

Statistical analysis of the causes of ship accidents showed that 10 % of accidents are due to the influence of irresistible force, about 15 % are the result of technical imperfection and sudden failure of ship equipment, and the remaining 75 % account for the «human factor» regardless of the cause of the accident. A detailed analysis of the causes of accidents reveals that they are caused by the actions of individuals, dominated by organizational errors by a group of operators in the preparation and execution of the maneuvering control process. At the same time, there is a gap between the complexity of modern equipment and the psychological capabilities of the human operator as an element of the human-machine system.

Analysis of accidents in the Bugsky-Dnestrovsky Liman Canal over the past 20 years has shown that 58.5 % of accidents occurred in the dark and under conditions of limited visibility. There were two causes of accidents: grounding and allision, 84.3 %; collisions, 28.8 %. This indicates the insufficient preparation of bridge crews for navigating the canal.

This paper has considered a procedure of bridge crew navigation training for planning safe motion coordinates while entering/leaving a port along the trajectory points, as well as actions in case of a pre-emergency and techniques to predict it. The coordinates of the travel points are determined at the intersection of rectilinear segments of the recommended safe rectilinear path on a chart. It is a relevant task to use new methods of planning the path and controlling the movement along it, taking into consideration the area for maneuvering, maneuverable properties of the vessel, as well as external influences, for timely detecting the deviation of parameters from those planned. The calculation of the planned coordinates is performed for the center of gravity of the vessel for the characteristic points of the path of movement (the beginning and end of a turn, the onset of braking) and trajectory points (rectilinear segments of the path through 0.2 cables, and curvilinear sections through 10 degrees). Coordinates of the assigned path are represented in the form of the linear matrices of the path rectilinear and curvilinear sections. The navigational motion control system consists of the devices to automatically determine deviations from planned coordinates and decision support systems to correct deviations detected. The proposed method to plan and control motion was investigated by computer simulation, the test was carried out under natural settings. Their results showed that the calculated optimal assigned trajectory enables accident-free guidance of the center of gravity along the predefined path by ship's control means and meets the established criteria of optimality. The proposed method could be used in the development of controls for automated vessels and is the only possible one for vessels with unattended operation

Keywords: navigational training, trajectory points, decision support systems, pre-emergency, unattended operation

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IMPROVING THE NAVIGATIONAL PREPARATION OF A BRIDGE CREW FOR ENTERING / LEAVING A PORT, INCLUDING ACTIVITIES IN CASE OF EMERGENCY

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1. Introduction

The preparation of a bridge crew for mooring operations includes two stages: organizationally administrative; navigational.

The organizationally administrative stage is aimed to determine the board of mooring, the structure and placement of mooring crews on the tank and stern, the number of mooring ends and cranes, as well as their distribution, other details of the process of mooring order.

Navigational training takes much time, so it should be carried out in advance. This training implies studying the navigational conditions of the area of confined port waters and port area, planning the coordinates of trajectory points of the path after the pilot's reception to the pier and from the berth to the landing site of the pilot when exiting the port.

General requirements and recommendations for planning a transition from the departure port dock to the pier of the port of arrival are outlined in the following documents:

1. Resolution by IMO A.893 (21)-1999 «Flight Planning Guide».
2. International Convention on Standards of Training, Certification, and Watch Keeping for Seafarers, 1978/95 (STCW-78/95).
3. Recommendations on the organization of navigator service on naval vessels of Ukraine (RShSU-98).
4. Bridge Procedures Guide, ICS, 2016 (BPG); FIFTH EDITION.
5. Bridge crew Management, IMO, 2002 (BTM).

However, the requirement to carry out planning from the berth to the berth is not met in the practice of navigation.

Existing IMO documents regulate in detail the planning from the moment the pilot disembarks at the departure port to the moment the pilot is admitted at the port of arrival.

The reason for this is the lack of methodology for planning the trajectory, as well as the explanation that the arrival of a pilot on board is accompanied by handing over a «Pilot's passage plan» to the captain of the ship.

The analysis of a Pilot's passage plan content in various parts of the world has revealed that such plans were not suitable for navigational purposes, as described in these documents. For this reason, a captain must prepare himself to handle the maneuvering when entering/leaving a port and formalize this as a «Ship's pilot passage plan» for navigational purposes.

Such a plan should be used as an IMO regulatory document for the captain. He has no other way to confirm that he is properly prepared to enter/exit a port. This shows the lack of a procedure of navigational training for the captain and an appropriate regulatory document in Ukraine and by IMO. For this reason, it is a relevant task to organize the navigational training for a captain to enter/exit a port and for sailing in dangerous areas of confined waters.

Since there is a risk of an accident when maneuvering in confined near-port and port waters, there is another aspect to the issue. This aspect is based on the need to prepare the crew involved in the multi-operator control over movement to be able to timely assess the moment of a pre-emergency and take the necessary measures. The compiled checklist on emergency response is of practical importance for preparing a bridge crew on ships, thereby reducing the risk of pre-emergencies.

This approach automates the process of controlling safe movement, including the use of decision support systems, preventing grounding and collisions with other vessels. The results of our research are very relevant for the training of navigators for small and long voyages, as well as pilots, as they could be used on a ship for automated planning of coordinates along trajectory points and for controlling movement along them for safe maneuvering, as well as for training navigators at specialized simulators to plan the movement.

2. Literature review and problem statement

The issue related to studying pilotage is very important at present as the number of accidents in the port still exceeds the number of accidents of ships at sea. An analysis of the causes of these events was given in work [1]. It was shown that accidents were related to the age of a pilot as the response to rapid changes in external factors weakens with age. The cited work states that the main cause of accidents in ports is the involvement of pilots who are over 65–68 years of age in the pilotage of ships. However, one must not draw conclusions about accident rates by referring only to the age of the person. For this reason, there are unresolved issues concerning the elimination of possible emergencies. In this regard, the proposed method for facilitating communication between the pilot and captain is relevant. It would not only help the pilot to respond adequately to possible changes in external factors but also reduce the risk of such factors.

Paper [2] reports a study aimed at verifying the reliability and validity of the proposed computer performance assessment tool for assessing marine pilotage. Typically, all pilots are trained on computer simulators of the navigation bridge. The cited paper describes an experiment that demonstrated the potential for greater reliability in assessing the effectiveness of

training at marine simulators, especially for the evaluation of technical skills. At the same time, it also confirmed the lack of reliability associated with conventional assessment methods, which should inspire further research and development of assessment methods at marine simulators. However, there is an unresolved issue related to planning the path and controlling the movement along it, taking into consideration the area for maneuvering, maneuverable properties of the vessel, as well as external influences, for timely detection of deviation of parameters from planned. The option of overcoming the relevant difficulties may be to introduce path planning with the help of trajectory points into software-based training. That could make it easier to control the ship.

Work [3] explores the task of pilotage planning. The main emphasis is not only on the safety of ship pilotage but also on the distribution of working shifts of pilots and making up schedules of their activities for each shift to navigate a vessel. The results of the cited work demonstrate that the branch and price algorithm is capable of solving instances of practical-related problems and that the algorithm outperforms the standard linear integer programming model and the solution method commonly used in practice. However, the issue of pilots' actions in emergencies and their interaction with the ship's crew was not included in the cited work. For this reason, compiling a checklist of emergency response could help reduce the risk of a fatal crash. Therefore, compiling and applying a check sheet is relevant on the ship.

The maneuverable characteristics of the vessel occupy the defining place among the necessary raw data for planning the path and organizing the movement. The most complete understanding of the inertial-braking qualities of the vessel in work [4] is provided by the values of the path and the time of braking under the condition of cargo and in the ballast, for all possible combinations of forward and reverse movement. All possible cases of using the combinations of forwarding and reverse modes would describe 50 path parameters and the same amount of time.

Currently, the ships have data for the condition of cargo and ballast in the form of linear charts by IMO, which are not adapted for computer processing and require special calculations for the current condition of the ship.

Stability data are not usually provided in ship documents. The vessel maneuverability data are available in part for rudder angles of 15° and 35°, usually, in the graphic form, making it impossible to use them for planning during maneuvering. When grading the rudder angles in 5°, about 70 parameters of maneuverability (forward, direct displacement, tactical diameter, and diameter of the established circulation) describe the geometric characteristics of circulation, 10 % of which are available on the ship, in the graphic form.

Given the lack of necessary data on ships, it is not possible to plan the trajectory with the precision necessary for guaranteed control safety. That does not allow for analytical planning of the coordinates of curvilinear sections of the path, which requires that this problem should be singled out as a fundamental one [4].

To provide the necessary data, it is recommended to use an estimation-experimental technique whose accuracy is about 8 %. It is recommended that the characteristics data should be presented as two tables that are placed on two A4 sheets. This form is convenient for computer processing and interpolating the required data for the current status of the ship.

The next most important issue in the planning of the moving process is to solve the task of planning curvilinear

sections of the path by trajectory points (TPs) [5] along the waypoints (WPs).

The following calculation sequence is recommended. Based on the coordinates from a WP table and the characteristics of maneuverability, for the chosen rudder angles, one determines the coordinates of the beginning and end of circulation by the method of segments [6], and then calculates the coordinates of intermediate TPs, which are represented in the form of the following matrices:

$$M_{tur12} = \left\| \left\| \begin{array}{c} \varphi_{ct1} \\ \lambda_{ct1} \end{array} \right\|, \left\| \begin{array}{c} \varphi_{t11} \\ \lambda_{t11} \end{array} \right\|, \left\| \begin{array}{c} \varphi_{t21} \\ \lambda_{t21} \end{array} \right\|, \dots, \left\| \begin{array}{c} \varphi_{it1} \\ \lambda_{it1} \end{array} \right\|, \left\| \begin{array}{c} \varphi_{n(t-1)} \\ \lambda_{n(t-1)} \end{array} \right\|, \left\| \begin{array}{c} \varphi_{PP1} \\ \lambda_{PP1} \end{array} \right\|, \left\| \begin{array}{c} \varphi_{et1} \\ \lambda_{et1} \end{array} \right\| \right\|, \quad (1)$$

for all $i \in \{1, \dots, n\}$, where n is the number of TPs along a curvilinear trajectory for WPs.

Next, one computes the coordinates of the points along the rectilinear trajectory from the initial first point $|\varphi_0, \lambda_0|$ before the turn $|\varphi_{ct1}, \lambda_{ct1}|$, and form an array of TPs in the form of the first travel matrix.

