaneous lateral and rotational movement. The author replaces the sum of these two movements with one rotational movement around another point - the pivot point. And this point is located in the bow of the vessel, which explains the leaning of the vessel on the wall of the dock. The author also formulates the concept of the center of lateral resistance (COLR) as the point of application of the resulting lateral hydrodynamic force and indicates that the position of the COLR depends on the center of gravity, the center of the underwater surface and the pressure field around the vessel. If the vessel has no speed, the COLR is between the center of gravity and the center of the underwater part of the vessel. If there is speed, the COLR shifts in the direction of the vessel's movement and the amount of such a shift does not exceed 10% of the vessel's length. The reason for COLR mixing is the redistribution of the pressure field around the vessel. The COLR is the fulcrum for the levers (center of rotation) and is not a pivot point.

In the work [5] the author uses a vector equation to determine the position of the pivot point, which makes it possible to obtain the vector of the pivot point position in space through 3 linear and 3 angular velocities of the vessel. For practical maneuvering, it is enough to take into account only the longitudinal, lateral and angular (in the yawing channel) speed, and the pivot point, in this case, will be located in the plane of the local horizon and determined by the abscissa and ordinate of the pivot point. A simplified mathematical model of the vessel was considered and the values of the abscissa, ordinate, and modulus of the pole position vector due to the components of the external force in the projections on the linked coordinate system axis were determined.

In the dissertation work [6] has been developed: a method for calculating the pivot point's abscissa for any arbitrary maneuver of the vessel; a method of calculating the dimensions of the water area occupied by the turning vessel using the pivot point's abscissa; a method of approximate determination of the pivot point's abscissa for river vessels and vessels of mixed navigation, which allows taking into account trim. The use of the pivot point's abscissa as a normalizing parameter of the vessel's turning speed is substantiated.

In the article [7], the author gives three important centers of the vessel rotation: the center of turning circle E, the physical center of the vessel rotation S and the pivot point P (imaginary center of rotation), which is the projection of the turning circle center on the longitudinal axis of the vessel. Examples of pivot point placement for various vessel movements are given: pure rotational movement around the rotation center S (yaw only); rotational movement around the rotation center S and lateral movement (Yaw+Sway); rotational movement around the rotation center S and longitudinal movement (Yaw+Surge); rotational movement around the rotation center S, lateral and longitudinal movements (Yaw+Sway+Surge).

In the article [8], the author introduces the term "pivot point concept" – an alternative, to the classical theory, vision of the vessel's rotation processes. The use of the provisions of the pivot point concept has been considered for several practical cases of conventional single-screw vessel maneuvering: minimization of the turning area; docking; reversal of a large vessel in the port.

In work [9], the issues of using machine learning for clustering, classification and outlier detection of sea vessels trajectories in the port area were considered. Grouping trajectories into clusters of similar behavior can help gain an overall picture of vessel movement patterns and help the operator spot irregular movements. Detecting trajectories of irregular behavior among a large group of normal trajectories is the task of outlier detection. A similarity-based approach is used to solve the problems of clustering, classification, and outlier detection, which is well suited to the nature of ship trajectories and moving objects in general. The method of trajectories outlier detection developed by the authors makes it possible to increase the safety of navigation.

In the article [10], the author proposed a system for forecasting the ship's maneuver using neuro-evolution – a process of continuous learning of an autonomous control unit created using an artificial neural network. The control unit monitors the input signals of motion sensors and calculates the parameters of the maneuvering vessel model necessary for forecasting. The prediction result is transmitted to the navigator to warn of possible dangers.

In work [11], the question of increasing the accuracy of predicting the movement of the vessel due to the integration of the vessel model and the machine learning (ML) module in the dynamic model of the vessel is considered. The ML module is used as a compensator for vessel model inaccuracies and allows to increase the amount of predefined knowledge about the vessel's movement, reduces the black box factor that usually occurs in forecasting. The predicted time is calculated to be 30 s, which is less than the actual time for docking operations. The proposed method was tested on the Research Vessel Gunnerus. The experiment showed that the inclusion of the ML module significantly increases the forecast accuracy.

