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FORMALITY MODEL OF CHOSEN APPROPRIATE TUG'S SERVICE BY METHOD OF BSLANCE HANDLING FORCES

Port tugs bring large vessels into the port and take them out of the port, assist them during mooring and unmooring, move vessels from one mooring to another, tilt vessels, tow port barges, transshipment mechanisms, dredgers and other floating objects. Calculation and evaluation methods of the optimal request for tugs bollard pull port operations, are very important in order to guarantee the navigational safety of the port and ships during the main ship operations in the port.

The most dangerous situations are situations of sudden failure of the power plant when maneuvering a vessel in the confined waters of ports, when tugboats become the only means of control that can prevent an accident. This is observed when the vessel moves in an area with hazardous sections of the waterway, calls into and out of the port, as well as when performing mooring operations. Line and / or port pilots, as well as tugs for escorting, escorting or when performing mooring operations of the vessel, are additionally involved in the process of navigating the vessel. In foreign ports, there are also very tense conditions in command management due to language barriers and the need for synergistic interaction of individual independent ship crews without prior preparation for a responsible mission.

In this paper done a focus to improve tug possibilities and decrease navigational risks in port areas by method of balance handling forces. Such decrease in risks at ports is important issue to overcome, since the correct and proper usage of port tugs could highly improve the situation there.

Keywords: *tugs, emergency situation, port maneuvering, energy balance of the control force.*

Defining the general matter and its connection to important scientific or practical objectives. The appropriate functionality of ports depends of safe operations by each services. Among the most challenge operations in ports are inbound / outbound of vessels, mooring and unmooring operations, where the tugs are of the utmost importance. Port tugs assist ships using the port channels, manoeuvring of ships turning at basins, shifting to and from berths. Nowadays, many vessels have thrusters, which replace some of the tug functions, but many ships, especially tankers, bulkers and other, do not possess such thrusters, which is why tugs are very important when it comes to the improvement of navigational safety [1–9].

Nowadays, tugs which operated in ports divide on a different type and capacity and mostly depend on ship size and port-external conditions (waves, wind, shallow water and current). The main risks at ports, which are pointed out by some authors, can be classified as follows: poor vessel and port staff knowledge and training; the human factor in general; inferior maintenance of port tugs; miserable communication between all parties during inbound / outbound the port, as well as mooring operations (in the case that the ship's crew, port pilot and tugs' masters communicate in different languages); wretched or outdated tug equipment; resourceless safety culture, etc. [3,8,10–13]. According to research made in India at 2021 [11], the main risk factor during pilotage with tugs was poor training (Fig. 1).