To form TP matrices of the entire travel, one forms arrays of travel matrices and TP turn matrices for all travel points in the following order:

– $M_{01}, M_{t12}, M_{12}, M_{t23}, M_{23}, \dots, M_{ti(i+1)}, M_{i(i+1)}, \dots, M_{t(m-1)m}, M_{(m-1)m}$, where M_{01} is the TP matrix of the linear section from the initial 0th WP to the point of giving a command to shift the rudder;

– M_{t12} is the TP turn matrix from the first WP to the second WP from the beginning H_{c1} to the end K_{c1} of a curvilinear segment; $M_{t12}, M_{t23}, M_{ti(i+1)}, M_{t(m-1)m}$ are the matrices of turn segments; $M_{12}, M_{23}, M_{i(i-1)}, M_{i(i+1)}$ are the TP matrices of rectilinear segments.

The calculation of the planned coordinates of TPs would be optimal as they are obtained for the maneuverable properties of a particular vessel with a reserve of control influences and are safe relative to navigational hazards.

The task of warranted safe control over the process of movement involves the need to guide the center of gravity of a vessel along the predetermined path, taking into consideration the actual width of maneuverable displacement. It also controls ship location by the high-precision tools for positioning and using available decision support systems to take timely and adequate measures to correct the deviations identified.

The formed matrix of the flight cycle «from pilot to pilot» can only be built on the ship because the pilot does not have the necessary data on the maneuverable properties of the vessel [8].

The main ways to improve accuracy, in addition to the application of a satellite system under a differential mode, include the need to calculate the abscissa of a turn pole (TP) [9, 11, 12]; accounting for the effect of the wind on the ship's movement [10]; recalculation of the coordinates of the satellite system's antenna to the center of gravity [13]; determining the abscissa of the position of the ship's center of gravity [14].

The calculation of the width of the maneuverable displacement in work [15] is performed automatically, typically when moving along the rectilinear sections of the path, with yaw angular rate ω_{pr} . At the turn's angular speed ω_r , the system is automatically switched to the mode of determining the abscissa of the pole of the turn and, based on it, the width of the maneuverable offset whose value is highlighted on the indicator of the navigation device. After the turn is over, the system automatically turns into an automatic mode for determining along the rectilinear sections of the path. At the same time, the shipmaster can control that the vessel safely passes areas of confined water, including curvilinear sections.

The issue of ship control under emergency is detailed in the International Code for the Management of Safe Ship Operation and The Prevention of Sea Pollution from Ships (ISM code). However, the Code contains information on the relationship and responsibilities of the coastal services, the ship's crew, and its organization when using the entire ship crew. During the ship movement when entering/leaving a port, the entire crew is busy performing the duties of ensuring safe motion in confined waters. For this reason, a special program and a checklist for preparing for emergencies are required. This situation can result in the loss or damage of a vessel, cargo, equipment, or other property, pollution of the environment, as well as loss or injury of people. There are no such recommendations at present.

Managing the safe operation of the vessel is primarily related to the organization and control of personnel in an emergency. The organization and control of personnel in emergencies, in turn, implies a clear-cut organization of the interaction between coastal and ship personnel. Emergency preparedness is regulated by section 8 of the ISM code. At the same time, the ISM code provides for the identification of possible risks, potential emergencies, planning activities for their prevention, as well as the elimination of consequences in the event of such situations.

Thus, navigation systems have been created to perform separate stages of planning and safe management of the planned path. However, the issue of complex navigational preparation of a bridge crew for multi-operator control of the ship when entering/leaving the port, including actions in case of a pre-emergency state, has not been addressed.

3. The aim and objectives of the study

The aim of this work is to improve the navigation plan for moving within a port area using a trajectory point method, as well as define the activities of the bridge crew in emergencies. That could enable the creation of a regulatory ISM code for representing work done in the form of a «ship's pilot passage plan» for navigational purposes.

That would make it possible to devise a regulatory IMO to record the mission accomplished in the form of a «Ship's pilot passage plan» for navigational purposes, which could prevent the possible errors by a captain or pilot in non-standard events.

To accomplish the aim, the following tasks have been set:

- to calculate the ship's braking path and the time when submitting commands to the telegraph using the path matrix;
- to build the matrices of trajectory points for a vessel entering/leaving a port;
- to compile a checklist of activities in pre-emergencies;
- to fulfill a shipboard pilotage plan.

4. The study materials and methods

Existing navigation devices on ships can produce information in a form that requires additional processing to make a decision. The need to use the operator's thinking abilities delays decision-making, which slows down control over the maneuvering process, including a pre-emergency.

To improve the accuracy and operative nature of information about the parameters of maneuvering, we shall indicate their location on the contour of the waterline as shown in Fig. 1.

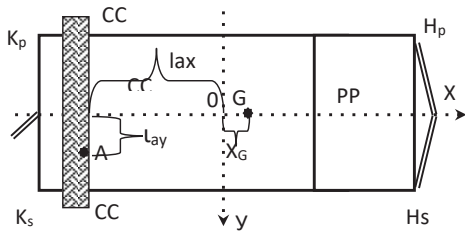


Fig. 1. Location of characteristic points on the contour of the waterline: *A* – the antenna of a satellite system; X_G – the center of gravity abscissa

Given the current state of shipbuilding science [4–10], the following navigational decision support systems can be offered, which produce information in the form ready for use in the process of maritime operations:

1. A navigation device for calculating maneuverable characteristics for the current state of a vessel and its mode of movement and representing data on the characteristics of braking and maneuverability in the form of tables, as given in Tables 1, 2.

2. A navigation device for calculating the abscissa of the center of gravity X_G [9]. This device makes it possible to automatically determine the coordinates of the ship's center of gravity by the characteristics of the empty ship, which are given in electronic format, based on the volume and location of the cargo. This makes it possible to speed up the process of controlling the ship along the predefined path.

3. A navigation device for the high-precision planning of the predefined route of the ship by the trajectory points of the center of gravity, representing the path in the form of the sum of the matrices of the coordinates of rectilinear and curvilinear sections of the path [5]. This device calculates, based on the available coordinates of the waypoints and characteristics of the maneuverability of the vessel, set in the program in advance, the matrices of the sections of the path along which the ship would navigate. The principle of work is based on the calculation of coordinates using a method of segments [12].

4. A system of selecting the number of tugboats for safe maneuvering under extreme conditions [3]. The principle of the system operation is based on determining the number of necessary tugboats by the magnitude of the force of inertia at the allowable speed in the port, which is necessary to ensure the guaranteed safety of maneuvering and to choose a mode of movement. The use of the device to inform the ship's control process during maneuvering when entering a port for

mooring could avoid an accident caused by motion control when there is a failure in the main engine operation.

5. A system for assessing the position of a turn pole and its visualization [9, 11, 12] makes it possible to calculate the TP abscissa based on the values of the vectors of the bow and stern tips of the vessel's waterline. These data come from the Doppler lag and show its position on the indicator. That notifies the shipmaster of the beginning of the turn and the expansion of the width of the maneuverable displacement lane.

6. A system for counting the coordinates of the satellite dish to the center of gravity of the vessel [9] makes it possible to significantly improve the accuracy of the ship's location. This is due to the fact that the corrections to the position of the antenna are many times higher than the radial rms error in determining the ship's location by modern satellite systems when they operate under a differential mode. The position of the antenna is given in the ship's documents regarding the origin of the coordinates in the form of a distance to the antenna along the $X-l_{ax}$ and $Y-l_{ay}$ axes, as shown in Fig. 1.

Table 1

Safmarine Nuba vessel circulation parameters

The angle of the transfer steering wheel	Parameters	Legend	Laden		In ballast	
			Experimentally estimated, buildings	Experimentally estimated, cables	Experimentally estimated, buildings	Experimentally estimated, cables
5°	Advance	l_1	7.48	6.61	6.18	5.46
	Direct displacement	l_2	7.1	6.27	5.59	4.94
	Tactical diameter	D_{tact}	13.62	12.03	10.83	9.56
	Constant diameter	D_{turn}	14.36	14.36	11.26	9.95
10°	Advance	l_1	5.03	4.44	4.15	3.66
	Direct displacement	l_2	4.25	3.75	3.23	2.86
	Tactical diameter	D_{tact}	8.34	7.36	6.46	5.70
	Constant diameter	D_{turn}	8.57	7.57	6.47	5.72
15°	Advance	l_1	3.94	3.48	3.25	2.87
	Direct displacement	l_2	2.98	2.63	2.19	1.93
	Tactical diameter	D_{tact}	6.00	5.30	4.52	3.99
	Constant diameter	D_{turn}	6.00	5.30	4.35	3.84
20°	Advance	l_1	3.29	2.91	2.71	2.40
	Direct displacement	l_2	3.23	1.97	1.56	1.38
	Tactical diameter	D_{tact}	4.60	4.07	3.37	2.97
	Constant diameter	D_{turn}	4.47	3.95	3.08	2.73
25°	Advance	l_1	2.85	2.52	2.35	2.07
	Direct displacement	l_2	1.71	1.51	1.14	1.00
	Tactical diameter	D_{tact}	3.65	3.22	2.58	2.28
	Constant diameter	D_{turn}	3.43	3.03	2.22	1.96
30°	Advance	l_1	2.52	2.23	2.08	1.83
	Direct displacement	l_2	1.33	1.18	0.82	0.73
	Tactical diameter	D_{tact}	2.95	2.60	2.00	1.77
	Constant diameter	D_{turn}	2.66	2.35	1.58	1.40
35°	Advance	l_1	2.27	2.01	1.87	1.65
	Direct displacement	l_2	1.04	0.92	0.58	0.51
	Tactical diameter	D_{tact}	2.40	2.12	1.55	1.37
	Constant diameter	D_{turn}	2.06	1.82	1.09	0.96
Angular speed of involuntary circulation $\pm\omega_0=0.12$						
Rear steering angle $\pm\delta_0=3^\circ$						