The article [12] discusses the issues of automatic control of the vessel’s movement around the pivot point. A three-point scheme for determining the position of the pivot point has been proposed: "Center of gravity – Center of rotation – Pivot point", in which the pivot point is counted from the center of rotation, and not from the center of gravity, as was previously believed. The formula of the rotation center displacement relative to the gravity center, depending on the longitudinal speed of the vessel has been obtained. For the linearized model of the vessel, the final formulas for calculating the controls are obtained, which ensure the rotation of the vessel around the given position of the pivot point. The control area and control lines were built, the coefficient of distribution of controls between the executive devices of the vessel was investigated. The optimal control of the vessel rotation around the pivot point was considered.

In the works [13-15], other issues of using automatic control modules in automated system to solve functional problems have been also investigated: automatic route planning and automatic divergence [13]; automatic guidance of the optical axis of the CyScan measuring system to the center of the reflector, to increase the accuracy and reliability of the dynamic positioning system in case of strong side and keel sway [14]; automatic optimal control of the redundant structure of executive devices [15], etc.

In the works [16-18], the issues of the strength of vessel hulls, the creation of materials resistant to corrosion and those that can withstand large loads, and the prediction of the type and size of damage, depending on the direction of application of external forces and moments, have been considered. The results obtained by the authors of the works can be taken into account in the algorithms of automatic control when maneuvering a vessel in compressed waters, in order to minimize damage in the event of a collision.

3. Materials and methods

The object of research is the control processes of a single-screw conventional vessel using a pivot point. The research used a systematic approach, analysis and synthesis, methods of automatic control theory, solid body mechanics, aerodynamics and hydrodynamics, differential calculus, mathematical analysis, programming and mathematical modeling. Equipment was also used: a personal computer with the Windows 10 operating system and the Microsoft Office 2016 application package, the MATLAB-2019 environment with integrated application program libraries and specialized software developed by the authors: the program manager disp12.m, the complete mathematical model of the vessel ship12. m, Runge-Kuta numerical integration method runge12.m, external influences meteo.m, sensors for measuring ship movement parameters sensor.m, automatic control sysctr12.m etc.

4. Results

The control scheme of a conventional single-screw vessel is shown in Fig. 2.

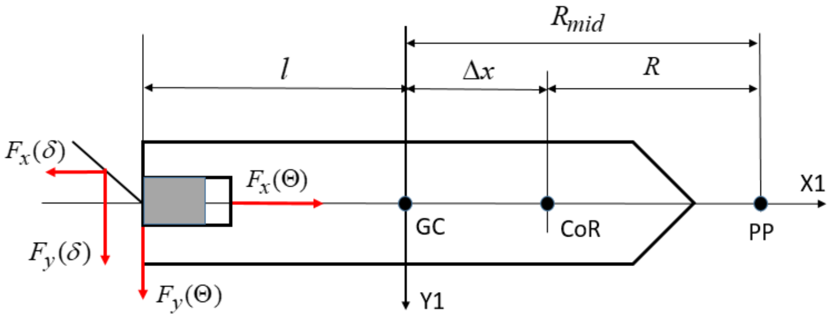

Figure 2: Control scheme of a conventional single-screw vessel

The diagram shows: linked coordinate system OX1Y1Z1, gravity center GC, rotation center CoR, pivot point PP. The telegraph deflection Θ of the power plant leads to a change in revolutions (or the pitch of the propeller), which creates the propeller force $F_x(\Theta)$, lateral force $F_y(\Theta)$ and yaw moment $M_z(\Theta) = -F_y(\Theta)(l + \Delta x)$ relative to the rotation center . Rudder deflection δ leads to the creation of a lateral force $F_y(\delta)$, a yaw moment $M_z(\delta) = -F_y(\delta)(l + \Delta x)$ relative to the rotation center and additional resistance force $F_x(\delta)$ from the deflection δ of the rudder.

