Assessment of the impact of waves on the steering of the vessel by deviations from the given line

Yu I Yudin, A L Boran-Keshishyan, V V Perevozov

Admiral Ushakov Maritime State University, 93, Lenin Ave., Novorossiysk, 353924, Russian Federation

E-mail: udinui@rambler.ru

Abstract. Steering by deviations involves a significant reduction in the influence of the "human factor" on the final result of the steering. Obviously, this can be achieved by automating the process of steering the vessel, including when performing mooring operations. At the same time, the participation of the boatmaster in the steering process is not excluded. Summarizing the existing approaches to automating the process of controlling the movement of the vessel, it is necessary to pay attention to the intellectualization of the entire process of steering the vessel, as an actual scientific direction of modern science in the field of navigation. Intellectualization is a higher level of improvement of steering of the vessel, it involves the use of innovative ideas for the implementation of steering processes. In particular, these ideas are based on the use of a method for steering by deviations from a given line (GL) of two points spaced along the length of the ship, at which navigation information sensors are installed that determine the kinematic and dynamic parameters of the ship's movement, namely, satellite navigation system receiver indicators and inertial sensors. To implement this method of control, both the main means of steering the vessel and the propulsion and steering complex, which includes active control means, can be used. The use of these and (or) other controls depends on the specific purpose of controlling the movement of the vessel.

1. Introduction

This article concerns, first of all, the control of the movement of a mooring vessel, which is moored to a given mooring object in open sea conditions, that is, in conditions of wind and wave loads.

At the final stage of mooring, when the traverse distance to the mooring vessel or any other mooring object is small, approximately three widths of the mooring vessel, control is used for deviations from the given line (GL). This line may be stationary, or it may move in a plane-parallel manner following the movement of the mooring object, for example, a mooring vessel moving in one way or another in open sea conditions.

The steering strategy of the mooring vessel at this stage has certain features, it is carried out according to the deviations of the bow and stern points spaced along the length of the mooring vessel from the selected GL, which moves along with the mooring vessel parallel to its diametrical plane [9], [10], [11]. At this stage, it is possible to move the ship with large drift angles, even lagging, so to perform its simulation, a mathematical model is selected in the movements [5]

These models allow us to describe motion with arbitrary drift angles. We have chosen the model proposed by A. P. Tumashik [5]. The developed software product allows you to simulate the controlled movement of the ship with a wide range of possible combinations of external factors that
affect the nature of its movement. This article, taking into account the limitations of its volume, presents an analysis of the results of simulating the lag motion of a mooring vessel in the most unfavorable direction of the wave in relation to the mooring vessel, that is, the wave moves into the side of the vessel, creating the maximum load on the controls, which are selected as maneuvering devices (MD). In this case, the mathematical model of MD is used.

2. Problem statement
The wave puts in front of the steering by deviations from the given line (GL) a number of tasks that occur due to the characteristics of the wave effects on the vessel. In particular, this is due to the fact that even a small change in the parameters of the wave can change the signs of the forces acting on the hull of the vessel from its side. First of all, this applies to the wavelength \( \lambda \), as it is known, its value determines the value of the key wave parameter \( \mu = \frac{2\pi \cos(q_w)}{\lambda} \) (\( q_w \)-the course angle of the wave), on which the signs of the reduction coefficients \( x_{1kr} \) and \( x_{2kr} \) depend [3], [5], [6], [7]. This is the reason for the difficult behavior of the vessel when maneuvering with the steering for deviations from the PL in the conditions of wave action. Conducting model experiments, as in the case of simulations with wind action [1], [2], here we consider the wave from the traverse directions with respect to the vessel, as only in this case is it possible to carry out the movement of the vessel with a lag without the operation of the main propulsion system, at the maximum load on the MD.

3. Description of the research results
Already from the first simulations, it turns out that with the actions of a traverse wave of 5 points, the maximum thrust of the PUT \( T_{eprmax} \) of at least 110 kN should be chosen to resist it. Figure 1 shows the three trajectories of the tanker under the action of the steering by deviations. On all trajectories, the initial course of the tanker is \( \varphi_0 = 60^\circ \), the wave direction is \( 150^\circ \), the wave length is 70 m and the score is 5 points. The trajectories differ in the maximum thrust of the maneuvering devices: \( T_{eprmax} = 130 \) kN ("red"), \( T_{eprmax} = 120 \) kN (black) and \( T_{eprmax} = 110 \) kN ("green"). Thrust impulse when controlling movement on all trajectories \( \Delta T_{epr} = 20 \) kN.

