UDC 656.61.052:681.51
DOI: 10.15587/2706-5448.2022.269364

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DEVELOPMENT OF AUTOMATIC CONTROL METHODS OF VESSEL ROTATION AROUND THE PIVOT POINT WITHOUT DRIFT

The object of research is the processes of automatic control of the vessel rotation around the pivot point with zero drift. In recent years, the number of vessels and their sizes has increased significantly, while the size of ports has grown much more slowly. There is an urgent need to optimize control processes, especially in compressed waters. One of the directions of such optimization is the use of the pivot point concept – an alternative vision of the vessel movement during its maneuvering. It is shown that the circulation radius and the position of the vessel on circulation are determined by the pivot point abscissa and ordinate. Linearized models of the two most common control schemes are considered: the control scheme of a single-screw conventional vessel without a bow thruster and the control scheme of a single-screw conventional vessel with a bow thruster. For the steady state of each of these schemes, controls were obtained that ensure the circulation of the vessel around a pivot point position without drift angle. This makes it possible to reduce the width of the traffic lane, increase traffic safety, reduce hydrodynamic resistance and fuel consumption, create favorable conditions for carrying out technological operations, for example, mooring, and reduce the influence of the human factor on control processes. The workability and effectiveness of the developed methods were verified by mathematical modeling of the MSC Container Ship (Dis. 32025t) automatic mooring without drift angle on the imitation modeling stand created by the authors on the basis of the Navi Trainer 5000 navigation simulator. The obtained capabilities are explained by the use of the mathematical model of the vessel in the on-board controller of the automated system and modern mathematical apparatus. The developed methods can be used on the vessels, provided to integration into the existing automated system of an on-board controller with open architecture, to increase the capabilities of automatic vessel movement control. Today, all automated systems already use the electronic principle of generating and transmitting signals from control devices (power plant telegraph, rudder, bow and stern thruster telegraphs and etc.) to executive devices, which greatly simplifies the integration of the on-board controller and the creation of a closed circuit of automatic control.

Keywords: *navigation safety, control processes optimization, safe separation of vessels, automatic control module, pivot point.*

Received date: 04.11.2022
Accepted date: 17.12.2022
Published date: 20.12.2022

How to cite
Zinchenko, S., Tovstokoryi, O., Sapronov, O., Petrovskyi, A., Ivanov, A., Tymofeiev, K. (2022). Development of automatic control methods of vessel rotation around the pivot point without drift. Technology Audit and Production Reserves, 6 (2 (68)), 16–21. doi: https://doi.org/10.15587/2706-5448.2022.269364

1. Introduction

Over the past 10 years, there has been a trend of significant growth in vessel speeds and dimensions, while port sizes have increased much more slowly, which requires optimization of control processes in confined waters. Therefore, the development of traffic control methods that optimize operations in ports and bottlenecks is an urgent scientific and technical task.

One of the optimization directions is the use of the pivot point concept. The study of the pivot point behavior and its use during vessel maneuvering was previously considered by many authors [1–3].

Thus, in the work [3], the author investigates the behavior of the vessel's rotation center (the author calls it the pivot point). Using the example of two tugboats that push the vessel with a log, it is shown that the appearance of the longitudinal speed of movement leads to the vessel rotation. The author explains this effect by a change in the shoulders of tugboats due to the forward shift of the rotation center.

The properties of the pivot point, as a conditional point, were considered in the work [4]. The author provides a formula for determining the pivot point position through the lateral speed of the vessel's gravity center and the angular rate of the vessel's rotation around the gravity center. The author linearized the differential equations of lateral and angular motions, considered the steady state of the linearized model of the vessel, gave the formula for determining the pivot point position through the hydrodynamic characteristics of the vessel and control.

Experiments with the rotation center (the author also calls it the pivot point) in the port of Revel are described in article [5]. By using motors to produce symmetrical lateral forces, it was found that in the absence of forward motion, these lateral forces cause net lateral displacement, and, in the presence of longitudinal speed, rotational motion also appears. According to the author, this is due to the movement of the rotation center in the direction of the vessel's motion. The author also gives practical recommendations for using the shifting effect the rotation center to control the vessel, for example, to increase the steering torque or reduce the influence of external factors.