The linearized model of longitudinal, lateral and angular movements can be written as

$$\begin{cases} m\dot{V}_x = \frac{\partial P_x}{\partial \Theta}\Theta - \frac{\partial F_x}{\partial \delta}\delta - \frac{\partial F_x}{\partial V_x}V_x \\ m\dot{V}_y = \frac{\partial P_y}{\partial \Theta}\Theta + \frac{\partial F_y}{\partial \delta}\delta - \frac{\partial F_y}{\partial V_y}V_y \\ I_z\dot{\omega}_z = -\frac{\partial P_y}{\partial \Theta}\Theta(l + \Delta x) - \frac{\partial F_y}{\partial \delta}\delta(l + \Delta x) - \frac{\partial M_z}{\partial \omega_z}\omega_z \end{cases}, \tag{5}$$

where m is the mass of the vessel, I_z is the vessel inertia moment in the yawing channel, $\frac{\partial P_x}{\partial \Theta}$ is the sensitivity coefficient of the propeller thrust force $P_x(\Theta)$ to the telegraph deflection angle Θ, $\frac{\partial P_y}{\partial \Theta}$ is the sensitivity coefficient of the lateral force $P_y(\Theta)$ from the screw rotation to the telegraph deflection angle Θ, $\frac{\partial F_x}{\partial \delta}$ is the sensitivity coefficient of the additional resistance force $F_x(\delta)$ to the steering deflection angle δ, $\frac{\partial F_y}{\partial \delta}$ is the sensitivity coefficient of the lateral force $F_y(\delta)$ to the angle of the rudder deflection δ, $\frac{\partial F_x}{\partial V_x}$ is the sensitivity coefficient of the longitudinal resistance force of the hull $F_x(V_x)$ to the longitudinal speed of the vessel V_x, $\frac{\partial F_y}{\partial V_y}$ is the coefficient of sensitivity of the hull lateral resistance force $F_y(V_y)$ to the lateral speed of the vessel V_y, $\frac{\partial M_z}{\partial \omega_z}$ is the sensitivity coefficient of the hull resistance moment $M_z(\omega_z)$ to the angular rate of the vessel rotation ω_z, l is the shoulder from the rudder and the propeller to the middle frame, Δx is the rotation center displacement relative to the gravity center, depending on the longitudinal speed of the vessel.

For steady motion of the vessel $\dot{V}_x = 0$, $\dot{V}_y = 0$, $\dot{\omega}_z = 0$ and system (5) will take the form

$$\begin{cases} \frac{\partial P_x}{\partial \Theta}\Theta - \frac{\partial F_x}{\partial \delta}\delta - \frac{\partial F_x}{\partial V_x}V_x = 0 \\ \frac{\partial P_y}{\partial \Theta}\Theta + \frac{\partial F_y}{\partial \delta}\delta - \frac{\partial F_y}{\partial V_y}V_y = 0 \\ -\frac{\partial P_y}{\partial \Theta}\Theta(l + \Delta x) - \frac{\partial F_y}{\partial \delta}\delta(l + \Delta x) - \frac{\partial M_z}{\partial \omega_z}\omega_z = 0 \end{cases} \tag{6}$$

Let us find the longitudinal and lateral linear velocities, as well as the angular velocity of the steady motion of the vessel from system (6)

$$\begin{cases} V_x = \frac{\partial V_x}{\partial F_x}\left(\frac{\partial P_x}{\partial \Theta}\Theta - \frac{\partial F_x}{\partial \delta}\delta\right) \\ V_y = \frac{\partial V_y}{\partial F_y}\left(\frac{\partial P_y}{\partial \Theta}\Theta + \frac{\partial F_y}{\partial \delta}\delta\right) \\ \omega_z = \frac{\partial \omega_z}{\partial M_z}\left(-\frac{\partial P_y}{\partial \Theta}\Theta(l+\Delta x) - \frac{\partial F_y}{\partial \delta}\delta(l+\Delta x)\right) \end{cases} \tag{7}$$

Substitute the equation of system (7) into the first and second equations of system (3) to determine the pivot point abscissa R_x and ordinate R_y.

$$\begin{cases} R_x = -\frac{V_y}{\omega_z} = -\frac{\frac{\partial V_y}{\partial F_y}\left(\frac{\partial P_y}{\partial \Theta}\Theta + \frac{\partial F_y}{\partial \delta}\delta\right)}{\frac{\partial \omega_z}{\partial M_z}\left(-\frac{\partial P_y}{\partial \Theta}\Theta(l+\Delta x) - \frac{\partial F_y}{\partial \delta}\delta(l+\Delta x)\right)} = \frac{\partial V_y}{\partial F_y}\frac{\partial M_z}{\partial \omega_z}\frac{1}{(l+\Delta x)} \\ R_y = \frac{V_x}{\omega_z} = \frac{\frac{\partial V_x}{\partial F_x}\left(\frac{\partial P_x}{\partial \Theta}\Theta - \frac{\partial F_x}{\partial \delta}\delta\right)}{\frac{\partial \omega_z}{\partial M_z}\left(-\frac{\partial P_y}{\partial \Theta}\Theta(l+\Delta x) - \frac{\partial F_y}{\partial \delta}\delta(l+\Delta x)\right)} = -\frac{\partial V_x}{\partial F_x}\frac{\partial M_z}{\partial \omega_z}\frac{1}{(l+\Delta x)}\frac{\left(\frac{\partial P_x}{\partial \Theta}\Theta - \frac{\partial F_x}{\partial \delta}\delta\right)}{\left(\frac{\partial P_y}{\partial \Theta}\Theta + \frac{\partial F_y}{\partial \delta}\delta\right)} \end{cases} \tag{8}$$