Table 2

The brake characteristics of Safmarine Nuba vessel in a tabular form

Active and Passive Braking										
Engine forward	In ballast $D_{bal}=19,283$ tons, $T_{mid}=5.79$ m									
	AHDS		AHS		AHH		AHM		AHF	
Engine astern	5.2 knots		7.5 knots		11.0 knots		12.6 knots		15.2 knots	
	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}
Stop	0.25	0.21	1.77	1.98	4.03	5.37	4.65	6.58	5.37	8.24
ASF	1.4	0.8	3	2.57	5.3	6	5.9	7.17	6.6	8.83
ASH	2.6	1.4	4.3	3.17	6.6	6.56	7.2	7.77	7.9	9.43
ASS	3.8	2	5.6	3.76	7.9	7.15	8.5	8.36	9.2	10
ASDS	5.2	2.74	7.07	5.08	9.33	8.57	9.94	9.82	10.67	11.55
Laden $D_{car}=39,650$ tons $T_{cp}=10.42$ m										
Engine forward	AHF		AHM		AHH		AHS		AHDS	
Engine astern	14.5 knots		12.0 knots		10.3 knots		7.0 knots		5.0 knots	
	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}
Stop	10.5	15.79	8.96	12.4	7.48	9.67	2.56	2.76	0.25	0.21
ASF	12.4	16.95	10.9	13.56	9.43	10.83	4.51	3.92	2.1	1.12
ASH	14.4	18.11	12.86	14.72	14.6	12	6.5	5.08	4	2.04
ASS	16.35	19.27	14.8	15.9	13.3	13.15	8.4	6.24	5.9	3
ASDS	18.48	20.83	16.93	17.37	15.46	14.59	10.54	7.59	7.57	4
Characteristics of acceleration										
-	In ballast $D_{bal}=19,283$ tons, $T_{mid}=5.79$ m									
	AHDS		AHS		AHH		AHM		AHF	
t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	
Stop	18.7	10.3	13	10.3	8.9	10.3	7.7	10.3	6.4	10.3
AHDS	-	-	6.9	7.4	6.4	9.2	5.8	9.5	5.2	9.8
AHS	-	-	-	-	4.8	7.5	4.8	8.4	4.5	9.1
AHH	-	-	-	-	-	-	2.05	4	3.2	7
AHM	-	-	-	-	-	-	-	-	2.3	5.2
-	Laden $D_{car}=39,650$ tons $T_{mid}=10.42$ m									
	AHF		AHM		AHH		AHS		AHDS	
t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	
Stop	13.6	20.8	16.4	20.8	19.1	20.8	28.1	20.8	39.4	20.8
AHDS	10.9	19.7	12.4	19.1	13.6	18.4	14.4	14.4	-	-
AHS	9.7	18.5	10.4	17.1	10.5	15.3	-	-	-	-
AHH	7	14.5	4.9	8.9	-	-	-	-	-	-
AHM	4.8	10.5	-	-	-	-	-	-	-	-
Vessel braking characteristics										
-	In ballast $D_{bal}=19,283$ tons, $T_{mid}=5.79$ m									
	AHDS		AHS		AHH		AHM		AHF	
t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	
AHF	15.3	19	9.3	15.1	4.5	9.7	2.8	6.6	-	-
AHM	14.5	17.1	8.3	12.8	2.5	4.9	-	-	-	-
AHH	13.7	15.6	7.3	10.7	-	-	-	-	-	-
AHS	10.3	10.4	-	-	-	-	-	-	-	-
-	Laden $D_{car}=39,650$ tons $T_{mid}=10.42$ m									
	AHF		AHM		AHH		AHS		AHDS	
t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	t_{min}	S_{cab}	
AHF	-	-	6	13.4	10.1	20.2	20.4	31	32.2	38.3
AHM	-	-	-	-	5.9	11.2	18.2	26.3	30.4	34.3
AHH	-	-	-	-	-	-	15.8	21.7	28.5	30.9
AHS	-	-	-	-	-	-	-	-	20.6	20

7. A system of high-precision control over the deviation of the center of gravity of the vessel, from the line of the predefined path, to prevent the ship's grounding, calculates the lateral displacement of the ship's CG relative to the nearest planned trajectory point. It allows for the timely identification of unacceptable sway to take adequate measures to compensate for it [7]. Continuous monitoring of lateral bias automatically makes it possible to assess in a timely manner an unacceptable shift relative to the planned trajectory determined by the high-precision TP matrix.

8. A device for assessing the risk of collision of ships on the course angle of the line of relative movement makes it possible to assess the risk of collision of ships based on a single information parameter – a change in the direction of RML. That makes it possible to increase the speed of decision-making by the shipmaster on the choice of maneuver for divergence.

9. A system for selecting the type of maneuver for divergence based on the nature of change in the line of relative movement during maneuvering [4] makes it possible to determine, based on a catalog, the nature of change in the relative movement based on the situation of convergence and to choose the type of maneuver. A given maneuver must comply with the rules of vessel divergence MPPSS-72/2016.

10. A navigational device for assessing excessive, dangerous, or emergency rapprochement makes it possible to automatically constantly monitor it and, according to the law of maneuver of the last moment, to determine the nature of change in the situation. Also, this device selects the type of maneuver for timely collision prevention.

11. A device for estimating the width of the maneuverable displacement [10] makes it possible to constantly determine the width of the maneuverable displacement and requires the introduction of data on the current angular velocity ω_r , the boundary value of the angular yaw rate ω_{pr} when following a constant course, and the accuracy in determining the location of the radial root mean square error M_0 . It takes time to enter and calculate these data. For this reason, better and faster methods for determining maneuverable bias should be used, which make it possible to constantly show the true width of the maneuvering bias, without the need to enter the data required for calculations.

In the curvilinear motion shown in Fig. 2, the width of the maneuverable displacement of the vessel increases compared to the rectilinear section and is determined by the position of TPs. The limit for determining the nature of the movement is the magnitude of ω_{pr} . To establish the dependences describing the width of the maneuverable displacement

in curvilinear motion, the diagram of the ship's turn has been considered, depicted in Fig. 2. The diagram shows the location of TPs within the hull of the ship when moving forward. The case of TO location outside the hull is not necessary as it corresponds to the use of anchors, tugboats, and mooring ends and is not of interest for movement in the canals and fairways when the vessel is controlled by a steering wheel.

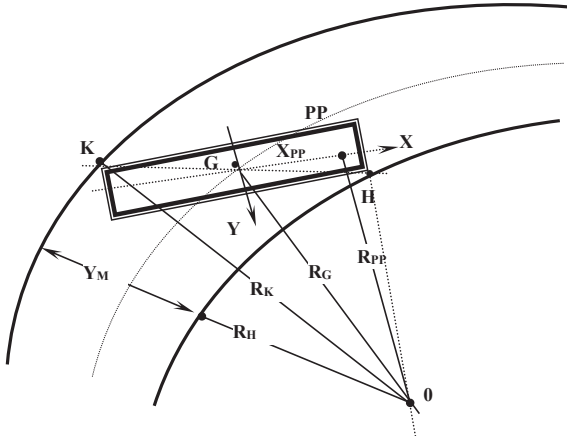


Fig. 2. Curvilinear motion scheme at the turn of a ship

Fig. 2 illustrates that the width of the maneuverable displacement lane is equal to the difference in the curvature radii of the trajectories of stern points R_s , bow points R_b , and can be calculated from the following formula:

$$Y_M = R_s - R_b, \quad (2)$$

Given the radial RMS error in determining the location M_0 , a formula for determining the likely width of the maneuverable displacement [15] when the ship rotates at Y_{MGK} :

$$Y_{MGK} = R_s - R_b + 2M_0 = \sqrt{\left(X_{PP} + \frac{L}{2}\right)^2 + \left(R_{PP} + \frac{B_c}{2}\right)^2} - \sqrt{R_G^2 + (L_x/2)^2} - R_G \cdot L_x \cdot \cos \gamma + 2M_0, \quad (3)$$

where X_{PP} is the abscissa of the turn pole; L is the length of the vessel between perpendiculars; R_{PP} is the TP circulation radius; B_c is the width of the ship; R_G is the curvature radius of the center of gravity; L_x is the characteristic linear size of CE, $L_x = \sqrt{L^2 + B_c^2}$; γ is the inner angle:

$$\gamma = \alpha - \beta = \arcsin(R_{PP}/R_G) - \arcsin((B_c/2)/(L_x/2)). \quad (4)$$

The above formalized model (3) to determine the likely width of the maneuverable displacement in the curvilinear motion of the vessel establishes its dependence on the abscissa of TP and the radius of circulation at the designated angle of the rudder. Thus, the value of TP abscissa and the value of the circulation radius of the center of gravity and the stern of the vessel set the size of the water area required to turn a vessel and for safe maneuvering.

Work [10] gives a block diagram (Fig. 3) of the algorithm of operation of the navigation device to estimate the width of the maneuverable displacement.

The width of the lane occupied by the vessel when moving along a constant course is the value of projections of

the extreme points of characteristic linear size $L_x = \sqrt{L^2 + B_c^2}$ onto the line perpendicular to the vector of movement of the ship:

$$B_t = L_x \cdot \sin \left(C + \arctg \left(\frac{B_c}{L} \right) \right), \quad (5)$$

where C is the total angle of displacement.

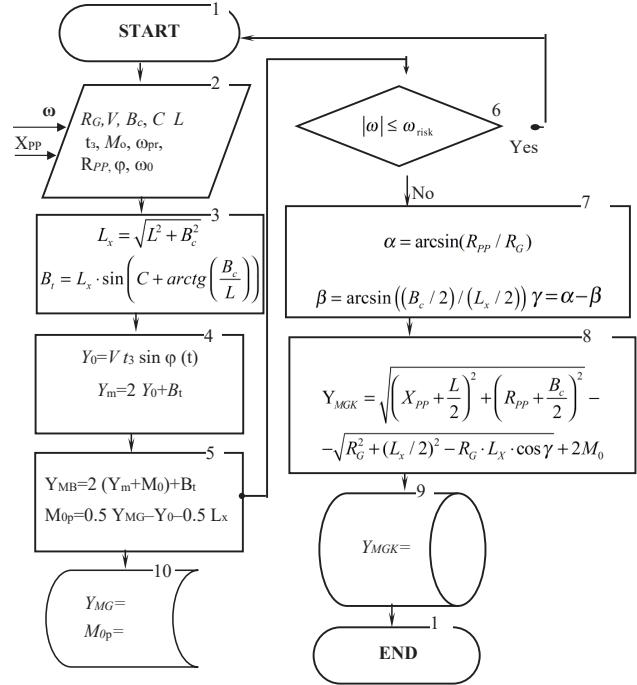


Fig. 3. Flowchart of the system of control and registration of the probable width of the ship's maneuverable displacement lane

The width of the maneuverable displacement Y_m is determined from the following formula:

$$Y_m = 2 Y_0 + B_t, \quad (6)$$

where Y_0 is the lateral shift of CG from the line of the planned path due to yaw. It can be defined from the following formula:

$$Y_0 = V t_3 \sin \phi(t), \quad (7)$$

where t_3 is the delay in processing information by a control system; $\phi(t)$ is the yaw angle; V is the speed of the ship on ag.

