Assessment of the quality of control of the ship "crosshair" under wind load conditions

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Abstract. There are few ports in the Far North. Therefore, it is not difficult to assume that most of the cargo operations in the future will be implemented in the open part of the sea space of the Arctic regions. In this regard, the safe maneuvering of a tanker at the offshore oil terminal when carrying out cargo operations with hydrocarbon raw materials is one of the most important and urgent tasks. When performing this type of operation, the main threat to environmental safety is a rupture of the cargo line hose and damage to the underwater pipeline due to the tanker piling up on the oil terminal. Therefore, the improvement of the methods of controlling the movement of the tanker during its positioning at the oil terminal in the process of carrying out the operation of loading oil is significant. Improving tanker control technologies can contribute to improving the quality of control, reducing the likelihood of emergencies, and, as a result, increasing the safety of cargo operations when transshipping oil products in the open sea.

1. Introduction

The proposed method for controlling the movement of a tanker performing cargo operations at an oil terminal [4], [5] in the open sea involves keeping the tanker in a given position relative to the terminal with minimal dependence on weather conditions area of cargo operations. The goal of stabilizing the position of a tanker during a cargo operation at an oil terminal is fundamentally different from the goal of stabilizing a vessel, for example, engaged in drilling operations. Since, when stabilizing the tanker's position, the task is not posed to hold the tanker at a given point (a point with given coordinates, the values of which are constant) with known permissible deviations from it.

Following the safety requirements for carrying out cargo operations at the oil terminal, the tanker must constantly be on a straight line passing through the center of the oil terminal. The diametrical plane of the tanker must coincide with the specified line. The distance between the anchorage points of the mooring line must be within the admissible values, excluding the breakage of a mooring line. As a result, a break in the hose through which oil is transferred from the terminal to the tanker. At the same time, it is allowed changing in time the direction of the line passing through the center of the oil terminal, taking into account the hydrometeorological conditions in the area of cargo operations. That is, in contrast to the case of stabilization of the vessel at a given point, when the tanker stabilizes in a given direction relative to the oil terminal, a change in the position of a given point is permissible.
The research task is to determine the possibility of practical implementation of the proposed method for controlling the movement of the tanker. In this case, the authors propose to use a method of controlling the tanker movement with a crosshair to stabilize it in a given position. A crosshair is a two-axis moving coordinate system. The origin of the coordinate system is aligned with a point specified on the plane, and the direction of one of the axes is oriented in a given way on the plane. The control law provides for the formation of a control signal from the values of the lateral and longitudinal deviations of two points spaced along the ship’s length from the axes of the crosshair. The purpose of control is achieved by bringing the tanker to a position where the position of one of its points, for example, the center of gravity, coincides with the position of a given point, and the direction of the tanker's center plane coincides with the direction of one of the crosshair axes. The proposed control method involves minimizing energy costs for carrying out these cargo operations and sharply reducing the influence of the human factor on the safety of cargo operations. Table 1 presents the main technical characteristics of the tanker that was used in the experiments.

**Table 1.** The main technical characteristics of the tanker.

| Parameters                          | Parameter values |
|-------------------------------------|------------------|
| Maximum length, \( L_{\text{max}} \), m | 269.9            |
| Length between perpendiculars, \( L_{bp} \), m | 255.3            |
| Length at the waterline, \( L_w \), m     | 262.6            |
| Width, \( V \), m                     | 44               |
| Draft, \( d \), m                     | 14               |
| Displacement completeness coefficient, \( C_v \) | 0.8131          |
| Volumetric displacement, \( V \), m\(^3\) | 131528.4        |
| Frontal sail area, \( S_m \), m\(^2\)   | 792              |
| Side sail area, \( S_{dp} \), m\(^2\)   | 2853             |
| Number of masts, \( M \)              | 2                |
| Propeller diameter, \( D \), m         | 8.1              |
| Propeller pitch, \( P_{0.7} \), m      | 5.671            |

2. Coordinate systems

Figure 1 shows coordinate systems. O-X_0Y_0 is a fixed coordinate system fixed on a plane, and G-xyz is a movable coordinate system associated with the ship.
3. Mathematical model

Controlling the movement of a tanker with a crosshair involves performing complex maneuvering, the characteristic features of the vessel's movement with large drift angles $\beta$ and low, and sometimes extremely low linear speed $\omega$.