![Figure 1. Three vessel trajectories with different maximum thrust of the MD (T_{eprmax}) and its position on one of the trajectories ("green"). The radius of the scale circle on the left is 300 m](image)

Movement along these trajectories occurs at different speeds, which is characterized by the value of the transverse component of the linear velocity \( v_y \) and, as a result, the duration of the movement. However, on all trajectories, the control goal is achieved – the tanker enters the given line (GL) (shown in "purple" color in the figure). In Figure 1, on the left, the "green" trajectory shows the position of the tanker with a "blue" circle at 3706 from the movement. The field on the right shows the position of the tanker relative to the GL at the specified time on an enlarged scale (M=20). The numerical values of a number of kinematic characteristics of the vessel and the forces acting on its hull during movement [6], [7] along the trajectories for 1200 s of movement are given in Table 1.
Table 1. Power and kinematic parameters of the vessel movement on the trajectories shown in Figure 1.

| Characteristics at t = 1200 s | "Red" | "Black" | "Green" |
|-------------------------------|-------|---------|---------|
| Thrust pulse $\Delta T_{epr} = 20$ kN/s |       |         |         |
| Maximum thrust of the MD, $T_{eprmax}$, kN | 130   | 120     | 110     |
| Transverse variable wave force, $Y_w$, kN | -4687 | -4687   | -4690   |
| Variable wave moment, $M_w$, kNm | -4197 | -4305   | -4192   |
| Constant transverse force, $Y_CkN$ | -117  | -117    | 117     |
| Constant wave moment, $M_CkNm$ | -1009 | -1039   | -1007   |
| Transverse component of the hydrodynamic force, $Y_H$, kN | -56   | -38     | -19     |
| Hydrodynamic moment, $M_H$, kNm | -1348 | -543    | -266    |
| Moment from MD, $M_{pr}$, kNm | 12870 | 11880   | 10890   |
| Thrust of the MD, $T_{epr}$, kN | 130 + 0 | 120 + 0 | 110 + 0 |
| Drift angle, $\beta^\circ$ | 96.0  | 96.2    | 96      |
| Angular velocity, $\omega^\circ / \text{min}$ | 7.2   | 1.9     | 0.9     |
| Angular acceleration, $d\omega/dt$, $^\circ / \text{s}^2$ | 0.0066 | 0.00624 | 0.0056 |
| The transverse component of the velocity $v_y$, m/s | 0.23  | 0.17    | 0.09    |
| Transverse acceleration, $dv_y/dt$, m/s$^2$ | -0.101 | -0.1    | -0.1    |

With a decrease in the maximum thrust of the MD, the vessel's movement to the GL slows down, the entire operation requires more time, although most of the power characteristics are approximately at the same level, except for the moment from the MD. The detailed nature of the changes in the various motion parameters is shown in Figure 2. It shows the nature of the change in the angular acceleration of the vessel (in Figure OM_k), all the forces (in Figure MW, MCW, MH, MP_k) acting on it, and the difference in the deviations of the bow and stern from the GL (in Figure On_k–Ok_k). All these characteristics are calculated for the average value of the maximum thrust of the MD $T_{eprmax} = 120$ kN, for which a "cross-section" of the values of the parameters considered above is presented in the third column of Table 1. The diagrams are expanded over a time interval of 0 - 500 s to increase the resolution of the images of the parameters. It is clearly seen that the vessel is affected by moments that have a different frequency spectrum. Thus, the variable wave moment $M_w$ (in Figure MW_k) has a high frequency, with a period of about 6-7 s, and the hydrodynamic moment $M_H$ (in Figure MH_k) has a low frequency with a period of about 120 s. This is natural, since the vessel dampens high-frequency vibrations, being their filter. This is particularly evident in the third diagram of Figure 2, which shows the difference in the deviations of the bow and stern points of the tanker from the GL. In this diagram, the high frequencies are not visible at all, they are completely filtered out.