As can be seen from the first equation (8), the pivot point abscissa does not depend on the controls Θ and δ, but depends only on the hydrodynamic characteristics of the vessel's hull and the arm $(l + \Delta x)$ of the lateral control forces to the center of rotation. The pivot point ordinate depends on controls Θ and δ, hydrodynamic characteristics of the vessel's hull and arm $(l + \Delta x)$.

Since the pivot point position is calculated from the rotation center, which also shifts, depending on the vessel speed, it is important to know the movement of the pivot point relative to a fixed point on the vessel's hull, for example, the middle frame. As can be seen from Figure 2, this distance is equal to

$$R_{mid} = \Delta x + R_x \tag{9}$$

After substituting equation (8) into equation (9), we get

$$R_{mid} = \Delta x + \frac{\partial V_y}{\partial F_y}\frac{\partial M_z}{\partial \omega_z}\frac{1}{(l+\Delta x)} \tag{10}$$

Let us write equation (10) in relative values

$$\bar{R}_{mid} = \overline{\Delta x} + \frac{\partial V_y}{\partial F_y}\frac{\partial M_z}{\partial \omega_z}\frac{1}{L^2}\frac{1}{(\bar{l}+\overline{\Delta x})}, \tag{11}$$

where $\bar{R}_{mid} = \frac{R_{mid}}{L}$ is the relative position of the pivot point, $\overline{\Delta x} = \frac{\Delta x}{L}$ is the relative displacement of the rotation center, $\bar{l} = \frac{l}{L}$ is the relative shoulder of the rudder and the propeller to the middle frame.

Displacement rotation center relative to the gravity center can be calculated using the formula

$$\Delta x = \frac{L}{2}\left(1 - \frac{V_{max}}{\eta V_x + V_{max}}\right) \tag{12}$$

or in relative quantities

$$\overline{\Delta x} = \frac{1}{2}\left(1 - \frac{1}{\eta \bar{V}_x + 1}\right) = \frac{1}{2}\left(\frac{\eta \bar{V}_x}{\eta \bar{V}_x + 1}\right) \tag{13}$$

where $\bar{V}_x = \frac{V_x}{V_{max}}$ is the reduced longitudinal speed of the vessel, $\eta = \frac{2\xi}{1-2\xi}$, ξ is the coefficient determined by the ratio of the rotation center maximum displacement to the vessel length.

Equations (11) and (13) determine the dependence $\bar{R}_{mid} = f(\bar{V_x})$.

Figure 3 shows the dependence of the rotation center position $\overline{\Delta x}$ relative to the middle frame, the pivot point position $\bar{R}_x$ relative to the rotation center and the pivot point position $\bar{R}_{mid}$ relative to the middle frame on the reduced longitudinal speed of the vessel $\bar{V_x}$. As can be seen from the graphs, when the vessel's speed increases, the position of the rotation center $\overline{\Delta x}$ shifts forward, and the position of the pivot point $\bar{R}_x$ relative to the rotation center $\bar{R}_x$ shifts back. This leads to the fact that the sum of these movements $\bar{R}_{mid}$ (pivot point displacement relative to the gravity center/middle frame) varies in a much smaller range.

So, for the entire range of forward speeds, the pivot point position relative to the middle frame is within $R_{mid} = (0{,}25 - 0{,}4)L$, and for the entire range of reverse speeds, the pivot point position relative to the middle frame is within $R_{mid} = (0{,}2 - 0{,}25)L$. The pivot point is always within the vessel's hull, forward of the middle frame. The shortest distance between the pivot point and the middle frame is achieved at the reverse speed $V_x = -0{,}5V_{max}$ and is about $R_{mid} = 0{,}2L$.