In work [6], using the example of a vessel moving backwards, the author shows that the implementation of the existing recommendations at that time leads to the piling on the pier. This is due to a misunderstanding of the pivot point position, which is actually placed at a distance of ~1/3 of the vessel's length from the bow, and not at a distance of ~1/4 of the vessel's length from the stern. Also interesting are the author's considerations regarding the physical center of rotation, which is between the gravity center and the center of lateral hydrodynamic resistance (COLR), taking into account the pressure field around the vessel. The author also emphasized that the rotation center and the pivot point are two different centers.

In work [7], for the first time, the condition for determining the pivot point position was recorded not in the scalar form $V_y+\omega_z R=0$ used by predecessors, but in the vector form $\mathbf{V}+\omega\times\mathbf{R}=0$. The use of the vector equation showed that the scalar form is a special case of the vector form and determines only one of the three components of the vector $\mathbf{R}$ – the abscissa of the pivot point. The vector form allows to determine also the ordinate and the applicate of the pivot point, i. e., in the general case, the pivot point is located in the three-dimensional space of the bound coordinate system (BCS), and not only on its longitudinal axis OX_1. For practical maneuvering, only the abscissa and ordinate of the pivot point are used, which together determine the position of the circulation center.

Formulas for calculating the width of the vessel's traffic lane are given in work [8], depending on the abscissa and ordinate value of the pivot point. The connection between the pivot point abscissa and the fixed radius of circulation was revealed. The equation of the lateral and rotational motion of the vessel was constructed, when the position of the pivot point coincides with the rotation center.

In article [9], the issues of using the pivot point to optimize the processes of controlling the vessels movement without longitudinal speed have been considered. It is shown that:

- gravity center, rotation center and pivot point are three different centers;
- the abscissa of the pivot point should be counted from the rotation center, and not from the gravity center, as was previously believed;
- obtained dependence of the rotation center position on the speed of the vessel;
- received controls that realize the vessel movement around the given pivot point position;
- the control distribution coefficient was investigated;
- there were built optimal controls.

The purpose of the study is to develop methods for automatic control of the vessel rotation around the pivot point without drift angle for the most common schemes: a conventional single-screw vessel without a bow thruster and a conventional single-screw vessel with a bow thruster. This will make it possible to reduce the width of the traffic lane, increase traffic safety, reduce hydrodynamic resistance and fuel consumption, create favorable conditions for technological operations, such as mooring, and reduce the influence of the human factor on traffic control processes.

2. Materials and Methods

The object of research is the processes of the automatic vessel rotation control around the pivot point without drift. The research used a systematic approach, analysis and synthesis, methods of automatic control theory, solid body mechanics, hydrodynamics, mathematical analysis, linear algebra, differential calculus, and field experiment. And also used equipment: a personal computer with the Windows 10 operating system and the MS Office 2016 suite of application programs, the MATLAB environment and imitation modeling stand developed by the authors on the basis of the Navi Trainer 5000 navigation simulator.

3. Results and Discussion

In article [7], the author proposed a vector formula for determining the position of the pivot point:

$$\mathbf{V}+\omega\times\mathbf{R}=0, \tag{1}$$

where $\mathbf{V}=(V_x,V_y.V_z)$ is the vessel's linear speed vector; $\omega=(\omega_x,\omega_y,\omega_z)$ is the vessel's angular rate vector; $\mathbf{R}=(R_x,R_y,R_z)$ is the vector of the pivot point position. After opening the vector product:

$$\omega\times\mathbf{R}=\begin{bmatrix}\mathbf{i} & \mathbf{j} & \mathbf{k}\\ 0 & 0 & \omega_z\\ R_x & R_y & R_z\end{bmatrix}=\mathbf{i}(-R_y\omega_z)-\mathbf{j}(-R_x\omega_z)+\mathbf{k}(0),$$

there were obtained values of the abscissa and ordinate of the pivot point:

$$\begin{cases} V_y+R_x\omega_z=0 \;\rightarrow\; R_x=-\dfrac{V_y}{\omega_z},\\ V_x-R_y\omega_z=0 \;\rightarrow\; R_y=\dfrac{V_x}{\omega_z}.\end{cases} \tag{2}$$

Fig. 1 shows the components of the vector $\mathbf{R}=(R_x,R_y)$.