According to these circumstances, for carrying out the research, a mathematical model of the vessel was chosen, developed, and proposed by A.P. Tumashik [7], [8]. This model is represented by the system of equations (1):

$$
\begin{align*}
(m + \lambda_{11}) \frac{d\nu_x}{dt} - (m + \lambda_{22}) \nu_y \omega &= X \\
(m + \lambda_{22}) \frac{d\nu_y}{dt} + (m + \lambda_{11}) \nu_x \omega &= Y \\
(I_z + \lambda_6) \frac{d\omega}{dt} &= M_z
\end{align*}
$$

where $m$, $I_z$ are mass and moment of inertia of the vessel; $\lambda_{11}$, $\lambda_{22}$, $\lambda_6$ are attached masses during the longitudinal and transverse motion of the vessel and the attached moment of inertia during the rotational movement of the vessel; $\nu_x$, $\nu_y$ are longitudinal and transverse components of the linear speed of the vessel $\nu$; $\omega$ is the angular velocity of the vessel.

Forces and moments presented in the mathematical model:

$$
\begin{align*}
X &= X_H + X_P + X_A + X_M \\
Y &= Y_H + Y_{PR} + Y_A + Y_M \\
M_z &= M_{H} + M_{PR} + M_A + M_M
\end{align*}
$$

in equations (2) – (4) the following parameters are presented:
- the variables with the index "H" represent the components of the hydrodynamic force and its moment, arising on the hull of the vessel during its movement;
- the variable with the index "P" represents the force created by the main propulsion unit, taking into account the hydrodynamic interaction of the ship's hull and the propeller;
- the variables with the index "PR" represent the forces and the moment created by the thrusters;
- forces and moments with the index "A" are components of aerodynamic force and moment;
- the variables representing the mooring link are indicated by the index "M."

It is obvious that

$$
\nu = \left(\nu_x^2 + \nu_y^2\right)^{1/2}
$$

$$
\beta = \begin{cases} 
\arccos\left(\frac{\nu_x}{\nu}\right), & \text{if } \nu_y < 0 \\
-arccos\left(\frac{\nu_y}{\nu}\right), & \text{if } \nu_y > 0 
\end{cases}
$$
4. Hydrodynamic forces on the tanker’s hull

Dependencies represent hydrodynamic forces on the tanker’s hull:

\[
X_H = C_{slt} 0.5 \rho F_{dp} \nu^2 \\
Y_H = C_{slt} 0.5 \rho F_{dp} \nu^2 \\
M_H = 0.5 \rho F_{dp} L_{bp} \left[ C_{mll} \nu^2 - C_{mll} L_{bp}^2 \omega - C_{moo} \left( \frac{1}{\pi} \nu^2 + L_{bp}^2 \omega^2 \right) \times \sin(\pi \Omega) \right]
\]

(5)

The given area of the submerged part of the diametrical buttocks of the tanker

\[
F_{dp} = \sigma_{dp} L_{bp} d \\
\sigma_{dp} = 0.962 + \frac{0.054 L_{bp} \times \tau}{d} \\
\tau = \frac{d_a - d_f}{L_{bp}} \\
d = \left( d_a + d_f \right) / 2
\]

Generalized tanker angular velocity

\[
\Omega = \frac{L_{bp} \omega}{\sqrt{\nu^2 + (L_{bp} \omega)^2}}
\]

The hydrodynamic characteristics of the tanker’s hull included in expressions (5) are calculated in the following sequence [7]

\[
C_{slt} = -0.27 \times \sin \left[ (\pi - \varphi) \times \left( 1 - \text{Abs} \left( \frac{\beta}{\beta_s} \right) \right) \right]
\]

\[
\varphi = \arcsin \left[ \frac{C_{slt}(\beta = 0)}{0.27} \right]
\]

\[
C_{slt}(\beta = 0) = \frac{R}{0.5 \rho \nu^2 F_{dp}}
\]