A possible width of the maneuvering shift lane is determined by the linear addition of Y_m and the rms error in determining the ship location M_0 :

$$Y_{MGK} = 2(Y_m + M_0) + B_t. \quad (8)$$

The required and sufficient condition for the safe passage of a single vessel through a limited area is to comply with the requirement that the allowable width of the safe lane Y_{MP} is greater than the current width of the lane Y_{MT} , that is, $Y_{MP} > Y_{MT}$. From this inequality, it is possible to determine the requirements for the necessary accuracy of determining the location M_{0p} to ensure the non-emergency passage of the limited water area, taking into consideration the maximum value of the angle of the shift $C = 90 - \arctg(B/L)$,

when the width of the lane occupied by the ship is maximum and equal to L_x :

$$M_{0p} < 0.5Y_{mb} - Y_0 - 0.5L_x. \tag{9}$$

Thus, the system operates under two modes. The principle of its work is based on the fact that when turning the angular velocity increases significantly, and the shipmaster assigns such a value to the ω_{pr} parameter at which the system automatically enters a turn mode. Determining the width of maneuverable displacement in rectilinear motion under a constant mode; automatically switch to determine the width of the shift in curvilinear motion, and switch to a constant course after the turn.

A list of the initial data needed to operate a system that permanently determines the likely width of the lane is given in Table 3.

Table 3

Initial data for a system that permanently determines the likely width of the lane

No.	Designation	Parameter name	Calculation source
1	ω_f	Angular yaw rate	Sensor
2	ω_{pr}	Angular yaw rate at constant course	Shipmaster
3	X_{pp}	Turn pole abscissa	Navigation device
4	ϕ	Yaw rate at constant course	Shipmaster
5	C	Total drift angle	Shipmaster
6	L	Vessel length between perpendiculars	Ship documents
7	B_c	Width amidships	Ship documents
8	t_d	Information processing delay time	Shipmaster
9	V	Vessel speed on the lag	Sensor
10	R_G	Gravity center circulation radius	Ship documents
11	R_{pp}	Turn pole radius	$R_{pp} = \sqrt{R_G^2 - X_{pp}^2}$
12	M_0	Radial RMS error in determining the location	Ship documents
Output data			
1	Y_{MG}	Likely width of rectilinear movement lane	
2	Y_{MGK}	Likely width of curvilinear movement lane	
3	M_{0p}	Required accuracy for determining the location for confined waters	

In order to organize safe navigation, the system must operate continuously in areas of coastal and confined waters.

Before entering the area of confined waters, the shipmaster must assess the angle of yaw ϕ and the corresponding angular velocity ω_{pr} , the total drift angle C for the accepted control technique. The manual or automatic control technique influences the parameters that determine the width of the side shift lane Y_0 .

Using those navigation devices makes it possible to develop a system of information support for the planning process and for safe control of the vessel in preparing and maneuvering when entering/leaving a port for navigational purposes. The data provided by navigation devices could help the shipmaster to reduce the risk of accidents under con-

finned conditions, which is relevant at present. However, there is another aspect to the issue related to that the crew members are positioned, in this case, for rush jobs. The usual ship schedule for alarms does not take this fact into consideration.

A method to solve this problem is to use techniques from information theory about the failure of control tools, as well as programs to prepare the bridge crew to work in emergencies.

The means of solving the goals set is to use computer simulation of the operations of the ship's safe maneuvering system when the ship's controls are not functioning. The solution technology involves constructing a ship control emergency flowchart and programs to prepare bridge operators to work in extreme situations.

Our examination of the causes of ship accidents that actually occurred shows that they are caused by inadequate activities by the shipmaster regarding the current situation. That makes it impossible to ensure that his functional responsibilities in the maneuvering management system are performed.

Therefore, the organization of control over the movement of a ship under standard, as well as confined conditions, and in emergencies requires the use of meaningful models and algorithms that are adequate to the conditions of navigation. When working under standard conditions, the shipmaster operates at the level of stable skills. Under extreme conditions, it is necessary to use thought operations to find solutions to emerging problems of maneuvering control, which leads to a slowdown in the control process.

The speed of the control process and the lack of time to obtain correct information about the process of movement requires the pre-preparation of activities by the bridge crew under extreme conditions when the means of motion and maneuvering fail.

The adequacy of the ship's control process under different sailing conditions is ensured on the principles of synergistic team control. The increase in maneuvering efficiency as a result of three-operator control is due to the combination of navigation information from coastal sources, ship navigation devices, and a pilot on board the ship. However, the peculiarity of the ship's synergistic control system is that the responsibility for the decision is on the captain. That substantiates the recommendation for a captain to prepare to manage the bridge crew independently under any conditions while considering the information from the shore and pilot as additional and auxiliary.

In normal conditions, navigation safety is justified by two activities of the shipmaster. First, it is proper planning of the trajectory and control over the position of the center of gravity of the vessel relative to the predefined path. Second, a timely assessment of excessive, dangerous, or accidental rapprochement at shallow depths or other vessels.

The determining factor, in this case, is to calculate a safe speed of movement under extreme navigation conditions. An accident is due to the inadequacy of a shipmaster's activities to the specificity of a situation. At the same time, the main factors influencing the choice of mode of movement and control are the following two – the speed of the ship and the distance to the danger D_{ob} , at the time of its detection, or failure of main controls.

The proposed algorithm for selecting a safe speed is based on comparing the distance to danger with the characteristics of the ship, the capacity of tugboats, and taking into consideration the time required to make a decision and execute it. The dependences to calculate safe speed under extreme conditions were derived inversely for an event where the danger

is right along the bow of the ship, is stationary, and the main engine of the ship failed at speed V_{0p} . No collision would occur if the distance D_{ob} at which the danger was detected makes it possible to assess the situation, make a decision, and stop the movement using tugboats at a safe distance from the danger (Fig. 4):

$$D_{ob} \geq S_L + m_D + S_{pr} + S_{br} + S_s + D_{st}, \quad (10)$$

where S_L is the distance from the radar antenna to the ship's extreme bow point; m_D is the RMS error in determining the distance to danger; S_{pr} is the distance that the ship travels during decision-making; S_{br} is a braking path traveled by ship until tugboats stop it; S_s is the navigation reserve introduced by the shipmaster to compensate for errors of factors taken into consideration; D_{st} is the distance from the danger at which the ship stops.

The values of S_L and m_D are known to the shipmaster. The value of S_{pr} can be calculated from the following formula:

$$S_{pr} = V_{0p} \cdot t_{pr}, \quad (11)$$

where V_{0p} is the allowable speed of a vessel according to the rules of a port; t_{pr} is the time to analyze the situation and make a decision from the moment the engine failure was detected to a command to tugboat-assisted braking.

The value of t_{pr} depends on the extent to which the bridge crew is prepared to make a decision in an accident. Experience with shipmasters on the bridge, as well as studies into the speed of perception, show that the duration of the process

of analyzing the situation and making a decision takes about 1 minute.

In order to calculate safe maneuvering, inequality (10) must be solved relative to S_{br} by accepting $D_{st}=0$, that is, considering the extreme case of a stop at distance S_s :

$$S_{br} = D_{ob} - S_L - m_D - S_{pr} - S_s. \quad (12)$$

Safety can be ensured when the force of the tugboat propeller thrust provides for stopping a ship when its main engine fails. This can be achieved by taking into consideration the recoil of the anchor, provided $\sum_{i=1}^n P_{x_{bi}} \geq kV_{0p}^2 - \sum_{i=1}^2 P_{ai}$, that is the force of the tugboat thrust along the X axis is equal to the force of the propeller resistance when operating at FA required to damp the inertia kV_{0p}^2 .

Taking into consideration formula (12), a block scheme of the algorithm [4] was built, shown in Fig. 5. This takes into consideration the allowable speed of movement in the port rules V_{0p} when maneuvering on the water area, the current speed V_f and the allowable speed of movement V_{ex} , calculated by the force of tugboat thrust along the X axis. A value of the navigation reserve is taken equal to 0.1 cable when driving in the port area, and up to 1 cable in the near-port waters.

After entering the relevant data, a computer screen displays the message «Follow the safe speed V_{sp} =knots». This problem can be solved graphically using data on the characteristics of braking the vessel in the form of a dependence of the path and time on the initial speed, the required force of the propeller, and the power of the tugboat.

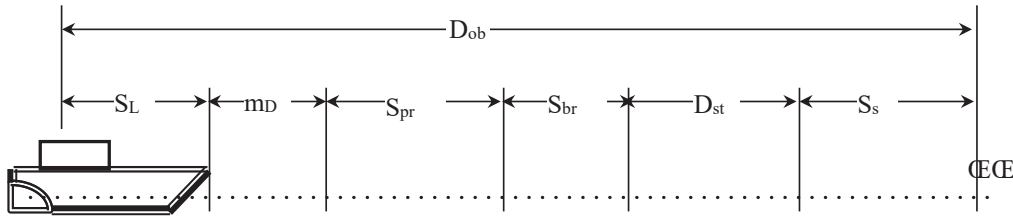


Fig. 4. Ship movement when the main engine fails

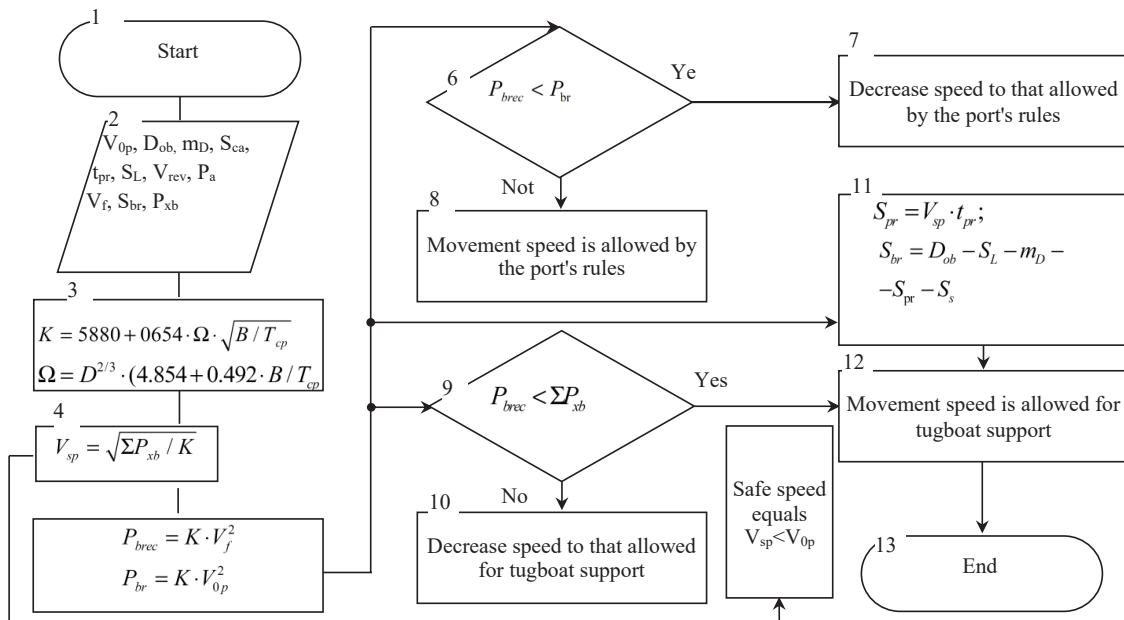


Fig. 5. Flowchart for calculating the safe speed when the main engine fails

The allowable speed of movement for tugboat support V_{sp} can be calculated from the following formula:

$$V_{sp} = \sqrt{\Sigma P_{xb} / K}, \quad (13)$$

where ΣP_{xb} is the total force of tugboat thrust along the X axis; K is the hydrodynamic resistance factor of the accompanying vessel.