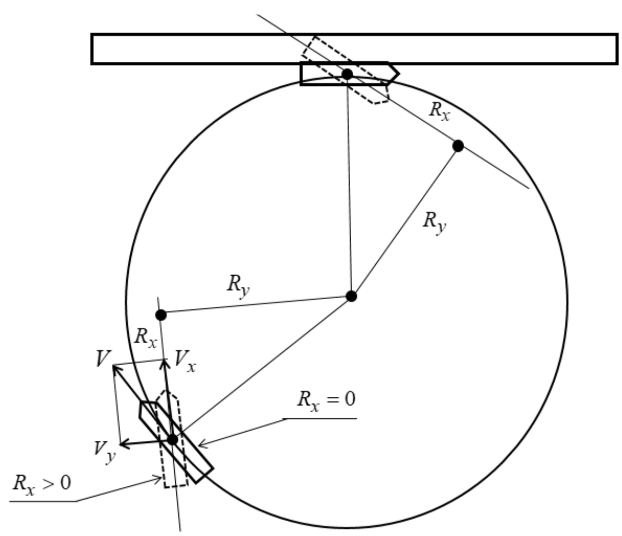

Fig. 1. The abscissa and ordinate of the pivot point

As can be seen from Fig. 1, the pivot point determined from the vector equation (1) is nothing but the center of circulation, the position of which is determined by two coordinates R_x and R_y. The abscissa of the pivot point R_x determines the vessel's position on the circulation, and the ordinate of the pivot point R_y determines the circulation radius. It also follows from the first equation of the system (2) that the movement of the vessel without a drift angle $(V_y = 0)$ is possible if the abscissa of the pivot point is $R_x = 0$. The position of the vessel in this case is shown in Fig. 1 with a solid contour. If the abscissa of the pivot point is placed in front of or behind the rotation center, the vessel will move with the drift angle, shown by the dashed contour in Fig. 1. The presence of the drift angle increases the width of the vessel's traffic lane, hydrodynamic resistance, fuel consumption and creates conditions for the vessel to pile up on the mooring wall.

Let's consider the possibilities of controlling the vessel rotation with a zero drift angle for the two most common schemes: the control scheme of a single-screw conventional vessel without a bow thruster (BT) and the control scheme of a single-screw conventional ship with a bow thruster, which are used on more than 85 % of ships, Fig. 2.

In Fig. 2 shows the power plant (PP), the rudder and the bow thruster, also there are marked the position of the gravity center (GC), the position of the rotation center (RC), abscissa R_x and ordinate R_y of the pivot point. The PP propeller creates the thrust force $P(\theta)$, lateral force $F_y(\theta)$ and moment:

$$M_z(\theta) = -F_y(\theta)(l_P + \Delta x),$$

where θ is the telegraph deflection angle; l_P is the shoulder of strength $F_y(\theta)$ to the gravity center GC; Δx is the displacement of the rotation center relative to the gravity center, in the presence of longitudinal speed [10]. The rudder creates a lateral force $F_y(\delta_R)$, the resistance force from the deflection of the rudder $-F_x(\delta_R)$ and the controlling moment:

$$M_z(\delta_R) = -F_y(\delta_R)(l_R + \Delta x),$$

where δ_R is the angle of rudder deflection; l_R is the shoulder of strength $F_y(\delta_R)$ to the gravity center GC. BT creates a lateral force $F_y^{BT}(\Theta_1)$, control moment:

$$M_z(\Theta_1) = F_y(\Theta_1)(l_{BT} - \Delta x),$$

where Θ_1 is the BT telegraph deflection angle; l_{BT} is the BT shoulder to gravity center GC. The positive directions of forces and moments, linear speeds and angular rates coincide with the directions of the BCS axes X_1RCY_1.

The linearized system of differential equations of the vessel's motion in the BCS, for a conventional single-screw vessel with a BT, has the form:

$$\begin{cases}(m+\lambda_{11})\dfrac{dV_x}{dt} = \dfrac{\partial P}{\partial \theta}\theta - \dfrac{\partial F_x}{\partial V_x}V_x - \dfrac{\partial F_x}{\partial \delta_R}|\delta_R|,\\ (m+\lambda_{22})\dfrac{dV_y}{dt} = \dfrac{\partial F_y}{\partial \theta}\theta - \dfrac{\partial F_y}{\partial V_y}V_y + \dfrac{\partial F_y}{\partial \delta_R}\delta_R + \dfrac{\partial F_y}{\partial \theta_1}\theta_1,\\ (I_z+\lambda_{66})\dfrac{d\omega_z}{dt} = -\dfrac{\partial F_y}{\partial \theta}(l_P+\Delta x)\theta - \dfrac{\partial M_z}{\partial \omega_z}\omega_z - \\ -\dfrac{\partial F_y}{\partial \delta_R}(l_R+\Delta x)\delta_R + \dfrac{\partial F_y}{\partial \theta_1}(l_P-\Delta x)\theta_1,\\ |\Theta| \le \Theta^{\max}, |\Theta_1| \le \Theta_1^{\max}, |\delta_R| \le \delta^{\max},\end{cases} \quad (3)$$