R is resistance to the movement of the vessel at \( \beta = 0 \).

\[
C_{slt} = 0.5 C_1 \sin(2\beta) \times \cos(\beta) + C_2 \sin^2(\beta) + C_3 \sin^4(2\beta)
\]

\[
C_{mll} = m_1 \sin(2\beta) + m_2 \sin(\beta) + m_3 \sin^3(2\beta) + m_4 \sin^4(2\beta)
\]

\[
C_{moo} = 0.059 C_2
\]

\[
C_{moo} = C_{moo} + n_1 \left[ \text{Abs} \left( \sin(\beta) \right) \right] + n_2 \left[ \text{Abs} \left( \cos(2\pi - 4 \times \left| \beta \right|) \cos(\beta) + 0.1 \times \sin(2\beta) \right) \right]
\]

\[
C_{moo} = \left[ 0.739 + 8.7 \left( \frac{d}{L_{bp}} \right) \right] \times \left[ 1.61 \sigma_{dp}^2 - 2.87 \sigma_{dp} + 1.33 \right]
\]
\[ n_1 = 0.09 - C_{mao}^o - 0.0033 \left( \frac{L_{bp}}{B} - 7.0 \right) - 20 \left( \frac{d}{L_{bp}} - 0.005 \right)^2 + 0.4(\sigma_{dp} - 0.9) + 0.05(C_m - 0.9) \]

\[ n_2 = 0.008 \frac{L_{bp}}{B} + 0.9 \left( \frac{d}{L_{bp}} - 0.05 \right) + 0.45(\sigma_{dp} - 0.959) \]

5. The force created by the main propeller (propeller).

Controlling the movement of the tanker when using the "crosshair" has its characteristics. Specificity data should be considered. The value of the force created by the main propulsion unit \( X_p \) is determined in four quadrants at various combinations of the values of the longitudinal component of the tanker's speed \( \nu_x \) (m/s) and the engine speed \( n \) (1/s): \( \nu_x > 0, n > 0; \nu_x > 0, n < 0; \nu_x < 0, n > 0; \nu_x < 0, n < 0 \):

\[ X_p = 0.5 \rho (1 - t_p) \left[ \nu_x (1 - w_p) \right] + (0.7 \pi D)^2 \times 0.25 \pi D^2 K_p (\beta_p) \]

where \( \beta_p \) is the pitch angle, \( t \) is the suction coefficient, \( w_p \) is the co-flow coefficient, \( D \) is the propeller diameter, \( n \) is the rotor speed (1/s).

\[ \beta_p = \arctg \left[ \nu_x (1 - w_p) / (0.7 \pi D) \right] \]

The propeller thrust coefficient following Lammeren's recommendations [10] is presented in the form of a Fourier series:

\[ K_p = \sum_{k=0}^{20} \left[ A(k) \cos(k \beta_p) + B(k) \sin(k \beta_p) \right] \]

where the coefficients \( A(k) \) and \( B(k) \) are a function of the step ratio \( P/D \), the disk ratio \( A_d/A_0 \), and the number of screw blades \( z_b \). These coefficients were obtained using the data from [10].

When the tanker moves in reverse (\( \nu_x < 0 \)), the values of the associated flow coefficient and the suction coefficient are assumed to be: \( w_p = 0, t_p = 0 \).