Figure 3 shows the results of modeling the vessel's movement in the direction of the GL with a variation of the main parameters of the wave. At the same time, the maximum thrust of the MD is assumed to be equal to $T_{eprmax} = 100$ kN, and the thrust impulse is $\Delta T_{epr} = 10$ kN. The wave, as in the previous tests described above, acts from the starboard traverse direction of 150°. On three ship trajectories ("brown": $\lambda = 40$ m, 3 points, "blue": $\lambda = 60$ m, 4 points and "green": $\lambda = 40$ m, 4 points) the control system copes with the task of bringing the vessel to the GL. The fourth trajectory ("light green": $\lambda = 60$ m, 5 points), corresponding to the movement of the vessel at a wave of 5 points, is directed in the direction opposite to the position of the GL, that is, the vessel is moving away from the GL, and, as a result, the control task is not performed. However, if you increase the maximum thrust to $T_{eprmax} = 140$ kN and the thrust impulse to $\Delta T_{epr} = 30$ kN, the vessel will reach the GL. The trajectory of the vessel with the specified control of the MD is shown in "red" ($\lambda = 60$ m, 5 points, $T_{eprmax} = 140$ kN). This trajectory shows the position of the vessel at 2228 s of movement, it is indicated by a "blue" circle, the position of the vessel relative to the GL is represented by a screenshot in Figure 3 on the right in an enlarged scale.
Figure 2. Force and kinematic parameters of the vessel's motion on the trajectory of approach to the GL (angular acceleration, °/s², moments of kNm, deviation difference, m),

\[ T_{\text{max}} = 120 \text{ kN}, \quad \Delta T_e = 20 \text{ kN}. \]

Figure 3. The trajectory of the approach of the vessel to the GL at different values of the wave parameters.

The values of the control quality criteria are used for numerical comparison of the control quality of the vessel when approaching the GL along the trajectories shown in Figure 3. The values of two criteria were selected as quality indicators:

\[ Q_1 = \sqrt{\sum_k (\psi_k - \psi_0)^2} \]

\[ Q_2 = \sqrt{\sum_k \left[ (d_n(k+1) - d_n(k))^2 + (d_k(k+1) - d_k(k))^2 \right]} \]

In this case, the first of them \((Q_1)\) evaluates the change in course \(\psi\) on the trajectory, the second \((Q_2)\) evaluates the change in the deviations of the nose \(d_n\) and stern \(d_k\) from the GL. The results of these calculations are presented in Table 2.

Table 2. Indicators of the quality of steering on trajectories with different wave scores.

| Trajectory color (wave length, m, wave score) | Number of control points | \(Q_1\) | \(Q_2\) |
|---------------------------------------------|--------------------------|--------|--------|
| "green" (40, 4)                            | 2000                     | 0.0930 | 0.0141 |
| "brown" (40, 3)                            | 1200                     | 0.0780 | 0.0727 |
| "blue" (60, 4)                              | 1600                     | 0.0866 | 0.572  |
| "red" (60, 5)                               | 2300                     | 0.0830 | 0.0075 |
Based on the data in Table 2, it can be concluded that the steering of the vessel for approaching the GL has a relatively higher quality when moving along the "red" trajectory. This is visually consistent with the view of the specified trajectory in Figure 3, where this trajectory looks the least meandering.

Above, we considered various options for steering the vessel movement to perform its approach to the GL under the action of oncoming waves to the side. However, it is of particular interest to steer the movement of the vessel to perform its approach to the GL under the action of a passing wave. In this regard, simulations of motion control were performed in the case of a passing traverse wave, which indicate that the wave passing to the board is a kind of stabilizing factor for the operation of the control system for deviations from the GL. A series of model tests was performed under the following conditions: wave from the direction of 330° at the initial course of the tanker \( \psi_0 = 60° \), the maximum thrust of the MD \( T_{\text{eprmax}} = 50 \text{ kN} \), the thrust impulse \( \Delta T_{\text{epr}} = 2 \text{ kN} \), the wavelength \( \lambda = 60 \text{ m} \), the score of 3, 4, 5 points. As can be seen, the values of \( T_{\text{eprmax}} \) and \( \Delta T_{\text{epr}} \) are significantly lower than in the case of oncoming traverse waves (for example, \( T_{\text{eprmax}} = 100 \text{ kN} \) and \( \Delta T_{\text{epr}} = 10 \text{ kN} \)). The vessel's trajectories are shown in Figure 4: "black" - 5 points, "green" - 4 points, "brown" - 3 points. On all trajectories, the deviation control system solves the task of moving to the GL, but for different times, depending on the score. The position of the tanker on the "brown" trajectory is indicated by a blue circle.