where m is the mass of the vessel; I_z is the inertia moment of the vessel; $\lambda_{11,}\lambda_{22,}\lambda_{66}$ are the attached masses and inertia moment of water; V_x, V_y, ω_z are the longitudinal, lateral and angular speed of the vessel; $\partial F_x/\partial V_x$, $\partial F_y/\partial V_y$, $\partial M_z/\partial \omega_z$ are the hydrodynamic characteristics of the vessel; $\partial P/\partial \theta$, $\partial F_y/\partial \theta$, $\partial F_y/\partial \delta_R$, $\partial F_x/\partial \delta_R$, $\partial F_y/\partial \Theta_1$ are the control characteristics; $\Theta^{\max}$, $\Theta_1^{\max}$, $\delta^{\max}$ are the restrictions on the PP telegraph deviation, the BT telegraph deviation and the rudder deviation. For steady motion ($dV_x/dt = 0$, $dV_y/dt = 0$, $d\omega_z/dt = 0$), from system (3) let's obtain:

$$\begin{cases}V_x = \dfrac{\partial V_x}{\partial F_x}\left(\dfrac{\partial P}{\partial \theta}\theta - \dfrac{\partial F_x}{\partial \delta_R}|\delta_R|\right),\\ V_y = \dfrac{\partial V_y}{\partial F_y}\left(\dfrac{\partial F_y}{\partial \theta}\theta + \dfrac{\partial F_y}{\partial \delta_R}\delta_R + \dfrac{\partial F_y}{\partial \Theta_1}\Theta_1\right),\\ \omega_z = \dfrac{\partial \omega_z}{\partial M_z}\begin{pmatrix}-\dfrac{\partial F_y}{\partial \theta}(l_P+\Delta x)\theta - \dfrac{\partial F_y}{\partial \delta_R}(l_R+\Delta x)\delta_R + \\ +\dfrac{\partial F_y}{\partial \theta_1}(l_{BT}-\Delta x)\theta_1\end{pmatrix}.\end{cases} \quad (4)$$

Substitute system equation (4) into system equation (2):

$$\begin{cases}R_x = \dfrac{\partial V_y \partial M_z}{\partial F_y \partial \omega_z} \times \\ \times\left(\dfrac{\dfrac{\partial F_y}{\partial \Theta}\Theta + \dfrac{\partial F_y}{\partial \delta_R}\delta_R + \dfrac{\partial F_y}{\partial \Theta_1}\Theta_1}{\dfrac{\partial F_y}{\partial \Theta}\Theta(l_P+\Delta x) + \dfrac{\partial F_y}{\partial \delta_R}\delta_R(l_R+\Delta x) - \dfrac{\partial F_y}{\partial \Theta_1}\Theta_1(l_{BT}-\Delta x)}\right),\\ R_y = \dfrac{\partial V_x \partial M_z}{\partial F_x \partial \omega_z} \times \\ \times\left(\dfrac{\dfrac{\partial P}{\partial \Theta}\Theta - \dfrac{\partial F_x}{\partial \delta_R}|\delta_R|}{-\dfrac{\partial F_y}{\partial \Theta}\Theta(l_P+\Delta x) - \dfrac{\partial F_y}{\partial \delta_R}\delta_R(l_R+\Delta x) + \dfrac{\partial F_y}{\partial \Theta_1}\Theta_1(l_{BT}-\Delta x)}\right).\end{cases} \quad (5)$$