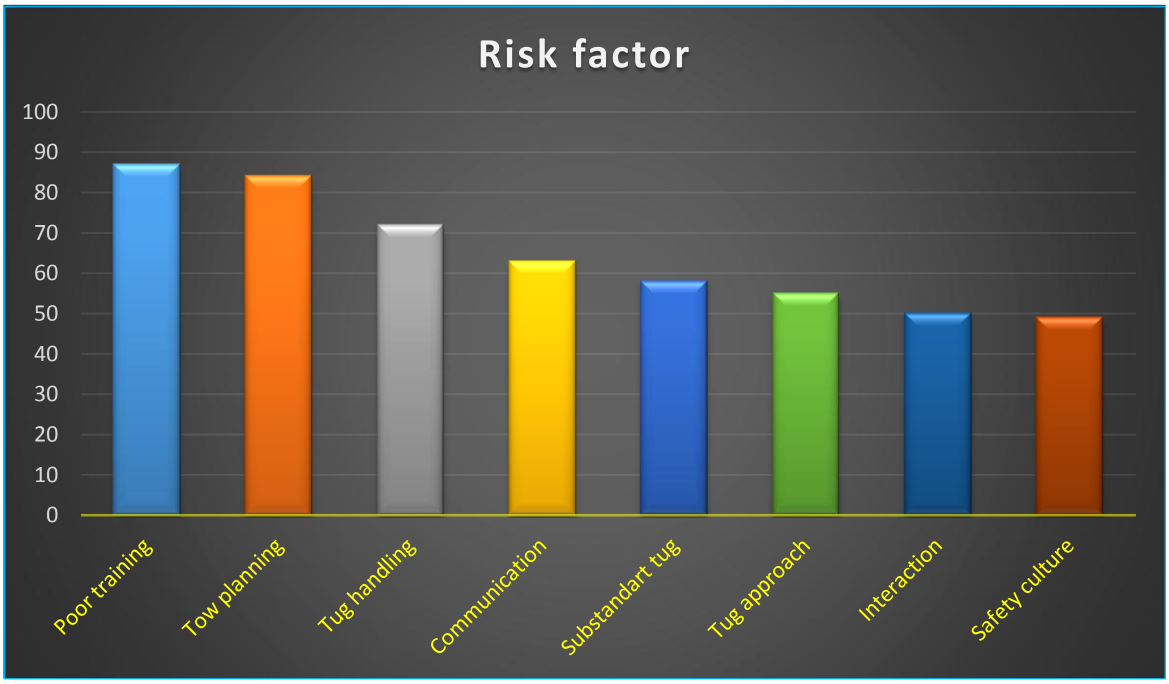

Fig 1. Risk’s factors combined with frequency in Indian’s ports in percentages

Port tugs influence on risks factors in many cases. The aim of this study is to improve tug possibilities and decrease navigational risks in port areas by method of balance handling forces. Such decrease in risks at ports is important issue to overcome, since the correct and proper usage of port tugs could highly improve the situation there.

The lack of practical recommendations and methodologies for the optimal number of tugs and bollard pull calculations may result in unreasonable risks or excessive measures being taken in real life situations. The main objective of this article is to improve and provide practical methods as well as suggest optimal decisions on proper tugs handling in ports and decrease the potential risks during ship maneuvering operations in complicated conditions.

Previous researches analysis and definition of new trends in problem solution. To begin the process of maneuvering is important to keep in mind a plan how maneuver is intended to the vessel, consider the wind, tide, state of the ship’s trim, draft, and freeboard, orient in navigation aids etc. To tackle with these multipurpose factors is better to use assistant of tugs. Due to this there is highly important to understand operator activity in organizing the work of tugboats, which has been managed at this research article [14]. The research [14] includes analysis of existing methods of preparation for maneuvering; improving the ways of organizing the management of the work of tugs; organization of the work of the bridge crew in case of multi-operator control and ship’s engine failure. However, article did not present the method to manage these problems.

Port tugs are important for port navigational safety, and different approaches to estimate the quantity and quality of requested tugs in ports (bollard pull) have been implemented [5, 7, 8, 16–18]. This also applies to transport and logistics systems functioning in pursuit of the sustainable development of these systems [4, 16, 19, 20]. Direct and indirect tugs used in port areas are associated with navigational safety [1, 9, 21–23].

Several studies address an interesting tugboat scheduling problem considering uncertainty in both container ship arrival and tugging process times for large container ports. For a large-scale problem, an ad hoc algorithm is designed to generate tugging chains such that the large-scale problem can be tackled effectively [5, 24].

The aim of many papers is to rank the vessels entering and leaving the restricted channel of multiharbour basins and generate the optimal traffic scheduling schemes for each vessel, to ensure the safety and efficiency of vessel navigation. In these studies, through analysis of the characteristics of a restricted channel in ports, a general structure of a restricted channel in multiharbour basins is proposed, and the key areas of vessel traffic conflict are specified [13, 25–29].