\[ \text{Figure 4. The trajectory of the vessel with a passing traverse wave: "black" - 5 points, "green" - 4 points, "brown" - 3 points (} \lambda = 60 \text{ m}). The radius of the scale circle is 300 m. \]

GL – "purple" straight line. Detailed results of vessel motion simulations are given in Table 3, which also shows the results of simulations with a wavelength variation \( \lambda = 30, 60, 90 \text{ m} \). The trajectories corresponding to the specified wavelengths are shown in Figure 5.

| Duration of the simulation, s | Wavelength, \( \lambda, \text{m} \) | Wave score | \( Q_1 \) | \( Q_2 \) | Color (figure) |
|-----------------------------|-----------------|------------|--------|--------|---------------|
| 890                         | 60              | 5          | 0.0882 | 0.0120 | "black" (4)   |
| 1100                        | 60              | 4          | 0.0981 | 0.0415 | "green" (4)   |
| 1400                        | 60              | 3          | 0.1070 | 0.2810 | "brown" (4)   |
| 890                         | 60              | 5          | 0.0882 | 0.0120 | "black" (5)   |
| 800                         | 30              | 5          | 0.0784 | 0.0520 | "green" (5)   |
| 1050                        | 90              | 5          | 0.0968 | 0.0214 | "brown" (5)   |

Figure 5 shows that the trajectories of the vessel's movement in the direction of the GL do not differ much from each other in appearance, this is typical for passing waves from the traverse. Recall that for the oncoming traverse wave, on the contrary, there was a strong dependence of the type of trajectory of the vessel in the direction of the GL on the wavelength, \( \lambda \) which in some cases corresponded to the instability of the steering process. For all trajectories, the quality indicators of motion steering \( Q_1 \) and \( Q_2 \) are given. In this case, you should pay attention to the fact that with a 5-
point wave, the control quality is higher with a wavelength of $\lambda = 60$ m. When it is increased to 90 m or reduced to 30 m, the quality of control decreases.

For one of the trajectories, Figures 6 and 7 provide additional information in graphical form. This is the "green" trajectory of the vessel from Figure 5, that is, corresponding to a wave of 5 points with a wavelength of 30 m, the maximum thrust of the MD $T_{\text{opmx}} = 50$ kN and the thrust pulse $\Delta T_{\text{opr}} = 2$ kN. Figure 6 shows diagrams of changes in the course of the vessel's movement in the direction of the GL: angular velocity $\omega$ (Omk), angular acceleration $\frac{d}{dt} \omega$ (Domk) and moments $M_w$ ($M_{wk}$), $M_H$ ($M_{Hy}$), $M_{pr}$ ($M_{pr}$) acting on it.

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Figure 5. The vessel's trajectories in a passing traverse wave: "black" - $\lambda = 60$ m, "green" - $\lambda = 30$ m, "brown" - $\lambda = 90$ m.

Figure 6. Changes in the angular velocity of the tanker ($^\circ$/s), angular acceleration (1/s$^2$) and all moments acting on the tanker (kN).

Figure 7. Change in the thrust of the bow and stern MD (kN) and the moment (kNm) from them for 500 seconds of movement.
Figure 6 shows that high-frequency and low-frequency components are present in the behavior of the vessel controlled by deviations. In addition, the angular acceleration \( \frac{d\omega}{dt} \) depends mainly on the variable component of the moment of impact of the wave \( M_w \). In Figure 6, in the lower diagram, this is a solid curve, which corresponds to a certain extent to the curve of change in angular acceleration, presented here in the middle diagram. The remaining moments are smaller and do not significantly affect the change in angular acceleration. Figure 7 shows the graphs of the time change in the thrust of the bow \( T_{epf} (T_{1k}) \) and the stern \( T_{epa} (T_{2k}) \) MD during the execution of the deviation control task. The antiphase change in the bow and stern MD thrust was incorporated in the control system operation algorithm. This provides a faster change in the torque generated by the operation of the MD, that is, a faster response of the vessel to changes in deviations. The nature of the change in this moment \( M_{pr} (M_{pk}) \) during the approach to the GL is shown in the lower diagram of Figure 7.