6. Bow thrusters

The tanker selected for the experiments is not equipped with thrusters. Therefore, the presence of thrusters in the bow and stern of the tanker is considered conditional. When determining the type of thrusters, the required maximum value of the thruster thrust was considered, based on the recommendations of Lips, i.e.

\[ T_{epr \text{max}} = 50S_{dp} + 150F_{dp} \]

In our case, in the presence of two thrusters of the same type, the maximum thrust of one of them with a full tanker load is \( T_{epr \text{max}} = 350 \text{ kN} \); therefore, a WÄRTSILÄ thruster of the WTT-3200 type with a maximum power of 3200kW and a propeller diameter \( D_{pr} = 3.0 \text{ m} \) was used as thrusters. The variant allows the tanker, when fully loaded, to rotate in place in calm with an angular velocity \( \omega = 0.4 \text{ °/s} \) and be held lagging to the wind with a speed of \( \nu_s = 25 \text{ m/s} \) [Hoffman], which corresponds to the conditions of the planned experiment

\[ Y_{PR} = T_{epr f, a} + T_{epr u} \]

\[ T_{epr f, a} (1 + t_{pr}) K_{Tpr f, a} N_{pr f, a}^2 D_{pr}^4 \]
\[ K_{Tpr(f,a)} = \frac{a_0 + a_1 J_{pr(f,a)}^2 + a_2 J_{pr(f,a)}^3 + a_3 \left( \frac{P_{pr(f,a)}}{D_{pr}} \right) + a_4 \left( \frac{P_{pr(f,a)}}{D_{pr}} \right)^2}{1 + b_1 J_{pr(f,a)}^2 + b_2 J_{pr(f,a)}^3 + b_3 \left( \frac{P_{pr(f,a)}}{D_{pr}} \right) + b_4 \left( \frac{P_{pr(f,a)}}{D_{pr}} \right)^2} \]

where \( T_{epr}, T_{epra} \) are the thrust of the bow and stern thruster, respectively; \( t_{pr} \) is the coefficient of suction of the bow thruster (taken equal to \( t_{pr} = 0.2 \) \[2\]); \( x_{pr}, x_{pra} \) are the abscissas of the installation points of the bow and stern thruster, respectively, \( J_{pr(f,a)} \) is the relative gait of the bow and stern thruster; \( K_{Tpr(f,a)} \) is the thrust coefficient of the bow and stern thruster; \( n_{pr(f,a)} \) is propeller speed of the bow and stern thruster; \( a_0, a_1, \ldots, b_1, b_2, \ldots \), \( c_0, c_1, c_2 \) are regression coefficients; \( P_{pr(f,a)} \) is the pitch of the bow and stern thruster (adjustable pitch propellers).

7. Mooring cable
The tanker is held at the terminal without sagging due to the horizontal component of the mooring line tension. The dependency determines this value

\[ T_M = E \times S \times \Delta l / l_0 \]

where \( E \) is Young’s modulus of the rope material; \( S \) is the cross-sectional area of the cable; \( \Delta l = l - l_0 \) is cable elongation under load; \( l_0 \) is initial cable length

\[ l = d_0 - d_1 x_M + d_2 x_M^2 \]

\( x_M \) is the abscissa of the cable attachment point on the tanker.

Mooring cable force components

\[ X_M = T_M \cos \gamma \]
\[ Y_M = T_M \sin \gamma \]
\[ M_M = Y_M x_M \]

\( \gamma \) is the angle of deviation of the mooring cable from the tanker centreline plane.

8. Aerodynamic forces on the tanker’s hull
Aerodynamic forces are calculated using the results of model experiments performed by Isherwood [11], considering the constant change in the values of the heading angle of the apparent wind \( q_A \) in the process of tanker maneuvering. The formulas determine the components of the aerodynamic load and the aerodynamic moment:

\[ X_A = C_{xA} 0.5 \rho a u_R^2 S_m \]
\[ Y_A = C_{yA} 0.5 \rho a u_R^2 S_d \]
\[ M_A = C_{mA} 0.5 \rho a u_R^2 S_d L_d \]

In formulas (6), the values of aerodynamic coefficients are determined in the format of the Fourier series:

\[ a_0 + a_1 J_{pr(f,a)}^2 + a_2 J_{pr(f,a)}^3 + a_3 \left( \frac{P_{pr(f,a)}}{D_{pr}} \right) + a_4 \left( \frac{P_{pr(f,a)}}{D_{pr}} \right)^2 \]
9. General principle of approach to research