Generalized ship maneuvering models based on the real-time modelling of ships navigating in ports are accessed and presented in [10, 11, 20, 33–39]. Two models of the prediction of ships' trajectories have been developed and considered the probability of ships leaving the channel or encountering navigational obstacles [20]: (1) an Auto Regressive and Moving Average eXogenous (ARMAX) model is adopted to identify the ship steering dynamic system; (2) the stochastic sequences of the inputs for the first model used are generated using a semi-Markov model. The papers describe the implementation of the semi-Markov model for rudder actions.

Maneuvering models are dedicated for the rapid estimation of hydrodynamic factors in deep and shallow waters and allow a rapid estimation and reconstruction of the vessels' sailing trajectories for single and double propeller vessels [34, 39–42]. Results are validated against experiments available for the zigzag and turning cycle trajectories of vessels with different hull forms and propulsion configurations [39].

Model predictive maneuvering control and energy management for all-electric autonomous ships also aim to bridge the gap among maneuvering control, energy management and the control of the Power and Propulsion System (PPS) to improve fuel efficiency and the performance of the vessel [34]. In this regard, for the ship motion control, a Model Predictive Control (MPC) algorithm is proposed which is based on Input–Output Feedback Linearization (IOFL). Through this algorithm, the required power for the ship mission is predicted and then transferred to the proposed Predictive Energy Management (PEM) algorithm, which decides on the optimal split between different on-board energy sources during the mission. As a result, the fuel efficiency and the power system stability can be increased.

Linear heave and surge movements recorded lower amplitudes compared to the values of standard thresholds [19]. The specific behavior of each vessel was analyzed in terms of its size, maritime conditions, and mooring location. Field campaigns, such as those performed in this work, are an effective way of analyzing the operational conditions of ports, which could help in identifying problems in the mooring zone [43–45].

The wave effects on ships moored in ports and a hybrid numerical model are proposed to estimate the transient response of a moored ship exposed to the two types of waves. The hybrid method is based on the combination of the 3D Rankine source method and impulse response theory. The 3D Rankine source method is applied to address the wash waves and the wave–structure interactions. The transient response is subsequently simulated in the time domain with the impulse response theory [46–48].

Human knowledge and experience accompanied by the ability to simulate the correct use of tugs in ports are of the utmost importance. These issues have been investigated by many researchers and seen by them as one of the key conditions for the correct use of tugs in ports [2, 3, 11, 12, 20, 27, 28, 32, 49, 50].

It should be noted that port configuration and ship maneuvering areas are different in particular ports [13, 15, 20, 21, 23]. The main factors influencing the optimal use of port tugs are as follows: types of manoeuvring operations performed by ships and the efficiency of tug assistance. On the one hand, ships moving in port areas must be safe. Therefore, it is very important to optimize the time of ship movement and minimize manoeuvres inside the port that mainly depend on the qualifications of people in charge [3].

Based on the conducted literature analysis, the following statements can be made:

1. The problem of decreasing or optimizing the use of port tugs is relevant, and further solutions in this area should be developed.
2. There is a need to look for solutions to reduce (optimize) the use of port tugs that would not require high volumes of investments.
3. To date, the influence of the human factor on port tug optimization has not been analyzed to the required degree.
4. The need to investigate the impact of a ship's crew and port pilots' qualifications and decisions on ship manoeuvring operations in port areas is justified, and further research in respect to how to decrease (optimize) the use of port tugs is required.

The research objective. The main aim of this work is to ensure safe maneuvering in extreme conditions in case of refusal of ship management. The existing methodology for selecting the number of tugs when inbound / outbound from the port does not take into account the power of the main engine of towing vessel, external influences and dimensions of the sea surface. Therefore, it is necessary to develop new methods for choosing towing. The method of solving the problem is a systemic analysis of the process of movement with a mathematical and vector form of presentation of its parameters and the use of differential calculus and theory of information. The method of solving the problem provides for the definition of the force of inertia, forces from vessel management equipment, the choice of tugs and the method of their use on the allowable speed in the port, vessel displacement and weather conditions. The research objectives are following:

1. Creating an algorithm for replacing control influences when refusing devices based on the analysis of the causes of emergency situations.
2. Calculation of the energy balance of the control force.
3. The algorithm for selecting the total towing power to normalize the velocity speed of the vessel when performing marine operations.