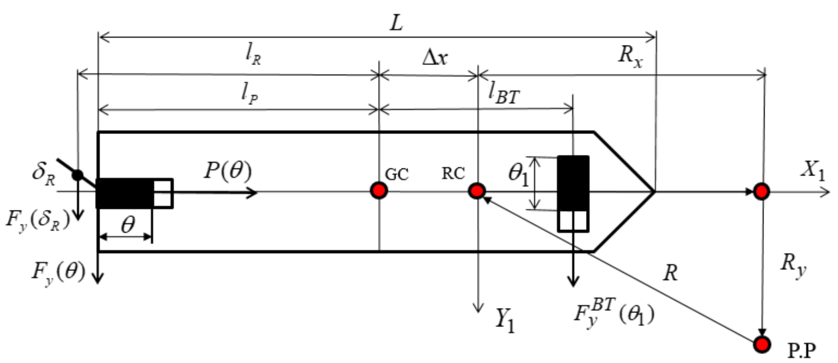

Fig. 2. Vessel control scheme

For the control scheme without BT, system (5) will have the form:

$$\begin{cases} R_x = \dfrac{\partial V_y \partial M_z}{\partial F_y \partial \omega_z}\left(\dfrac{\dfrac{\partial F_y}{\partial \Theta}\Theta + \dfrac{\partial F_y}{\partial \delta_R}\delta_R}{\dfrac{\partial F_y}{\partial \Theta}\Theta(l_P+\Delta x)+\dfrac{\partial F_y}{\partial \delta_R}\delta_R(l_R+\Delta x)}\right), \\ R_y = \dfrac{\partial V_x \partial M_z}{\partial F_x \partial \omega_z}\left(\dfrac{\dfrac{\partial P}{\partial \Theta}\Theta - \dfrac{\partial F_x}{\partial \delta_R}|\delta_R|}{-\dfrac{\partial F_y}{\partial \Theta}\Theta(l_P+\Delta x)-\dfrac{\partial F_y}{\partial \delta_R}\delta_R(l_R+\Delta x)}\right). \end{cases} \quad (6)$$

As can be seen from the first equation of the system (5), the movement of the vessel with the BT is possible with zero drift $(R_x = 0)$, provided that there is a connection between the controls:

$$\begin{cases} \dfrac{\partial F_y}{\partial \Theta}\Theta + \dfrac{\partial F_y}{\partial \delta_R}\delta_R + \dfrac{\partial F_y}{\partial \Theta_1}\Theta_1 = 0, \\ \delta_R = -\dfrac{\partial \delta_R}{\partial F_y}\left(\dfrac{\partial F_y}{\partial \Theta}\Theta + \dfrac{\partial F_y}{\partial \Theta_1}\Theta_1\right). \end{cases} \quad (7)$$

For a vessel without BT, the movement with zero drift $(R_x = 0)$ is possible provided that there is a connection between the controls:

$$\begin{cases} \dfrac{\partial F_y}{\partial \Theta}\Theta + \dfrac{\partial F_y}{\partial \delta_R}\delta_R = 0, \\ \delta_R = -\dfrac{\partial F_y}{\partial \Theta}\dfrac{\partial \delta_R}{\partial F_y}\Theta. \end{cases} \quad (8)$$

After substituting the second equation of system (8) into the second equation of system (6), the control Θ is shortened. This means that a vessel without BT can move without a drift angle with only one radius of circulation in each direction, which is determined by the geometric and hydrodynamic characteristics of the vessel:

$$R_y = \frac{\partial V_x}{\partial F_x}\frac{\partial M_z}{\partial \omega_z}\left(\frac{\dfrac{\partial P}{\partial \Theta}\dfrac{\partial \Theta}{\partial F_y} \pm \dfrac{\partial F_x}{\partial \delta_R}\dfrac{\partial \delta_R}{\partial F_y}}{l_R - l_P}\right). \quad (9)$$

For the MSC Container Ship (Dis. 32025t), the characteristics of which are given below, the radius of circulation calculated by formula (9) is equal to:

$$R_y = \frac{1.71e^9}{0.169e^6}\left(\frac{\dfrac{1.045e^6}{0.26e^6}+\dfrac{0.67e^6}{4.79e^6}}{154-152}\right) = 21.05 \text{ km}.$$

Let's rewrite the second equation of system (5) in the form:

$$\delta_R = -\left(\frac{\dfrac{\partial F_y}{\partial \Theta}(l_P+\Delta x)R_y + \dfrac{\partial M_z}{\partial \omega_z}\dfrac{\partial V_x}{\partial F_x}\dfrac{\partial P}{\partial \Theta}}{\dfrac{\partial F_y}{\partial \delta_R}(l_R+\Delta x)R_y - \dfrac{\partial M_z}{\partial \omega_z}\dfrac{\partial V_x}{\partial F_x}\dfrac{\partial F_x}{\partial \delta_R}}\right)\Theta + \left(\frac{\dfrac{\partial F_y}{\partial \Theta_1}(l_{BT}-\Delta x)R_y}{\dfrac{\partial F_y}{\partial \delta_R}(l_R+\Delta x)R_y - \dfrac{\partial M_z}{\partial \omega_z}\dfrac{\partial V_x}{\partial F_x}\dfrac{\partial F_x}{\partial \delta_R}}\right)\Theta_1. \quad (10)$$