At the last stage of the research, additional conditions were introduced that complicate the task of approaching the vessel with the GL. The simulation of the vessel's movement in the direction of the GL is performed under the condition that the GL itself is mobile, that is, if the GL not only moves plane-parallel, but also rotates around a point on it with an angular velocity, for example, 0.03°/s. This rotation can occur clockwise or counterclockwise. The trajectory of the vessel in the process of moving towards the mobile GL and its position are shown in Figure 8. On the right margins of the picture, you can see that the control goal has been achieved, the tanker has reached the GL ("purple" straight). At the same time, despite its rotation, the vessel's diametrical plane remains approximately parallel to the GL by the time it reaches it. All this suggests that the control system for deviations from the GL successfully coped with the task of bringing the vessel to the GL.

Such simulations with the complicated task of approaching a rotating GL were carried out under conditions of wind or wave action. Examples of such simulations are shown in Figures 9 and 10. Thus, Figure 9 shows 4 tanker trajectories under the action of waves and the rotation of the GL. Specifically, the "black" trajectory corresponds to the following conditions: no agitation, GL does not rotate, maximum thrust MD \( T_{epmax} = 50 \text{ kN} \), thrust impulse \( \Delta T_{ep} = 2 \text{ kN} \);

![Figure 8](image1.png)

**Figure 8.** The trajectory of the tanker and its position under the condition of rotation of the GL: a - counterclockwise ("green" trajectory), b - clockwise ("black" trajectory).

![Figure 9](image2.png)

**Figure 9.** The trajectory and position of the vessel under the action of the waves and the rotation of the GL.
Figure 10. The trajectory and position of the vessel under the action of the wind and the rotation of the GL.

"green" trajectory is a traverse counter wave of 4 points, $\lambda = 60$ m, $T_{epr\text{max}} = 120$ kN, $\Delta T_{epr} = 30$ kN; "brown" is the same wave, rotation of the GL clockwise at a speed of 0.03°/s, $T_{epr\text{max}} = 120$ kN, $\Delta T_{epr} = 30$ kN; three "blue" trajectories, GL rotates counterclockwise – differ in the values of the thrust and momentum of the MD: upper $T_{epr\text{max}} = 120$ kN, $\Delta T_{epr} = 30$ kN, Middle $T_{epr\text{max}} = 130$ kN, $\Delta T_{epr} = 40$ kN, Lower $T_{epr\text{max}} = 150$ kN, $\Delta T_{epr} = 40$ kN. The last of the presented trajectories corresponds to the fulfillment of the condition of the vessel's exit to the GL. On this trajectory, the position of the ship 1228 s is given in the form of a "blue" circle, shown in the left half of Figure 9, while the position of the vessel relative to the GL is shown in the right part of Figure 9 in an enlarged scale. It is clearly visible that despite the difficult maneuvering conditions, the control system brings the vessel to the GL parallel to it.

Figure 10 shows the four trajectories of the vessel's movement in the direction of the GL under the action of the wind load and the rotation of the GL. Specifically, the "black" trajectory corresponds to the following conditions: no wind, GL does not rotate, maximum thrust MD $T_{epr\text{max}} = 50$ kN, thrust impulse $\Delta T_{epr} = 2$ kN; "green" trajectory is a traverse headwind of 10 m/s, $T_{epr\text{max}} = 100$ kN, $\Delta T_{epr} = 30$ kN; "brown" is the same wind, rotation of the GL clockwise at a speed of 0.03°/s, $T_{epr\text{max}} = 120$ kN, $\Delta T_{epr} = 30$ kN; "blue" trajectory is the same wind, the rotation of the GL counterclockwise, $T_{epr\text{max}} = 120$ kN, $\Delta T_{epr} = 30$ kN. On this last trajectory, the "blue" circle shows the position of the ship at 1458 s, in Figure 10 on the right – its position at this moment relative to the GL. Clearly visible is the good performance of the task in front of the control system - the vessel went to the GL and its diametrical plane is parallel to it.

In addition to Figures 9 and 10, two tables 4 and 5 are presented, in which numerical values of quality indicators $Q_1$ and $Q_2$ are given for the specified trajectories, which confirm visual assessments of the operation of the control system using the steering method for deviations from the GL.