Presenting the main material of a research with a full grounding of received scientific results

1. *The analyze of selecting the total towing power to normalize the velocity speed of the vessel when performing marine operations*

To ensure safe maneuvering, the degree of preparation of the navigators for interaction in the organization of ship traffic control in normal, cramped conditions and in emergency situations is of decisive importance. When working in extreme conditions, it is necessary to use mental operations to find a solution, which leads to a slowdown in the control process. To obtain correct information about the movement process, under such conditions, preliminary preparation for the action of the bridge team, in case of failure of the means of movement and maneuvering, is necessary. For this reason, the development of meaningful models of the control process and the algorithm of the actions by bridge team in emergency situations is very relevant.

Automatic systems for managing the heading, speed and position provide the functions of the systems and the method of information support for decisions made on motion control.

The ability to work in the bridge team in emergency situations requires the Master to simultaneously perform operator functions for managing the vessel and operational functions for managing people with a severe time deficit that persists throughout the emergency.

In the process of interaction of human operator (HO) with elements of human-machine systems, analyzers, memory and thinking, the speed of intellectual actions and anthropometric data are considered as its engineering and psychological characteristics.

The specifics of the vessel motion control process determine visual (receptor - eye) and auditory (receptor - ear) analyzers as the main ones. At the same time, visual information occupies about 90%, the use of auditory signals and speech is in second place, and the remaining analyzers occupy an insignificant share.

If there has been a change in the composition of the controls, then the operator needs to process the incoming declarative information on control over the parameters of the control process to correct the planned route.

The safety of maneuvering in case of failure of the controls was usually not ensured due to the lack of necessary information about the maneuvering characteristics of the vessel as a control object and the relevant data on the current state of its technical devices, which are necessary to control the movement process and support the decision made.

The preparation for maneuvering and its implementation will be considered as consisting of three stages: planning of trajectory points; management of the movement process in accordance with the preliminary plan; adjustment of the original plan for the choice of devices used, in case of failure of controls or changes in external conditions during the movement.

The analysis of the process of traffic control in case of accidents will be carried out by the operational - structural description, presented in the form of algorithms. In this case, the description will be carried out in a strictly defined sequence of elementary operations. To do this, the control process is decomposed into qualitatively different elementary operations, and the logical connections between them are determined to determine the order in which they follow. The criterion of elementality is the ability of the operator to perform such an operation accurately on the basis of information in the form of knowledge.

In this case, we will consider the following characteristic points of the vessel: control center (CC) - a point on the bridge of the vessel, where the navigator is located, who evaluates his position relative to the signs of the navigation situation; pivot point (PP) - a point on the line of the diametrical plane within the ship or outside it, around which the hull rotates; the center of gravity (CG) is the point on the DP line at which the resultant of gravity is applied. When considering the management of a conventional vessel, it is conditionally accepted as located on the midship frame.

All forces acting on the ship are divided into three groups: dynamic, external and reactive. The dynamic forces include forces created by the ship's controls and external ones to give the vessel linear and angular motion. External forces include forces from the wind, waves of the sea, currents. Reactive forces include forces and moments resulting from the movement of the vessel.

The sources of control forces (internal and external) are propeller stop force; steering power; force from the anchor device; force from the towing device; force from the mooring device; thruster power. Since during the entire time of movement the vessel moves with changing parameters (heading, speed, position), we will assume that maneuvering occurs throughout the entire transition, however, it is of a different nature, depending on its position in relation to the point of departure and arrival, as well as the nature of navigational conditions. This effect is especially manifested when sailing in extreme conditions when inbound / outbound the port and when the ship's devices fail.