Similarly, one can calculate a safe speed based on the characteristics of maneuverability, and, instead of the value of S_{br} , one needs to use the value of forwarding at a rudder angle of 15° .

To describe the maneuvering process, we operate with discrete units of time – minutes, hours, and days. Discreteness makes it possible to strictly formalize the predefined algorithm and describe external influences. The actual process of movement differs from the planned one due to the unpredictability of external influences and the possible failure of the ship's controls.

Real time of simple systems is one-dimensional, and complex systems – multidimensional. The speed, pace, and other characteristics of the time changes in the parameters describing the maneuvering process are different. The time models used tend to allow reversibility but do not properly take into consideration the multidimensionality and heterogeneity of real time. Planning the trajectory of the movement when maneuvering, work [5] proposed an inverse method whose peculiarity is that it is built at the end of the maneuver, taking into consideration maneuverable characteristics.

Information about the maneuvering process is based on its hierarchy. Conditionally, when providing information on the bridge for operational use, it is recommended to produce it by a technique of three zones.

The first zone is the information that is employed directly at the moment, which is in front of your eyes on a desktop.

The second zone is information that may be urgently needed as an addition to the basic info, or the information that a shipmaster works with in case of an emergency.

The second zone is located at the surface of a work desk and the adjacent section. In a computer, the analog of the second zone can be pictograms of work folders (catalogs) displayed on the «desktop», containing original information about the ship, which is used relatively rarely in the current state.

This program can be applied to prepare for maneuvering for the predefined load condition.

The third zone should be on the desktop, an analog of the third zone can be pictograms of work folders. In the computer version, the third «archive» zone can be hidden inside the folder structure or even stored on external media, for example, recorded on CDs.

For easy orientation in large amounts of accumulated information, it is a good idea to use a coder to quickly determine which section a unit of storage belongs to.

The codifier should be easy to work with, and it can be based on numbers, symbols of operations performed, or the nature of archival data.

For a high-precision automatic procedure for planning the trajectory of navigation under confined conditions, a maneuvering control system is proposed, including elements of tugboat planning and an assessment of the background of an accident; the system is illustrated in Fig. 6.

When the main engine fails, the tugboats provide safe movement as the choice of their power is based on the size of the propeller's thrust force for the allowable speed in the port.

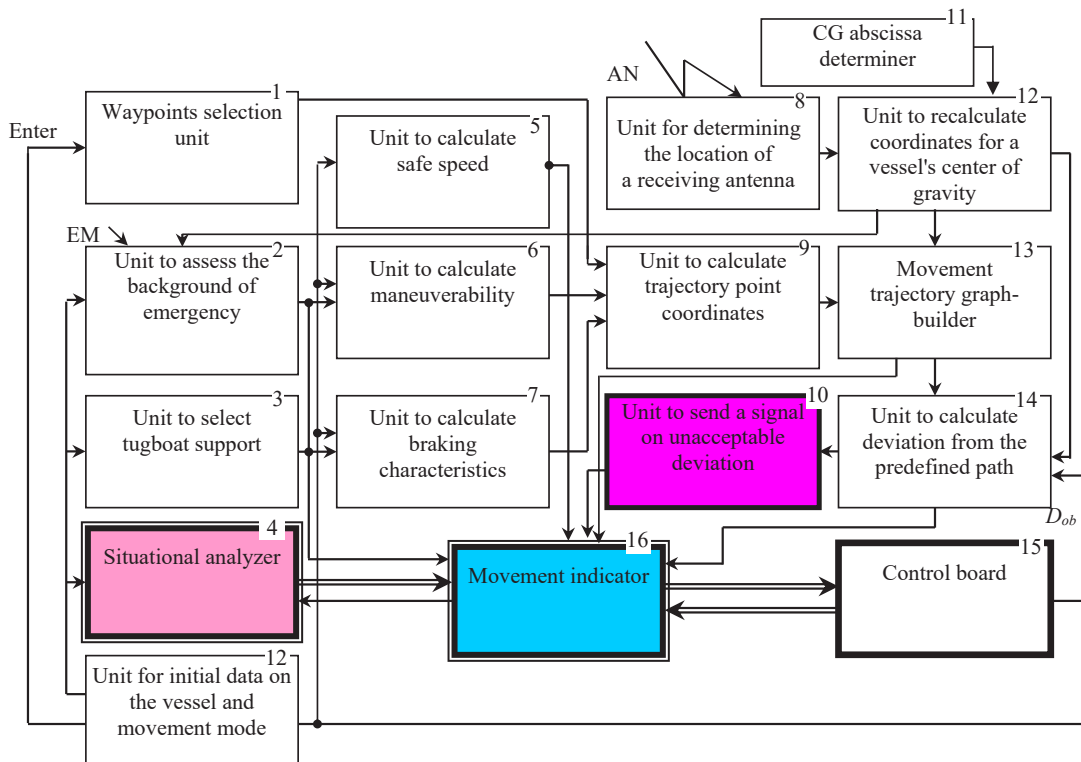


Fig. 6. Functional scheme of the ship's emergency control system in case of emergency

5. Results of studying the trajectory of the ship's center of gravity using trajectory points matrices

5. 1. Calculating the onset of braking using a path matrix

This system is designed for navigational purposes to ensure the safe entering/leaving a port by a ship. A given plan includes planning for a safe path and controlling the movement along it personally by the captain, including the use of maneuverability data, which the pilot usually does not have.

The following algorithm of calculations and graphic constructions is recommended for devising a regulatory document for the captain to prepare the vessel for entering/leaving a port and represent it as a motion scheme for navigational purposes:

1. Determine the coordinates of waypoints at intersections of rectilinear sections along the line of the recommended path from the coordinates of the port entrance point to the pier, enter them into Table 4. Depending on the configuration of the operating area and the maneuverable characteristics of the vessel, calculate the course, distance, turning angle, and the angle of rudder shift along each section of the path; fill in a WP table. Further calculations are as follows.

Table 4

Waypoints for a scenario planning by an inverse technique for the motor ship Safmarine Nuba to enter the port of Chernomorsk, pier Fishing Port 8

No.	Point coordinate	Distance, cable	Course to next point	Turning angle	Rudder shift angle
0	$\varphi=46^{\circ}18,93' \text{ N};$ $\lambda=30^{\circ}41,58' \text{ E}$	11.9	288.5°	–	–
1	$\varphi=46^{\circ}19,30' \text{ N};$ $\lambda=30^{\circ}39,95' \text{ E}$	4.4	345.7°	57.2	10°
2	$\varphi=46^{\circ}19,71' \text{ N};$ $\lambda=30^{\circ}39,80' \text{ E}$	1.3	020.8°	35.1	10°
3	$\varphi=46^{\circ}19,83' \text{ N};$ $\lambda=30^{\circ}39,86' \text{ E}$	–	–	–	–

2. Choose a value of the brake track S_{br} for the mode SA – FAS from Table 2; mark its value from a center of gravity when stopping at the pier; derive the starting point of braking.

Assume that the entire length of the way from the passage of the canal to mooring the dock was traveled by ship at the smallest forward motion (the smallest forward motion speed for this vessel is 5.0 knots). According to the maneuvering vessel characteristics, the distance of active braking for the smallest forward motion is 0.21 cable. We start calculation from the final third point. The distance from it to the starting point of braking (S_{br}) is 0.21 cable. To this end, we use formulas (14) to (18) calculate the coordinates of the beginning of braking, which would form the braking matrix. The results of our calculations are given in Table 5.

$$DLat = S_{br} \cdot \cos K, \tag{14}$$

where K is the course before the turn begins.

$$DLon = DMP \cdot \operatorname{tg} K, \tag{15}$$

where DMP is the difference of the meridional parts.

The difference of the meridional parts can be determined from formula (16).

$$DMP = 3437,75 \cdot \ln \left[\operatorname{tg} (45^{\circ} + \varphi_e / 2) \div \operatorname{tg} (45^{\circ} + \varphi_c / 2) \right], \tag{16}$$

$$\varphi_{br} = \varphi_e + DLat, \tag{17}$$

where φ_k is the latitude of a turning point.

$$\lambda_{br} = \lambda_e + DLon, \tag{18}$$

where λ_k is the longitude of a turning point.

Table 5

The coordinates of the starting point of braking

M_{br}	φ_{br}	λ_{br}
	46°18,43880' N	30°46,2675' E

5. 2. The matrix of trajectory points for entering/leaving a port

The next step is to build a matrix of the ship's path:

1. Determine the angle of turning for each WP.
2. Determine a rudder shift angle based on the value of a turn angle and the characteristics of turning for it.
3. Based on the coordinates of a waypoint and the characteristics of turning, use a method of segments to determine the coordinates of the starting point and the end of the turn. The results of our calculations of points 2–4 are given in Table 4.

4. Use a method of segments to calculate the coordinates of trajectory points in the curvilinear section of the path, build a TP matrix for a given WP.