There are many approaches to assessing the quality of control of a ship with a "crosshair," which can be found, for example, in [1] [3] [9]. All of them are based on some root-mean-square (or modular) estimate of the deviation of the selected parameter from the set value at a given time interval. In our case, it is natural to take for such an estimated parameter the square of the deviation $\Delta r$ of the center of gravity (CG) of the vessel from the center of the crosshair (point O in Fig. 2):

\[
C_{xl} = \sum_{k=0}^{2} A(k) \times \cos(kq_R)
\]

\[
C_{yl} = \sum_{k=0}^{2} B(k) \times \sin(kq_R)
\]

\[
C_{yl} = \sum_{k=0}^{2} C(k) \times \sin(kq_R)
\]

\[\int_0^t \Delta r^2 \, dt \]

\[
Q_\Sigma = \frac{1}{l} \int_0^l \Delta r^2 \, dt
\]

Naturally, in numerical modeling, the integral will be implemented as a summation, which is performed overall points of the tanker’s maneuvering trajectory. In this case, the limitation on the deviation $\Delta r \leq \Delta r_{\text{max}}$ is the ultimate goal of controlling the vessel with the "crosshair."

The local task of such a study is to calculate the deviation $\Delta r$, which is not directly observed during maneuvering. Let us express the deviation through the observed characteristics, which are the deviations of the bow and stern points of the tanker from the coordinate axes $OX$ and $OY$ (Fig. 2).
Let the distances of the bow and stern points of the tanker, which are chosen for control, be $x_F$ and $x_A$, respectively. Then the coordinates CG in the $XOY$ coordinate system can be found as the coordinates of the point dividing the segment $FA$ in the ratio $\lambda = x_F/x_A$. Since the coordinates of these characteristic points $F(d_{xF}, d_{yF})$ and $A(d_{xA}, d_{yA})$ are observed in the process of maneuvering control, the coordinates CG will be determined by the known formulas:

$$
\Delta x_{CG} = \frac{d_{xF} + \lambda \cdot d_{xA}}{1 + \lambda} = \frac{x_A \cdot d_{xF} + x_F \cdot d_{xA}}{x_A + x_F}
$$

$$
\Delta y_{CG} = \frac{d_{yF} + \lambda \cdot d_{yA}}{1 + \lambda} = \frac{x_A \cdot d_{yF} + x_F \cdot d_{yA}}{x_A + x_F}
$$

These coordinates determine the distance CG of the tanker from the center of the crosshair O:

$$
\Delta r^2 = \Delta x_{CG}^2 + \Delta y_{CG}^2 = \left( \frac{x_A d_{xF} + x_F d_{xA}}{x_A + x_F} \right)^2 + \left( \frac{x_A d_{yF} + x_F d_{yA}}{x_A + x_F} \right)^2
$$

It is this expression for the deflection of the CG tanker that we will use when assessing the control efficiency in the maneuvering process.

10. Analysis of research results

The study of the wind action is reduced to the simulation of the tanker movement under the influence of the deviation control system at different wind directions $q_a$ and its speed $\nu_a$. To simulate the movement of a tanker, we will choose a wind speed $\nu_a = 20 \text{ m/s}$. These results allow the opportunity to assess the quality of control in extreme conditions. The conclusions drawn from the results of such an assessment will make it possible to judge the possibility of using the proposed control method in more favorable conditions for carrying out cargo operations.

Figure 3 shows the four trajectories of the ship (lines of different colors) in different wind directions. The main goal of the simulation is to show that the trajectory is shifted in the wind direction. However, at the same time, the control system successfully fulfills these aerodynamic effects. Figure 4 presents the trajectories, which are shown in the following order: in the absence of wind, with wind from the directions: 320°, 150°, 60°, and 240°. The heading angle of the wind is essential. In our case, this is the wind, either acting along the centerline or perpendicular to it.