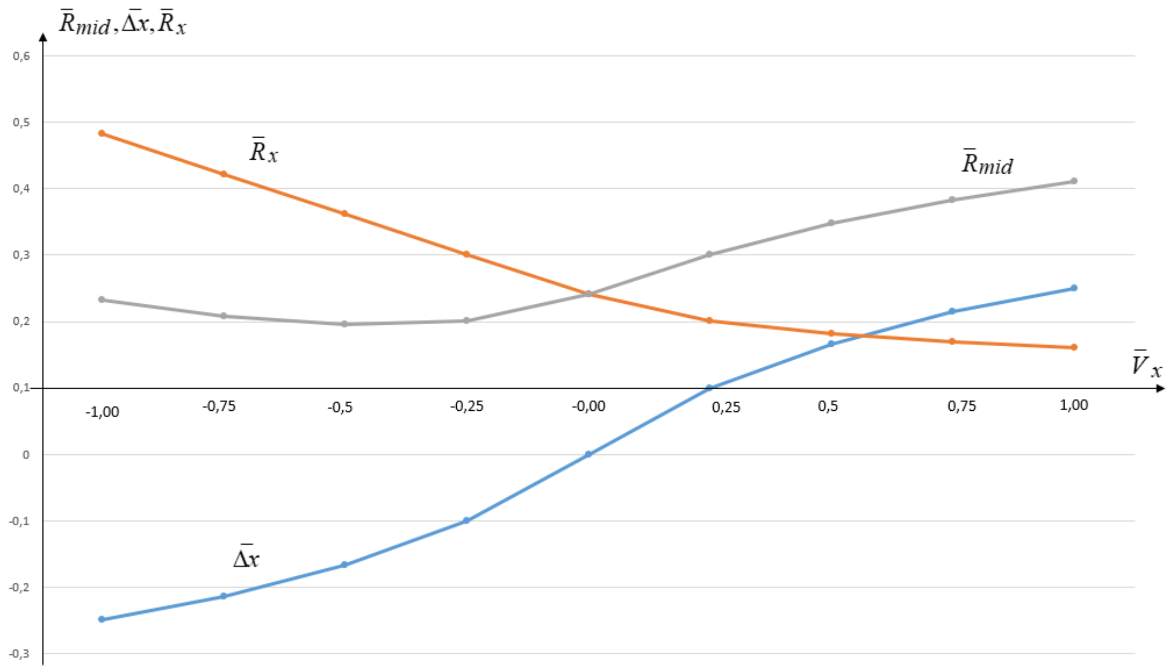

Figure 3: Dependence $\bar{R}_{mid}, \overline{\Delta x}, \bar{R}_x$ on the reduced longitudinal speed of the vessel

4.1. Experiment

Figures 4,5 present the results of mathematical modeling in the Matlab environment.