5. For each WP, determine the coordinates of the curvilinear trajectory by a method of segments, build a matrix for each of them.

The construction of these matrices employs formulas (14) to (18), substituting the segment S_{br} in formula (14) with a segment MC, calculated every 10° of the turn. In formulas (17), (18), instead of φ_c and λ_c , the turning point $M(\varphi_m; \lambda_m)$ is used. The matrices of the curvilinear sections of the turn (M_{t1}, M_{t2}) are given in Tables 6, 7.

It should be remembered that in order to calculate the first section, φ_{br} and λ_{br} are the coordinates of the starting point of the turn (φ_c, λ_c). For each section of the turn, the data on the latitude and longitude difference between each segment MC and ME were calculated. After deriving the segments of the latitude difference and the longitude difference, simple navigational formulas (17), (18) are used to determine the coordinates of these points.

Table 6

Matrix of trajectory points of turn 1

M_{t1}	φ_{e1}	46°19,24828' N	λ_{e1}	30°39,99608' E
	φ_{e11}	46°19,22911' N	λ_{e11}	30°39,97788' E
	φ_{e12}	46°19,37841' N	λ_{e12}	30°39,80175' E
	φ_{e13}	46°19,37846' N	λ_{e13}	30°39,94997' E
	φ_{e14}	46°19,37208' N	λ_{e14}	30°39,94691' E
	φ_{e15}	46°19,36040' N	λ_{e15}	30°39,94637' E
	φ_{e1}	46°19,41593' N	λ_{e1}	30°39,93882' E

Table 7

Matrix of trajectory points of turn 2

M_{t2}	φ_{e2}	46°19,59815' N	λ_{e2}	30°39,8086' E
	φ_{e21}	46°19,60553' N	λ_{e21}	30°39,80048' E
	φ_{e22}	46°19,62588' N	λ_{e22}	30°39,80177' E
	φ_{e23}	46°19,64750' N	λ_{e23}	30°39,80528' E
	φ_{e2}	46°19,77652' N	λ_{e2}	30°39,84258' E

6. From the first WP to the starting point of circulation, determine the coordinates of rectilinear segments in 0.2 cables; next, from the point of circulation end to the point of the beginning of the next turn, build the matrices of rectilinear sections.

When calculating these sections, it is necessary to take into consideration that the course to the next point remains unchanged. The matrices of the rectilinear sections of the ship's movement (M_{01} , M_{12} , M_{23}) when docking are given in Tables 8–10.

Table 8

Matrix of a rectilinear section between the starting point of movement 0 and the starting point of turn 1

M_{01}	φ_0	46°18,93' N	λ_0	30°41,58' E	φ_{043}	46°19,09373' N	λ_{043}	30°40,76564' E
	φ_{01}	46°18,93381' N	λ_{01}	30°41,56106' E	φ_{044}	46°19,09754' N	λ_{044}	30°40,74670' E
	φ_{02}	46°18,93762' N	λ_{02}	30°41,54212' E	φ_{045}	46°19,10134' N	λ_{045}	30°40,72776' E
	φ_{03}	46°18,94142' N	λ_{03}	30°41,52319' E	φ_{046}	46°19,10515' N	λ_{046}	30°40,70882' E
	φ_{04}	46°18,94523' N	λ_{04}	30°41,50425' E	φ_{047}	46°19,10896' N	λ_{047}	30°40,68988' E
	φ_{05}	46°18,94904' N	λ_{05}	30°41,48531' E	φ_{048}	46°19,11277' N	λ_{048}	30°40,67094' E
	φ_{06}	46°18,95285' N	λ_{06}	30°41,46637' E	φ_{049}	46°19,11658' N	λ_{049}	30°40,65200' E
	φ_{07}	46°18,95665' N	λ_{07}	30°41,44743' E	φ_{050}	46°19,12038' N	λ_{050}	30°40,63306' E
	φ_{08}	46°18,96046' N	λ_{08}	30°41,42849' E	φ_{051}	46°19,12419' N	λ_{051}	30°40,61413' E
	φ_{09}	46°18,96427' N	λ_{09}	30°41,40956' E	φ_{052}	46°19,12800' N	λ_{052}	30°40,59519' E
	φ_{010}	46°18,96808' N	λ_{010}	30°41,39062' E	φ_{053}	46°19,13181' N	λ_{053}	30°40,57625' E
	φ_{011}	46°18,97188' N	λ_{011}	30°41,37168' E	φ_{054}	46°19,13561' N	λ_{054}	30°40,55731' E
	φ_{012}	46°18,97569' N	λ_{012}	30°41,35274' E	φ_{055}	46°19,13942' N	λ_{055}	30°40,53837' E
	φ_{013}	46°18,97950' N	λ_{013}	30°41,33380' E	φ_{056}	46°19,14323' N	λ_{056}	30°40,51943' E
	φ_{014}	46°18,98331' N	λ_{014}	30°41,31486' E	φ_{057}	46°19,14704' N	λ_{057}	30°40,50049' E
	φ_{015}	46°18,98711' N	λ_{015}	30°41,29593' E	φ_{058}	46°19,15084' N	λ_{058}	30°40,48155' E
	φ_{016}	46°18,99092' N	λ_{016}	30°41,27699' E	φ_{059}	46°19,15465' N	λ_{059}	30°40,46261' E
	φ_{017}	46°18,99473' N	λ_{017}	30°41,25805' E	φ_{060}	46°19,15846' N	λ_{060}	30°40,44367' E
	φ_{018}	46°18,99854' N	λ_{018}	30°41,23911' E	φ_{061}	46°19,16227' N	λ_{061}	30°40,42473' E
	φ_{019}	46°19,00235' N	λ_{019}	30°41,22017' E	φ_{062}	46°19,16607' N	λ_{062}	30°40,40579' E
	φ_{020}	46°19,00615' N	λ_{020}	30°41,20123' E	φ_{063}	46°19,16988' N	λ_{063}	30°40,38685' E
	φ_{021}	46°19,00996' N	λ_{021}	30°41,18229' E	φ_{064}	46°19,17369' N	λ_{064}	30°40,6791' E
	φ_{022}	46°19,01377' N	λ_{022}	30°41,16336' E	φ_{065}	46°19,17750' N	λ_{065}	30°40,34897' E
	φ_{023}	46°19,01758' N	λ_{023}	30°41,14442' E	φ_{066}	46°19,18131' N	λ_{066}	30°40,33003' E
	φ_{024}	46°19,02138' N	λ_{024}	30°41,12548' E	φ_{067}	46°19,18511' N	λ_{067}	30°40,31109' E
	φ_{025}	46°19,02519' N	λ_{025}	30°41,10654' E	φ_{068}	46°19,18892' N	λ_{068}	30°40,29215' E
	φ_{026}	46°19,02900' N	λ_{026}	30°41,08760' E	φ_{069}	46°19,19273' N	λ_{069}	30°40,27321' E
	φ_{027}	46°19,03281' N	λ_{027}	30°41,06866' E	φ_{070}	46°19,19654' N	λ_{070}	30°40,25427' E
	φ_{028}	46°19,03661' N	λ_{028}	30°41,04972' E	φ_{071}	46°19,20034' N	λ_{071}	30°40,23534' E
	φ_{029}	46°19,04042' N	λ_{029}	30°41,03078' E	φ_{072}	46°19,20415' N	λ_{072}	30°40,21640' E
	φ_{030}	46°19,04423' N	λ_{030}	30°41,01185' E	φ_{073}	46°19,20796' N	λ_{073}	30°40,19746' E
	φ_{031}	46°19,04804' N	λ_{031}	30°40,99291' E	φ_{074}	46°19,21177' N	λ_{074}	30°40,17852' E
	φ_{032}	46°19,05184' N	λ_{032}	30°40,97397' E	φ_{075}	46°19,21557' N	λ_{075}	30°40,15958' E
	φ_{033}	46°19,05565' N	λ_{033}	30°40,95503' E	φ_{076}	46°19,21938' N	λ_{076}	30°40,14064' E
	φ_{034}	46°19,05946' N	λ_{034}	30°40,93609' E	φ_{077}	46°19,22319' N	λ_{077}	30°40,12170' E
	φ_{035}	46°19,06327' N	λ_{035}	30°40,91715' E	φ_{078}	46°19,22700' N	λ_{078}	30°40,10276' E
	φ_{036}	46°19,06708' N	λ_{036}	30°40,89821' E	φ_{079}	46°19,23080' N	λ_{079}	30°40,08382' E
	φ_{037}	46°19,07088' N	λ_{037}	30°40,87927' E	φ_{080}	46°19,23461' N	λ_{080}	30°40,06488' E
	φ_{038}	46°19,07469' N	λ_{038}	30°40,86033' E	φ_{081}	46°19,23842' N	λ_{081}	30°40,04594' E
	φ_{039}	46°19,07850' N	λ_{039}	30°40,84139' E	φ_{082}	46°19,24223' N	λ_{082}	30°40,02700' E
	φ_{040}	46°19,08231' N	λ_{040}	30°40,82246' E	φ_{083}	46°19,24604' N	λ_{083}	30°40,00806' E
	φ_{041}	46°19,08611' N	λ_{041}	30°40,80352' E	ϑ_{c1}	46°19,24828' N	Λ_{c1}	30°39,99608' E
φ_{042}	46°19,08992' N	λ_{042}	30°40,78458' E	–	–	–	–	

Table 9

Matrix of a rectilinear section between the point of the end of turn 1 and the starting point of turn 2

M_{12}	φ_{e1}	46°19,41593' N	λ_{e1}	30°39,93882' E
	φ_{11}	46°19,42756' N	λ_{11}	30°39,93057' E
	φ_{12}	46°19,43918' N	λ_{12}	30°39,92231' E
	φ_{13}	46°19,45081' N	λ_{13}	30°39,91406' E
	φ_{14}	46°19,46244' N	λ_{14}	30°39,90581' E
	φ_{15}	46°19,47407' N	λ_{15}	30°39,89755' E
	φ_{16}	46°19,48570' N	λ_{16}	30°39,88930' E
	φ_{17}	46°19,49733' N	λ_{17}	30°39,88104' E
	φ_{18}	46°19,50895' N	λ_{18}	30°39,87279' E
	φ_{19}	46°19,52058' N	λ_{19}	30°39,86453' E
	φ_{110}	46°19,53221' N	λ_{110}	30°39,85628' E
	φ_{111}	46°19,54384' N	λ_{111}	30°39,84803' E
	φ_{112}	46°19,55547' N	λ_{112}	30°39,83977' E
	φ_{113}	46°19,56709' N	λ_{113}	30°39,83152' E
	φ_{114}	46°19,57872' N	λ_{114}	30°39,82326' E
φ_{115}	46°19,59035' N	λ_{115}	30°39,81501' E	
φ_{e2}	46°19,59815' N	λ_{e2}	30°39,8086' E	