Figure 3. Trajectories of a tanker in different wind directions

($q_a = 240^\circ, 60^\circ, 150^\circ, 320^\circ$)
Let us consider the case when, at a selected wind speed \( \upsilon_a = 20 \text{ m/s} \), its direction is \( q_a = 195^\circ \) (wind from the aft heading angles of the starboard side). Figure 5 presents the trajectory of the tanker movement. This trajectory does not fundamentally differ from the trajectories shown in Figure 4. Differences arise only in the initial period when the control system fulfills large deviations from the crosshair, and a transient process occurs.

In addition, we present the resulting aerodynamic forces and moments (Fig. 6), as well as the thrust and moments that are generated by the tanker’s thrusters (Fig. 7).

In our opinion, the control system for deviations from the axes forming a “crosshair” does not cope well enough with the task of stabilizing the tanker near the target point, both in the absence of wind and under its influence. At the same time, we simulated a control strategy, in which the necessary thrusts of the tanker’s thrusters were found using the formulas:

\[
T_{eprF} = \frac{M_z + Y x_A}{x_F - x_A},
\]

\[
T_{eprA} = -\frac{M_z + Y x_F}{x_F - x_A}.
\]

where \( Y \) is the sum of the forces acting on the ship’s hull; \( M_z \) is the total moment of these forces.
In work [6], slightly different parameters of the control system of the main propulsion device and the bow thruster were used:

- in the law of control of the emphasis of the main mover

\[ T_e = (kN_{enorm}\gamma\%\upsilon)A \]

where \( A = 1/(a_3 L_{pp}) \); \( \gamma \% \) is percentage of the main engine load;

- in the law of control of thrusters’ drafts

\[ T_{eprF} = \left[ a_2(d_yA - d_yF) + a_1(d_yA - d_yF)x_A \right]/(x_F - x_A), \]

\[ T_{eprA} = \left[ -a_1(d_yA - d_yF) + a_1(d_yA + d_yF)x_F \right]/(x_F - x_A), \]

where \( a_1 = -18, a_2 = 3300, a_3 = 70 \) (thruster control parameters). Their numerical values were selected based on the results of assessing the quality of simulation of tanker movement control in the absence of wind load. In formulas (7), (8), the thrust of the bow and stern thruster are linked by a common relationship.

In this case, a slightly different control strategy was chosen for deviations from the "crosshair." The thrust of the bow and stern thrusters are selected independently of each other. Each of them is proportional to the corresponding deviations of the bow \( d_{xF} \) and stern \( d_{xA} \) points of the tanker from the axis of the crosshair \( OY \) (Fig. 2), taking into account the signs of these deviations:

\[ T_{eprF} = a_1d_{xF}; T_{eprA} = a_2d_{xA}; \]

Many simulations have been carried out that have been performed previously for a different method of selecting the thruster rods. At the same time, we will slightly change the nature of the movement of the point \( O \) (the center of the "crosshair") and the angle of rotation \( \chi \) of the \( OY \) coordinate system \( XOY \) relative to the fixed coordinate system \( X_0 Y_0 \). We will reduce the amplitude of movement of the crosshair to about 10 m, direct the longitudinal axis of the crosshair to a fixed point, in particular to the origin. This process is how we simulate the task of moving a tanker on a mooring line. Such a task is less rigid in terms of control but the closest to the simulated process. In addition, we use a different assessment of the quality of management. Since the simulation system remembers deviations from the crosshair axes, let us estimate the quality of control of the sum of squares of such deviations, referring the sum to the square of the tanker length. Let us refer this value to a second of simulation time and extract the square root. In fact, this is the classic standard deviation:

\[ Q = \left( \frac{\sum \left( \frac{d_{xF}^2 + d_{xA}^2 + d_{xF}^2 p^2 + d_{xA}^2 p^2}{L_{epr}^2 NN} \right)}{1/2} \right) \]