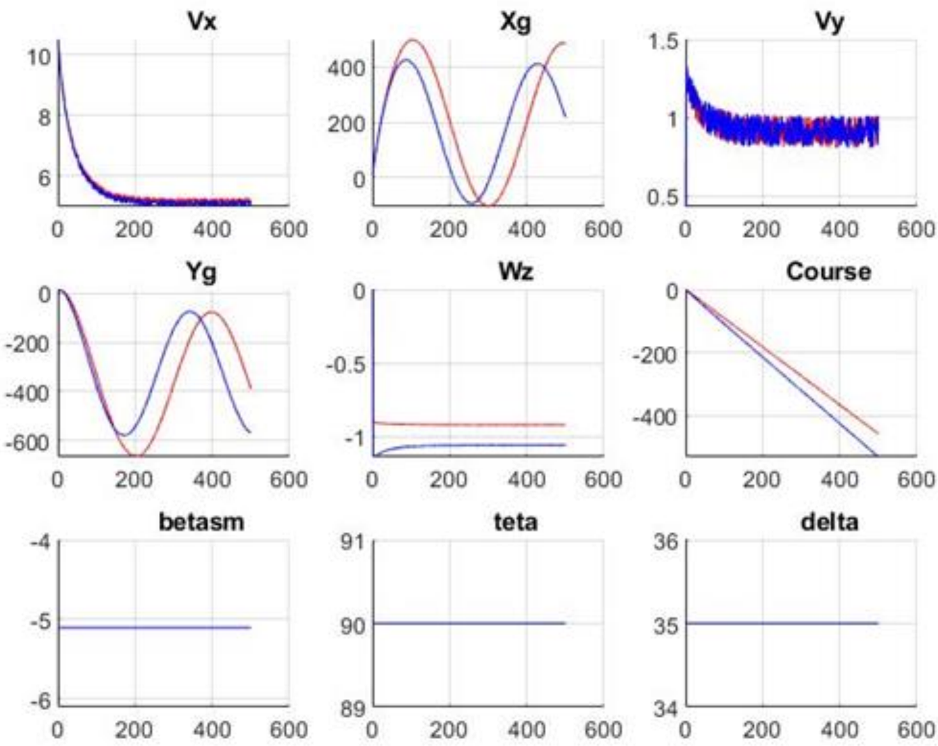

Figure 4: Graphs of changes over time of the single-screw vessel's movement parameters in turning circle: blue color – taking into account the rotation center displacement, red color – without taking into account the rotation center displacement

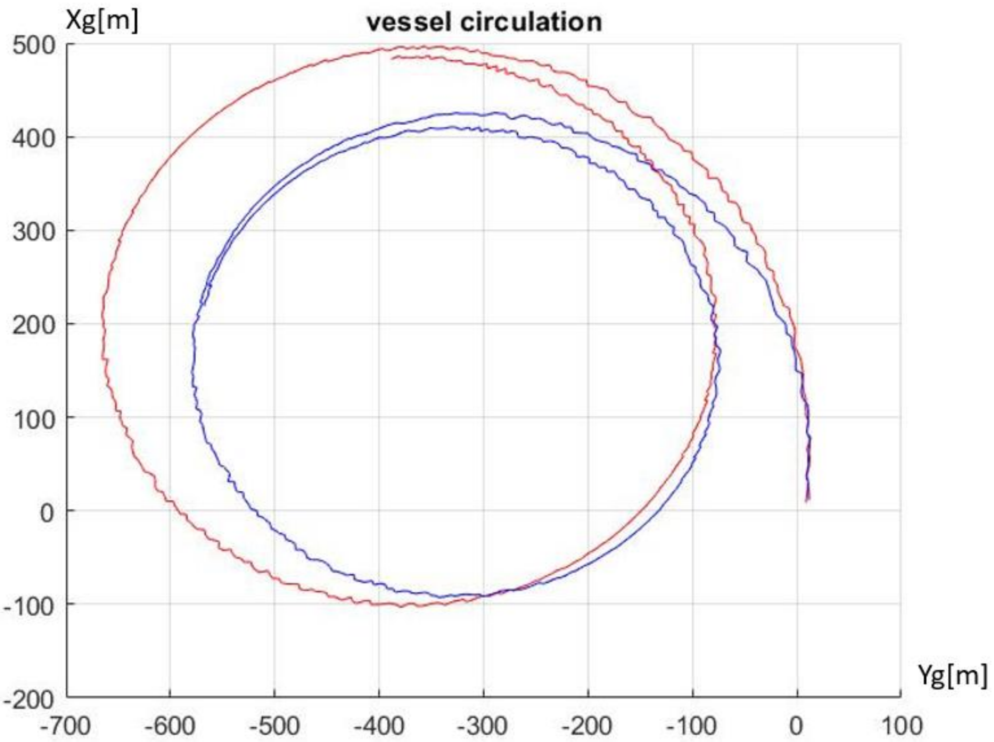

Figure 5: Turning circles of the conventional single-screw vessel: blue color – taking into account the rotation center displacement, red color – without taking into account the rotation center displacement

In the given graphs: $\mathrm{V_x}\,[\mathrm{m/s}]$ is the longitudinal speed of the vessel, $\mathrm{X_g}\,[\mathrm{m}]$ is the longitudinal displacement of the vessel, $\mathrm{V_y}\,[\mathrm{m/s}]$ is the lateral speed of the vessel, $\mathrm{Y_g}[\mathrm{m}]$ is the lateral displacement of the vessel, $\omega_z[\mathrm{dg/s}]$ is the yaw rate, $\mathrm{Course[dg]}$ is the vessel's course, $\mathrm{betasm[dg]}$ is the drift angle, $\mathrm{teta[dg]]}$ is the telegraph deflection angle, $\mathrm{delta[dg]}$ is the stern deflection angle.