Table 10

Matrix of a rectilinear section between the point of the end of turn 2 and waypoint 3

M_{23}	φ_{e2}	46°19,77652' N	λ_{e2}	30°39,84258' E
	φ_{21}	46°19,78774' N	λ_{21}	30°39,84629' E
	φ_{22}	46°19,79896' N	λ_{22}	30°39,84999' E
	φ_{23}	46°19,81017' N	λ_{23}	30°39,85369' E
	φ_{24}	46°19,82139' N	λ_{24}	30°39,8574' E
	φ_3	46°19,83' N	λ_3	30°39,86' E

A formula for determining a latitude difference would take a different form. The section MC for rectilinear matrices is replaced with a step κ , which, for the first point, is 2, for the next – 4, and so on. The formula for calculating the DLat of a rectilinear section is given below.

$$DLat = \kappa \cdot \cos K. \tag{19}$$

Form the points of the predefined path in the form of TP matrices containing coordinates at which to start, execute, and end turns, as well as rectilinear segments. Then the predefined algorithm of maneuvering control at mooring to Fishing Port 8 in the port of Chernomorsk M_m can be represented as the sum of the matrices of the rectilinear and curvilinear sections of the path:

$$M_m = M_{01} + M_{11} + M_{12} + M_{23} + M_{br}. \tag{20}$$

This is the optimal, safe, predefined algorithm for the operation of the ship's control system, the implementation of which could make it possible to be moored without accidents.

5. 3. Emergency activity checklist

A work program based on the ISM code Model Course 1.22, on the latest developments of decision support systems involving planning a path along the trajectory points was developed to prepare a bridge crew to control a vessel in the event of an accident; it is given in Table 11.

Table 11

A plan to prepare a bridge crew «Controlling a vessel in case of an accident»

Titles of topics according to the ISM code Model Course 1.22	Training time (hours)		
	Theoretical training	Practical training	Total
Basic principles of ship control when maneuvering	2.0	–	2.0
The ship's maneuverable characteristics, how to calculate, determine, and present data	2.0	–	2.0
Planning the trajectory of movement during maneuvering (mooring, anchoring)	2.0	–	2.0
Choosing a tugboat by type, displacement tonnage, and port rules. Preparing a bridge crew to work in emergencies. Training checklist	2.0	–	2.0
Introduction to the navigation bridge simulator	–	1.0	1.0
Test maneuvers for braking and controllability parameters	0.5	2.0	2.5
Maneuvering under wind and current conditions	0.5	2.0	2.5
Accounting for the skill level in the distribution of the functional responsibilities of a bridge crew	1.0	–	1.0
Organizing the interaction among members of the maneuvering control crew. Maneuvering control schemes	1.0	–	1.0
Introducing baseline data on the problem of planning a curvilinear trajectory movement	2.0	–	2.0
The impact of extensive shallow waters on a maneuvering process	0.5	2.0	2.5
Canal criterion. Navigating the canals	0.5	2.0	2.5
Ship plan of pilotage. How to interact with the pilot and port services	2.0	–	2.0
Organizing a bridge crew when navigating under confined conditions and with limited visibility. Features of documenting the crew's work and maneuvering process	2.0	2.0	4.0
Organizing the mode of work and rest of the control crew members on the navigation bridge	2.0	–	2.0
Anchoring planning and anchoring techniques	–	2.0	2.0
Planning the stay on the barrel and mooring techniques	–	2.0	2.0
Mooring planning, towing, and maneuvering when entering a port under normal conditions	–	2.0	2.0
Mooring planning, towing, and maneuvering when entering a port when the ship's main engine fails	–	3.0	3.0
Total for training	20.0	20.0	40.0
Output control (competence assessment) and discussion of training courses	–	–	4.0
TOTAL	–	–	44.0

For the quality training of a bridge crew to work under extreme conditions, in case of an accident involving a ship, it is proposed to use a checklist in the form given in Table 12.

Table 12

Checklist for preparing the activities of a bridge crew when the main engine fails

No.	Activity content	Measuring unit	Value	Note
1	Current data at the time of maneuvering:			Ship documents
	a) Displacement tonnage D	t	.....
	b) Average draft T_{mid}	m	.....
	c) Width amidships B	m	.....
2	Hydrodynamic resistance coefficient K	kg/m	.....	[1, 2]
3	Acceptable speed under port rules V_{op}	knot	.....	Port rules
4	Maximum rudder thrust force P_{max}	N	.....	[1, 2]
5	Tugboat thrust force along the X line P_t	N	.....	Specifications
6	Allowable movement speed for tugboat support V_{sp}	knot	.....	[1, 2]
7	Braking path from V_{op} to a stop S_{br} when operating backward medium FAS	cable	.....	[1, 2]
8	Advance l_1 at a rudder shift angle of 15°	cable	.....	[1, 2]
9	Navigation reserve S_{nr}	cable	.....	0.1 cable

Its application significantly reduces the time of assessing the situation and making a decision in case of an emergency.

Thus, the developed algorithms of intelligent activities for a bridge crew and the formalized models for calculating safe speed when the main engine fails, taking into consideration the maneuverable characteristics of the vessel, make it possible to ensure safe maneuvering in case of an accident.

5. 4. Ship pilotage plan

The results of our study were practically applied using the simulation at a simulator for entering/leaving a port by the vessel Safmarine Nuba, 210.5 meters long, to pier Fishing Port 8; the maneuvering scheme is shown in Fig. 7.

The dashed line depicts the trajectory of the center of gravity, built by a reverse technique. To use tugboat support, an order consisting of two tugboats was formed, as shown in Fig. 8.

In this case, the power of the bow and stern tugboats was equal to 3,200 kW (4,350 hp). The mooring ends are recommended to be served through the central clubs. The stern tugboat would reduce yaw when navigating a constant course, as well as help perform the turns, as well as for braking when the main engines fail. Thus, it is possible to reduce the risk of the ship landing on the curb. Taking into consideration the size of the piloted vessel, which is at the limit ratios relative to the parameters of the canal and operating area, it is recommended to use an escort tugboat, whose power may be slightly less than the main one.

After roping the stern and bow towing ends, their length is set at about 50 m, they are fastened. Given that the vessel is limited to the size, displacement of the shipping canal, tugboats help keep the vessel on the fairway axis, and, if necessary, damp the inertia. The escort tugboat goes to the bow and prepares to work for mooring.

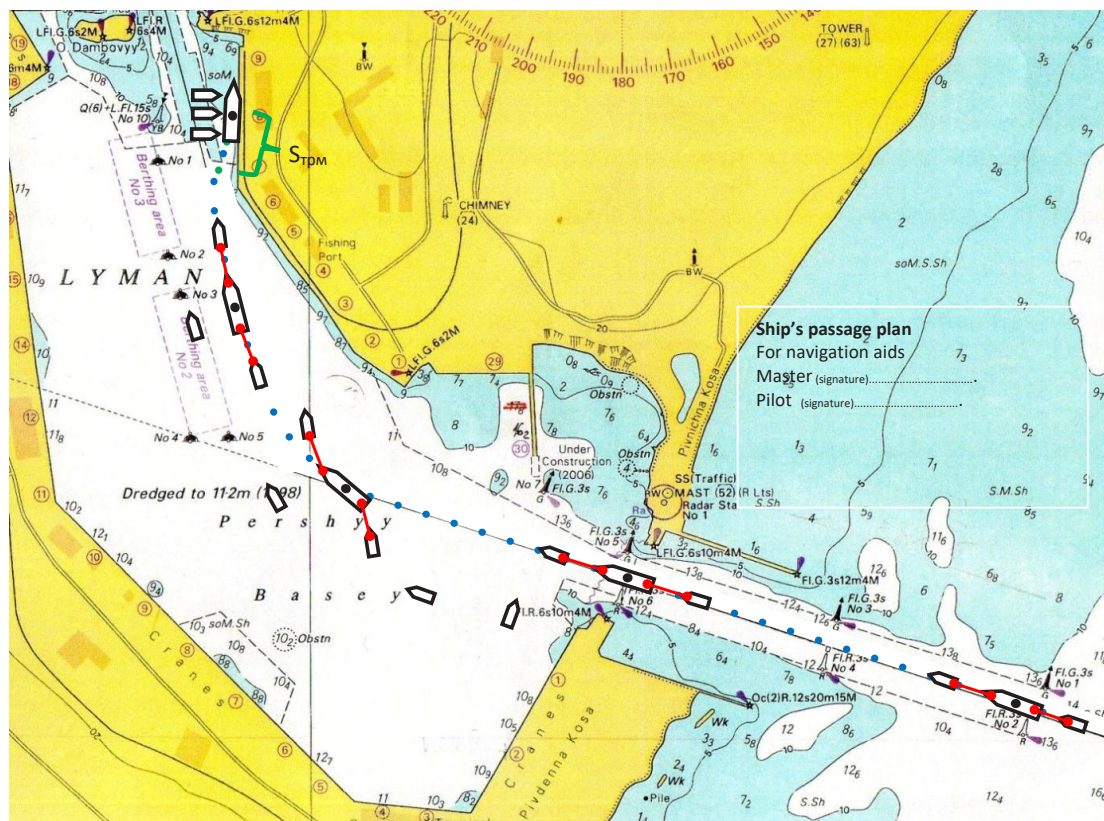


Fig. 7. Plan of ship pilotage to the dock



Fig. 8. Order of pilotage of ships with two tugboats

The technological mooring scheme is as follows. When approaching the first pair of buoys «1» and «2» of the approach channel, a pilot must be on board and the ship must follow at a maneuverable speed; according to the rules of the port, about 7 knots. The tugboat ends should be taken through the bow and stern locks as close as possible to the diametric plane.

The approach channel of the port, which has a width of 160 m, a length of 1,400 m, and a depth of 14.5 m, is used for ships to enter and exit the seaport of Chernomorsk. The depth near the pier, according to the passport of the water area, is enough to execute braking to a full stop, turn on the reverse course using tugboats, and maneuver during mooring.