This principle of assessing the quality of control has another advantage: it allows evaluating the quality separately by deviations from each axis of the crosshair, i.e., longitudinal \( d_{xF}, d_{xA} \), and transverse \( d_{xF}, d_{xA} \) deviations.
The results of such tests are presented below in graphical form. So, figure 8 shows the trajectory of a controlled tanker in the absence of wind. The purple line shows the direction to the anchorage point of the mooring line at the terminal, the blue circle shows the tanker with the direction of its diametrical plane, the red circle shows the target point and the crosshairs in it. By formula (9), we calculate \( Q_\Sigma = 2.8144 \). As you can see, the control copes with the task quite well, the movement of the tanker only in the first non-stationary period up to 6700 s has large amplitudes, then the movement becomes stationary, the amplitudes decrease and remain sufficiently small. The length of the simulation of the tanker movement controlled by the "crosshair" was 20000 s.

Figure 6. Aerodynamic forces (kN) and moment (kNm) at \( v_a = 20 \text{ m/s}, \theta_a = 195^\circ \).

Figure 7. Changes in bow and stern thrusters (kN) and their resulting moment (kNm) at \( v_a = 20 \text{ m/s}, \theta_a = 195^\circ \).
Figure 8. Tanker trajectory when controlling its movement with a "crosshair". The "crosshair" moves with an amplitude of 10 m along the directions of its axes with \( \tau_1 = 3600 \) s, \( \tau_2 = 1200 \) s. \( v_a = 0 \) m/s (\( Q_x = 2.8144 \)).

Figure 9 shows the trajectory of a tanker controlled by the "crosshair" under the action of wind \( v_a = 15 \) m/s, \( q_a = 330^\circ \), i.e., headwind, since the initial course of the tanker is \( \psi_0 = 330^\circ \). The black line shows the tanker's trajectory in the absence of wind load, the green line – in the presence of wind load. It is clearly seen that the headwind insignificantly worsens the quality of control, but the amplitudes of the steady-state motion increase. In contrast, the unsteady period of motion of its amplitudes has lower values. As a result, the quality of management deteriorated, but not significantly, the \( Q_x \) indicator became equal to 3.6464 instead of the previous value of 2.8144.

The crosswind has a different effect on the tanker's trajectory. Figure 10 presents the result of the wind action on the trajectory of the tanker at \( q_a = 60^\circ \). The tanker is significantly displaced to the left of the center of the "crosshair." However, despite its ability to return to the center of the "crosshair" at a given wind load, the amplitude of oscillatory movements is too large to recognize control "crosshair effective" in the given conditions. In this case, the maximum thrust of the tanker's thruster is equal to \( T_{eprmax} = 50 \) kN. Suppose they are increased to the value \( T_{eprmax} = 250 \) kN. In that case, the control becomes more efficient but within limits unacceptable for practical purposes since the amplitudes of the tanker's movements relative to the given position are quite large (Fig. 11).

Figure 10. Tanker trajectory with crosshair control. Wind: \( v_a = 15 \) m/s, \( q_a = 60^\circ \). \( T_{eprmax} = 50 \) kN.
Figure 11. The trajectory of the tanker with the control of the "crosshair". Wind: \( v_a = 15 \text{ m/s}, \quad q_a = 60^\circ \). \( T_{e\text{rmax}} = 250 \text{kN} \).

A tailwind \( v_a = 15 \text{ m/s}, \quad q_a = 150^\circ \) leads to a noticeable initial deviation, which then significantly decreases and in a steady state of motion does not lead to large deviations from the given position determined by the "crosshair." Figure 12 shows the trajectory of the tanker (brown line) along with its trajectory in the absence of wind load (black line).

Figure 12. The trajectory of the tanker movement with the control of the "crosshair." Wind: \( v_a = 15 \text{ m/s}, \quad q_a = 150^\circ \). \( T_{e\text{rmax}} = 50 \text{kN} \) (\( Q_\Sigma = 10.7651 \)).

All the results obtained indicate that the wind along the center plane of the tanker does not fundamentally change the performance of the control system. However, the quality indicators deteriorate, while the side wind affects the operation of the system radically. Without a significant increase in the limiting thrust of the thrusters, the system cannot cope with the assigned control task. We present in tabular form the results of calculating the quality indicator for all modeling options (Table 2).