The linkage between controls (10) provides movement with a given radius of circulation, and the linkage between controls (7) provides movement with a zero drift angle. The joint solution of equations (10) and (7) allows finding the relationship between the controls of a conventional single-screw vessel with BT, which provides movement with a zero drift angle and a given radius of circulation:

$$\Theta_1 = \frac{\left(\dfrac{\dfrac{\partial F_y}{\partial \Theta}(l_P+\Delta x)R_y + \dfrac{\partial M_z}{\partial \omega_z}\dfrac{\partial V_x}{\partial F_x}\dfrac{\partial P}{\partial \Theta}}{\dfrac{\partial F_y}{\partial \delta_R}(l_R+\Delta x)R_y - \dfrac{\partial M_z}{\partial \omega_z}\dfrac{\partial V_x}{\partial F_x}\dfrac{\partial F_x}{\partial \delta_R}} - \dfrac{\partial \delta_R}{\partial F_y}\dfrac{\partial F_y}{\partial \Theta}\right)}{\left(\dfrac{\dfrac{\partial F_y}{\partial \Theta_1}(l_{BT}-\Delta x)R_y}{\dfrac{\partial F_y}{\partial \delta_R}(l_R+\Delta x)R_y - \dfrac{\partial M_z}{\partial \omega_z}\dfrac{\partial V_x}{\partial F_x}\dfrac{\partial F_x}{\partial \delta_R}} + \dfrac{\partial \delta_R}{\partial F_y}\dfrac{\partial F_y}{\partial \Theta_1}\right)}\Theta. \quad (11)$$

Setting the PP telegraph deviation Θ, using formula (11) let's find the BT telegraph deviation Θ_1, and then using formula (7) let's determine the rudder deviation δ_R.

The workability and effectiveness of the vessel controlling rotation method around the pivot point without drift angle is verified by mathematical modeling of the MSC Container Ship (Dis. 32025t) automatic mooring processes on imitation modeling stand. The imitation modeling stand was created by authors on the basis of the Navi Trainer 5000 simulator and was previously described in [10]. The characteristics of the linearized vessel model are given in Table 1.

Table 1

The characteristics of the MSC Container Ship (Dis. 32025t)

Main characteristics		Characteristics of the linearized model	
Parameter	Value	Parameter	Value
PP power W, kWt	15890	$\partial P/\partial \Theta$, N/rad	$1.045e^6$
Water displacement V, t	32025	$\partial F_x/\partial V_x$, kg/s	$0.169e^6$
Maximum speed V_x^{max}, m/s	9.7	$\partial F_x/\partial \delta_R$, N/rad	$0.67e^6$
Length L, m	203.6	$\partial F_y/\partial \Theta$, N/rad	$0.26e^6$
Width B, m	25.4	$\partial F_y/\partial V_y$, kg/s	$3.93e^6$
Draft d, m	9.6/10	$\partial F_y/\partial \delta_R$, N/rad	$4.79e^6$
Bow thruster/Stern thruster	yes/no	$\partial M_z/\partial \omega_z$, Nms/rad	$1.71e^9$

In the simulator of the on-board controller of the imitation modeling stand, at each step of the calculation of 1 s:

1. The position of the contact point with the mooring wall in the BCS was determined.
2. For the current position of the vessel $x(n)=0, y(n)=0$ (BCS is always in the vessel rotation center) and the contact point $x^*(n), y^*(n)$, the current radius of circulation $R_y(n)$ tangent to the mooring wall at the contact point $x^*(n), y^*(n)$ was determined.
3. According to formula (11), the BT telegraph deviation $\Theta_1(n)$ was calculated, which ensured the vessel circulation with a radius $R_y(n)$ without drift angle.
4. According to the formula (7), the deviation of the rudder $\delta_R(n)$ was calculated, which ensured the vessel circulation with a radius $R_y(n)$ without drift angle.
5. Controls $\Theta(n)$, $\Theta_1(n)$, $\delta_R(n)$, received in the on-board controller were transmitted through the COM port

ISSN 2664-9969

and the local computer network to the MSC Container Ship (Dis. 32025t) mathematical model of the Navi Trainer 5000 navigation simulator.