Figure 4 presents the graphs of changes over time in the single-screw vessel's movement parameters in turning circle, obtained taking into account the displacement of the rotation center, are marked in red, and those obtained without taking into account the displacement of the rotation center, are marked in blue.

Figure 5 presents the turning circles of the conventional single-screw vessel, obtained taking into account the displacement of the rotation center, are marked in red, and those obtained without taking into account the displacement of the rotation center, are marked in blue.

As can be seen from the above results of mathematical modeling, the established diameter of the turning circle of conventional single-screw vessel without taking into account the rotation center displacement is 550m, and the established diameter of the turning circle of conventional single-screw vessel taking into account the rotation center displacement is 480m. The turning circle area, taking into account the rotation center displacement, decreased by 23%.

5. Discussion

The issues of automatic and manual control of the rotation of a single-screw conventional vessel around the pivot point are considered. The solution this problem is related to the need to clarify the trajectory of the vessel in turning circle and reduce the maneuvering area in ports and other restricted waters, since single-screw conventional vessels have low maneuverability, and their share in the total number of vessels exceeds 85%.

The known scheme "gravity center – pivot point" for calculating the pivot point position does not take into account the displacement of the rotation center relative to the gravity center/middle frame, which occurs when the speed of the vessel changes [1-8]. For the known scheme, the abscissa of the pivot point of a single-screw conventional vessel is practically independent of controls, which is not true.

In previous works [12], the authors proposed a refined scheme "gravity center – rotation center – pivot point" for calculating the pivot point position, which took into account the displacement of the rotation center and allowed to more accurately estimate the trajectory of the vessel and the maneuvering area. However, the position of the pivot point in the proposed scheme was determined relative to the rotation center (and not relative to a fixed point on the vessel's hull), which did not allow it to be used for manual control.

The use of machine learning techniques [9-11] to identify vessel characteristics, including the position of the rotation center and pivot point, has great promise in the future. However, the application of such methods requires significant computing power and time and can only be used in automatic vessel motion control systems. For conventional single-screw vessels, the use of such control systems is not economically feasible due to the significant difference between the capabilities of the executive devices structure and the capabilities of automatic control system.

In this article, a method of automatic and manual control of a single-screw conventional vessel using a pivot point has been developed, which allows to more accurately determine the position of the pivot point, the trajectory of the vessel and, due to this, to reduce the maneuvering area by 23%. This is achieved by using a refined scheme for calculating the pivot point position, taking into account the position of the rotation center. For the possibility of manual control, formulas were obtained and graphs were drawn that determine the pivot point position relative to a fixed point on the vessel's hull (gravity center/middle frame).

The obtained results can be applied to the manual or automatic control of a single-screw conventional vessel, provided that it is integrated into an automated system of an on-board controller with automatic rotation control module.

The obtained results are reproducible and can be used in practice both with manual control and with automatic control.

Further work may be related to the optimization of the maneuvering area based on the analysis of two components - the abscissa and the ordinate of the pivot point.

6. Conclusion

A method of controlling a single-screw conventional vessel using a pivot point has been developed.

Literary sources devoted to the study of the use of the pivot point for vessel maneuvering were analyzed.

Methods of automatic and manual control of a single-screw conventional vessel rotation around the pivot point have been developed, which allow to more accurately determine the turning circle trajectory and, due to this, to reduce the maneuvering area.

This is explained by the use of a scheme for calculating the pivot point position, which takes into account the displacement of the rotation center from the speed of the vessel.

For manual control, graphs are obtained that determine the pivot point position relative to a fixed point on the vessel's hull (gravity center/middle frame).

The workability and effectiveness of the developed methods were verified by mathematical modeling in the MATLAB environment.

The theoretical significance of the obtained result lies in the development of the automatic and manual control methods of a single-screw conventional vessel rotation around pivot point using a refined scheme for calculating the pivot point position.

The practical significance of the obtained result lies in the possibility of applying the developed methods for automatic and manual control of a single-screw conventional vessel rotation around the pivot point, more accurate prediction of the movement trajectory and, due to this, reducing the maneuvering area by 23%.

7. References

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