Table 2. Values of quality indicators of tanker movement control by "crosshair"

| Speed, \( v_a, \text{ m/s} \) and wind direction, \( q_a,^\circ \) | Values of quality indicators of tanker movement control by "crosshair" |
|----------------------------------------------------------|---------------------------------------------------------------------|
| Average over the entire control period                   | Period of unsteady motion \( t, \text{s} \)                          |
|                                                         | \( 1-20000 \) \qquad | \( 1-5300 \) \qquad | \( 5300-20000 \) |
| \( Q_{\text{long}} \)                                   | 1.0021 \qquad         | 1.5569 \qquad         | 0.7018 \qquad |
| \( Q_{\text{tran}} \)                                   | 2.6299 \qquad         | 4.0498 \qquad         | 1.8703 \qquad |
| \( Q_\Sigma \)                                          | 2.8144 \qquad         | 4.3387 \qquad         | 1.9977 \qquad |
| **15**                                                  | \( 1-20000 \) \qquad | \( 1-6700 \) \qquad | \( 6700-20000 \) |
| \( Q_{\text{long}} \)                                   | 2.0117 \qquad         | 2.4882 \qquad         | 1.7225 \qquad |
| \( Q_{\text{tran}} \)                                   | 3.0413 \qquad         | 4.0432 \qquad         | 2.3820 \qquad |
| \( Q_\Sigma \)                                          | 3.6464 \qquad         | 4.7475 \qquad         | 2.9396 \qquad |
| **330**                                                 | \( 1-20000 \) \qquad | \( 1-10000 \) \qquad | \( 10000-20000 \) |
| \( Q_{\text{long}} \)                                   | 3.8916 \qquad         | 5.4138 \qquad         | 0.9907 \qquad |
| \( Q_{\text{tran}} \)                                   | 10.0371 \qquad        | 14.0526 \qquad        | 2.0052 \qquad |
| **150**                                                 | \( Q_\Sigma \) \qquad | 10.7651 \qquad        | 15.0593 \qquad | 2.2365 \qquad |
The table lists the values for $Q_{\text{long}}$, $Q_{\text{tran}}$, and $Q$. These values make it possible to evaluate not only the total quality of control but also the contribution of control to it separately by longitudinal ($Q_{\text{long}}$) and lateral ($Q_{\text{tran}}$) deviations from the "crosshair" axes. In addition, Table 2 shows the values of the control quality for unsteady and steady periods of tanker movement when the "crosshair controls it." It is clear that in the initial period that the main component of the quality indicator is laid. Table 3 shows the indicators of the quality of control of the tanker's movement by the "crosshair," their average values for the entire period of control with different values of the thruster thrust.

Table 3. Values of quality indicators of tanker movement control "crosshair" (average for the entire period of control), with the wind: $v_\text{w} = 15 \text{ m/s}$, $q_\text{w} = 60^\circ$. Period time 20000 s.

| Quality indicators | Maximum thrust of the thruster, $T_{\text{rpm}(F,A)}$ kN |
|--------------------|------------------------------------------------------|
| $Q_{\text{long}}$ | 38.5090, 17.1889                                      |
| $Q_{\text{tran}}$ | 7.6089, 5.1353                                        |
| $Q$              | 39.2536, 17.9306                                       |

From the data in Table 3, it follows that an increase in the thrust of the thruster significantly affects the quality of control in the longitudinal direction; the quality indicator is halved. In the transverse direction, the quality of control increases slightly but not as significantly as in the longitudinal direction.

11. Conclusion
The results of the system simulations of tanker movement control during cargo operations at the oil terminal convincingly indicate the possibility of using the developed method of "crosshair" control. The proposed control method allows obtaining a technical result. The result is to ensure that the vessel is brought to a given position on the plane or to ensure the movement of the vessel along a given trajectory in compliance with the condition of periodically changing the given position, based on the requirements of energy efficiency and safety of a key ship operation. In our case, when performing a cargo operation for loading oil at an oil terminal on the open sea.

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