All these numerous tests once again confirm the promising opportunities of the steering system for deviations from the GL. When the vessel is moving in a lag, that is, it allows you to solve the pressing problems of automation and further intellectualization of key maritime operations.

Table 4. Indicators of the quality of control for deviations from the GL under the influence of waves (the trajectory of the vessel in Figure 9).

| Wave 4 points, direction 150°, $\lambda =60$ m | Angular velocity of GL, $\omega = 0.03$°/s | Exit time to the GL, t, s | Maximum thrust MD, $T_{epr\text{max}}$, kN | Thrust pulse MD, $\Delta T_{epr}$, kN | The value of the steering quality criterion, $Q_1$ | The value of the steering quality criterion, $Q_2$ | Color of the trajectory in Figure 9 |
|---------------------------------------------|---------------------------------------------|-----------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| no                                          | no                                         | 1500                        | 50                                          | 2                                          | 0.1106                                      | 0.0080                                      | black                                       |
| there is no wind                            | no                                         | 1300                        | 120                                         | 30                                         | 0.0495                                      | 0.0088                                      | green                                       |
| there is clockwise rotation                 | no                                         | 1000                        | 120                                         | 30                                         | 0.2857                                      | 0.0110                                      | brown                                       |
| there is counterclockwise rotation          | no                                         | 1400                        | 120                                         | 30                                         | 0.4013                                      | 0.0081                                      | blue                                        |


Table 5. Indicators of the quality of steering by deviations from the GL under the influence of wind (the trajectory of the vessel in Figure 10).

| Wind power 10 m/s, direction 150° | Angular velocity of rotation GL, ω=0.03°/s | Exit time to the GL, t, s | Maximum thrust MD, T_{max}, kN | ΔT_{er}, kN | The value of the steering quality criterion, Q_1 | The value of the steering quality criterion, Q_2 | Color of the trajectory in Figure 10 |
|----------------------------------|---------------------------------------------|--------------------------|-------------------------------|------------|---------------------------------------------|---------------------------------------------|-------------------------------------|
| no                               | no                                          | 1450                     | 50                            | 2          | 0.1119                                      | 0.0060                                      | black                               |
| there is clockwise              | 2250                                         | 100                      | 30                            | 0.0446     | 0.0060                                      | green                                       |                                     |
| there is counterclockwise       | 1200                                         | 120                      | 30                            | 0.3384     | 0.0094                                      | brown                                       |                                     |
| there is clockwise              | 1500                                         | 120                      | 30                            | 0.4290     | 0.0080                                      | blue                                        |                                     |

4. Discussion of the results

The simulations of the vessel's movement during the mooring operation using the control system based on the deviations of two specified points of the vessel from a given line under the conditions of wave impact on it allow us to draw a number of conclusions.

For the purposes of steering by deviations, it is sufficient to select bow and stern maneuvering devices, the maximum thrust of which does not exceed 150 kN (in this case, it is typical for the vessel whose model was used in the simulations), and the possible speed of change of thrust does not exceed 40 kN/s. In particular, these requirements are met, for example, by a ST12 type propulsion system.

Such steering system by deviations, changing the values of the current thrusts of the bow and stern MD, achieves the goal - to move the vessel in a lag parallel to the GL. The vessel performs such movement, in particular, when the wind is up to 15 m/s and the waves are up to 5 points, using the measured deviations from the GL. The steering is carried out separately by the bow MD on the deviation of the bow point, and the aft MD on the deviation of the aft point. The algorithm itself includes a comparison of deviations, taking into account both their absolute values and signs. The system is efficient and effective with the correct selection of the maximum thrust and thrust impulses in a single act of their change. The entire selection is made empirically in the form of a simulation of the mooring vessel's maneuver using its identified mathematical model.

5. Conclusion

The proposed method of steering the movement of a maneuvering vessel when performing vessel key operations, in particular, mooring operations in open sea conditions, can be practically implemented with the appropriate equipment of the vessel with control means. The introduced restrictions on the use of certain technical controls are determined, first of all, by the main dimensional characteristics of the vessel. Restrictions on weather conditions in the area of maneuvering of the vessel and the degree of safety of the maneuver performed can be determined by the results of maneuvering simulations with variations in external conditions in a wide range of possible combinations of these conditions, primarily different in the characteristic features of wind-wave loads, as well as the loading conditions of the vessel.

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