For maneuvering and mooring without the use of tugboats, it is necessary that the width of operating water should be at least $1.5 L_{\perp}$. When using tugboats, safe maneuvering and mooring can be ensured at the width of the operating area of up to $1.15 L_{\perp}$.

The pier is 220 meters long. Thus, the design parameters of the operating area make it possible to perform safe mooring and departure of ships from the pier with a length between perpendiculars of about 200 meters and a width of about 45 m using tugboats.

Features of maneuvering during mooring are determined by the pitch of the propeller, the side of the mooring, and the existence of a steering device.

After the bow of the ship approaches Fishing Port 8 pier, you begin to turn to the right with a rudder shift at 15° and work a bow tugboat to help turn to the left. If necessary, an escort tugboat prevents collision with the end of the breakwater. The difficulty of this stage is in the need to turn at an angle of about 70° . When maneuvering under wind conditions of 10 m/s or larger, a safety tugboat is required.

To check the activities of a bridge crew at mooring, we stopped

the main engine two hulls to the mooring place, the braking involved two tugboats, instead of operating the ME at the rear thrust. The maneuver, performed several times, has confirmed the hypothesis that when towing with a total thrust on hooks, equal to the thrust force of the engine propeller at reverse motion, the braking path and time are the same. The results of our calculation can be reduced to a flowchart shown in Fig. 9.

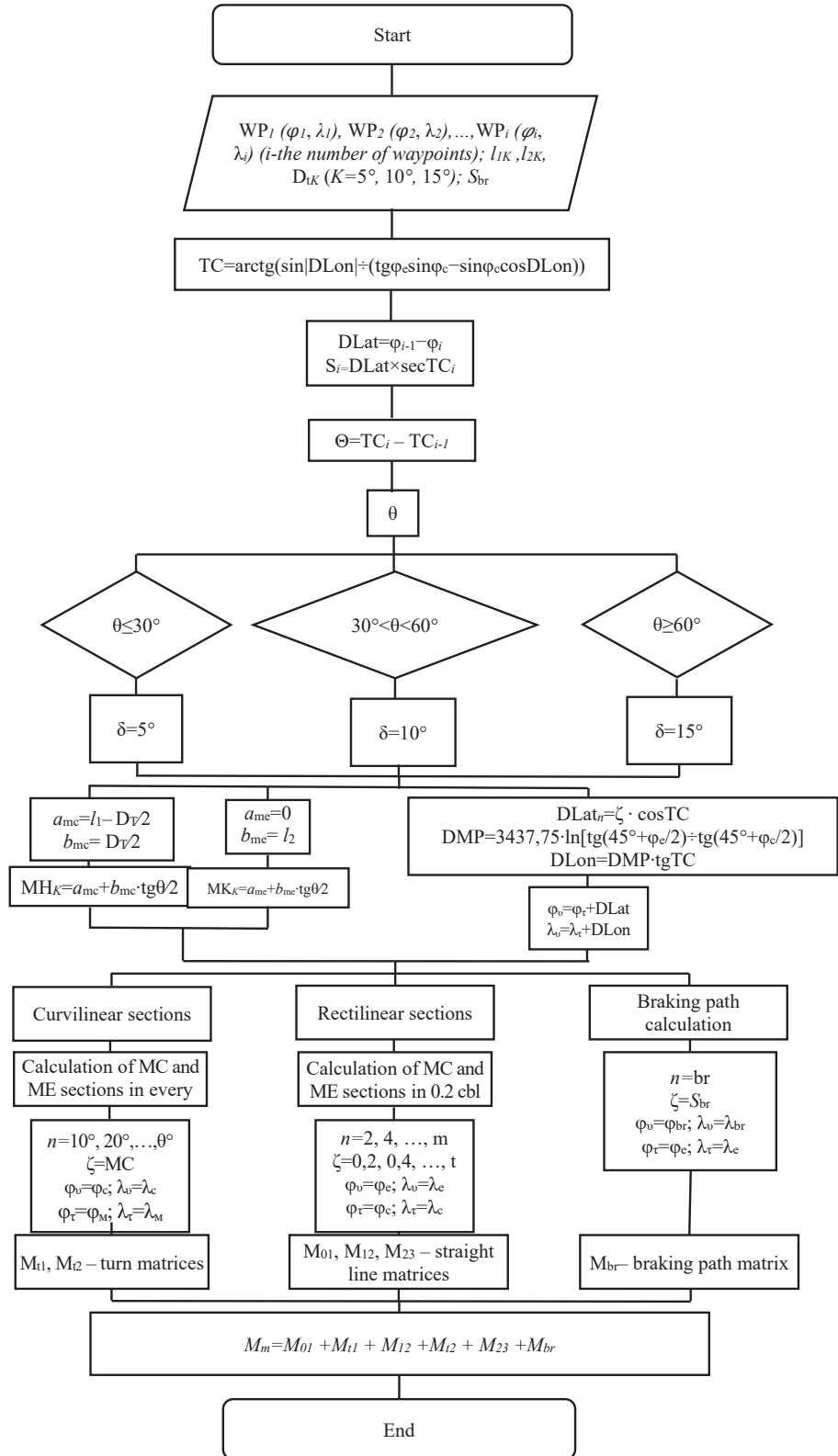


Fig. 9. Flowchart for calculating coordinates of the predefined maneuvering algorithm

After approaching the mooring site, the vessel is pressed to the dock; the ship's position is regulated. The recommended minimum scheme for mooring ends is three longitudinal and two springs from the foredeck and stern. After clamping the mooring ends, tugboats are free, the mooring is considered completed.

Two long (about 40 m) tugboat ends through the bow and stern central locks are enough for departure. The tugboats pull the vessel in parallel to the berth at a safe distance, working more by a bow tugboat on pulling, as shown in Fig. 8. Then the stern tugboat works to move the stern to reach the canal line. The bow tugboat stabilizes the movement, the rudder is straight. If necessary, the ship's machine briefly operates under reverse thrust.

6. Discussion of results of berthing a vessel using the mooring matrix of trajectory points

Thus, the algorithm was built in the form of a checklist for preparing a bridge crew to operate in emergencies. A flow-chart of the system of safe maneuvering has been developed for the case where ship control tools fail, as well as a program to prepare a bridge crew to operate in emergencies.

The proposed algorithms and models could be used in expert decision-making systems in TSS, navigation devices on ships, and when designing maneuvering control systems.

The developed algorithm for calculating the beginning of braking using the path matrices, given in Table 5, would help make it easier to decide on giving commands to the telegraph. Based on general recommendations that relate to the use of the telegraph during maneuvers, up to now they could not be used for each particular vessel. However, the resulting brake path matrix, shown by a green section in Fig. 7, shows that a given program calculates the time and place to send a command to the telegraph. This could simplify the pilot's work, as well as reduce the risk of giving a false command.

When manually planning a turn, the shipmaster acquires the required original data based on the characteristics of maneuverability before the turn begins. They include the coordinates of the starting and end of the turn, the bearings and distance to the landmarks in these moments. The rudder in the turn is controlled by a sailor. The control of the turn is to determine the location of a vessel at the moments of its beginning and end. The movement along the curvilinear trajectory is not controlled due to the fact that determining the location takes a long time, and such information lags by the time the control decision is made. To control the position of a vessel when turning, we constructed a method of trajectory points, which is represented in the form of curvilinear matrices with a step of 10° in Tables 6, 7.

The total matrix of the ship's approach, given in Tables 6–10, would make it possible to quickly control the center of gravity of the vessel, according to the specified path, as well as reduce the risk of deviation from the course and the occurrence of errors that are associated with strong confidence in «good maritime practice».

The checklists for activities in an emergency, given in Tables 11, 12, would allow the distribution of duties within a ship's crew, which could reduce the risk of the occurrence of such a situation. Their application significantly reduces the time of assessing the situation and making a decision in case of an emergency.

The ship's pilotage plan, shown in Fig. 7, is a pilot's layout of the ship's approach, which could be used for navigation. All available «Pilot passage plan» cards cannot be used in naviga-

tion, as confirmed by the inscription on them. The proposed call plan would make it easier for the pilot to operate.

Practical research has shown that a given technique for making up a plan of entering a port has made it easier for the bridge crew to work. And the reported checklist for the prevention of pre-emergencies has made it possible to reduce the risk of problems associated with navigation under confined conditions. Thus, our technological advancement is practically justified and could be used on ships to facilitate communication between the pilot and captain and to prepare a bridge crew.

The main advantage of the method for planning the path of the ship based on the table of waypoints by calculating the coordinates of trajectory points based on the angle of rudder shift for curvilinear trajectories is the representation of the path in the form of the sum of the linear matrices of coordinates of the rectilinear and curvilinear sections and automatic operational control over movement parameters. The proposed method could be used in the development of controls for automated vessels and is the only possible one for vessels with unattended operation. Also, a given method for building a path is very relevant in the preparation of a plan for entering/leaving path as it reduces the risk of misunderstanding between the captain and pilot during navigational pilotage, as well as reduces the risk of accidents related to the control over the resources at a navigation bridge.

Thus, optimizing the information on maneuvering, properly preparing a bridge crew for a timely assessment of the moment of emergency, and taking adequate measures to prevent it, could improve the safety of maneuvering. Our simulation of the mooring process at Fishing Port 8 berth in the seaport of Chernomorsk has confirmed the effectiveness of the accepted technique for selecting the tugboat support based on the balance of controlling forces.

7. Conclusions

1. The results of the preparation are represented as the sum of the linear matrices of an individual section, including curvilinear. In addition, the coordinates of the starting points of braking at the pier, the rudder shifts during the turn at a waypoint, the end of turns, and the angles of rudder shift in each of them are determined separately. Determining the braking path could make it possible to timely stop the movement of the ship by reversing the machine and safely finish mooring. Until now, there was no analytical calculation of the beginning of braking. The pilots relied only on their rich experiences.

2. Automatic devices for grounding warning, assessing the width of the maneuverable displacement lane, automated control over the process of approaching other vessels, and selecting a maneuver for divergence are required to control the movement process. The trajectory point matrix would build a predefined algorithm for the functioning of the maneuvering control system, including curvilinear sections. That could significantly reduce the onset of an emergency.

3. A checklist would help devise a procedure for compiling a regulatory document for the captain on «Ship's plan of entering/leaving a port» for navigational purposes, including the automation of its preparation. The checklist of emergency activities makes it possible to prepare a bridge crew to act in an unusual situation and define role functions in case of its occurrence.

4. The ship's pilotage plan allows for guaranteed navigational safety when the pilot and captain work together.

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