In Fig. 3 shows a screenshot of the Navi Trainer 5000 instructor's workplace during an automatic mooring experiment without a drift angle.

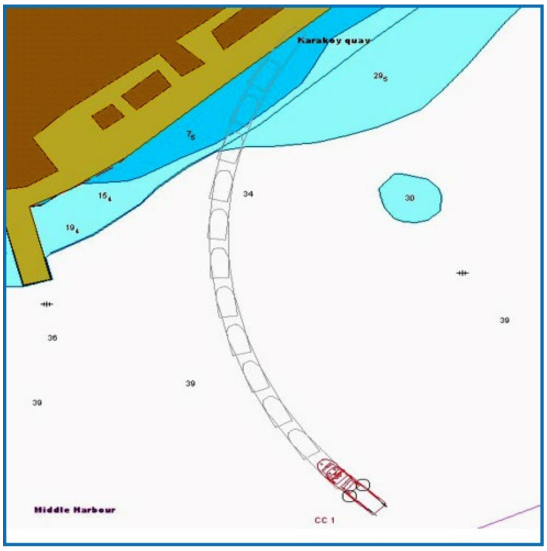

Fig. 3. Modeling of the mooring process without a drift angle

Summing up and taking into account the results of the experiment, the following can be noted.

A single-screw conventional vessel without BT can move without drift around the pivot point with only one radius of circulation in each direction, which is determined by the geometric and hydrodynamic characteristics of the vessel. A single-screw conventional vessel with BT can have a zero drift angle for various radii of circulation, the smallest of which is limited to the minimum speed of the vessel in circulation at which controllability is preserved.

The difference in the capabilities of the considered schemes is explained by the fact that the number of independent controls of a vessel with BT $(\Theta,\Theta_1,\delta_R)$ is equal to the number of freedom degrees to be controlled (longitudinal movement, lateral movement and angular movement in the yaw channel), and the number of vessel controls without BT (Θ,δ_R) is less than the number of freedom degrees, which are subject to control.

In practice, the movement of the vessel without a drift angle is carried out only on straight sections of the trajectory manually, or automatically, using the autopilot. It is quite difficult to maintain a zero drift angle on circulation sections manually, and technical means of automatic control do not exist. The developed methods can be used on vessel, provided they are integrated into the existing automated system with on-board controller and open architecture to increase the capabilities of automatic motion control, in this case, the capabilities of automatic circulation without drift angle.

Today, all automated systems already use the electronic principle of generating and transmitting signals from control devices (power plant telegraph, steering wheel, bow thruster telegraphs) to executive devices, which greatly simplifies the integration of the on-board controller and the creation of a closed circuit for the organization of automatic control.

The obtained results have both theoretical and practical significance. The theoretical significance lies in the development of methods for automatically controlling the vessel rotation around a given pivot point without drift angle. The practical significance lies in reducing the width of the traffic lane, increasing traffic safety, reducing hydrodynamic resistance and fuel consumption, creating favorable conditions for technological operations, for example, mooring a vessel, reducing the impact of the human factor.

The limitations of the developed methods include the impossibility of their use for manual control, as well as the requirement for a sufficient number of independent controls (at least three).

Further research is planned for redundant control schemes.

4. Conclusions

The work deals with the issues of automatic control of the vessel's rotation around the pivot point without a drift angle. Literary sources were analyzed, which investigated the issue of determining and using the pivot point for maneuvering. Linearized models of longitudinal, lateral, and angular motion are considered for two of the most common control schemes: a conventional single-screw vessel without bow thruster and a conventional single-screw vessel with bow thruster. For steady motions, the dependences of the abscissa and ordinate of the pivot point on the controls are obtained. Controls have been found that ensure the circulation of the vessel without drift angle. The different capabilities of the considered schemes are explained by the different control redundancy IU – the difference between the number of independent controls NU and the number of freedom degrees NS to be controlled. For a conventional single-screw vessel without bow thruster, the control redundancy is $IU=2-3=-1$ (insufficient control), and for a conventional single-screw vessel with bow thruster, the control redundancy is $IU=3-3=0$ (sufficient control). Vessels with sufficient and excess $IU>0$ control have greater maneuverability.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

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