To compile an algorithm for replacing control actions in the event of failure of devices that provide maneuvering, we will classify the forces that are used by the navigator in organizing the movement of the vessel, which is given on Fig. 2.

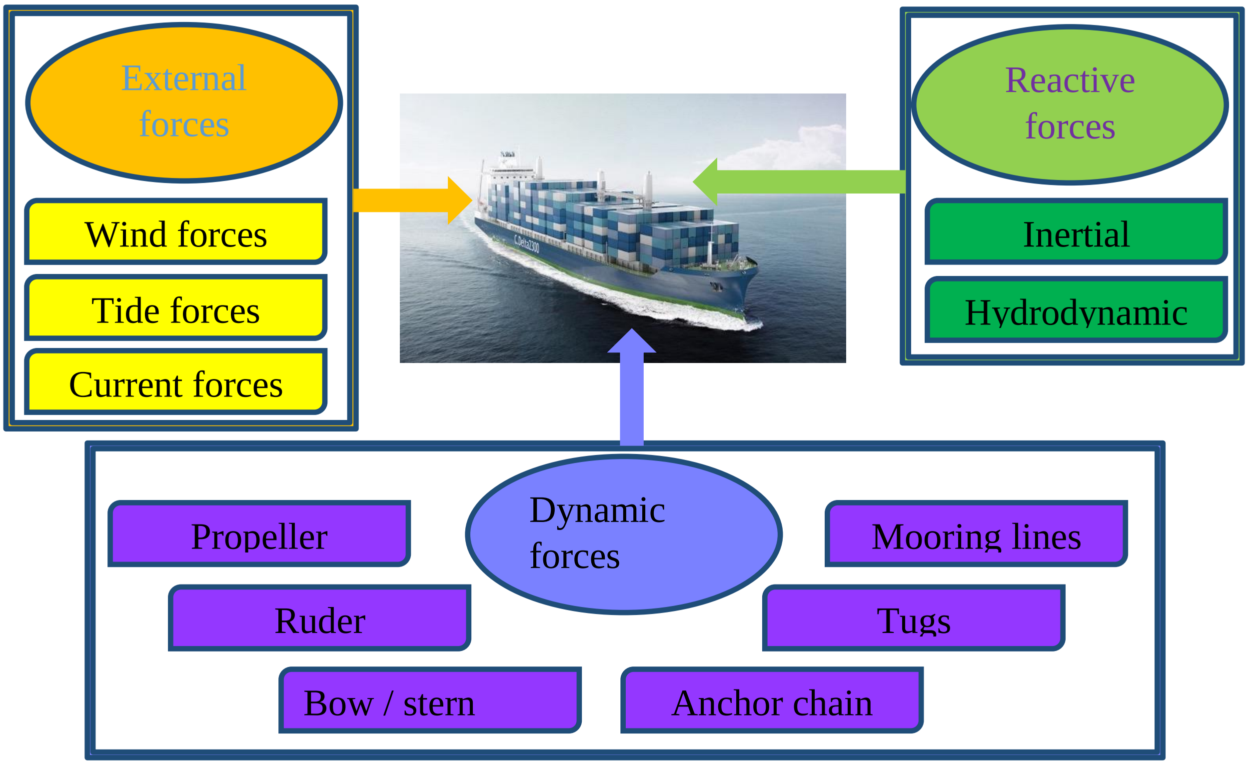

Fig. 2. Classification of forces influencing to the vessel during mooring operations

With further analysis of the causes of the incident, it is necessary to establish in which element of the system a failure occurred in its operation, and what factor is the determining factor, and what device should be used to compensate for the lost power for control.

Consistently checking all the devices included in the system, you can specifically specify which of the elements or their sum can compensate for the failed one.

2. ***Calculation of the energy balance of the control force***

To compile an energy balance, consider a brief characteristic of the forces.

The strength of the screw is the main active of dynamics forces of the vessel. The force of the exposure screw is determined by the formula

$$P_p = K_p \times \rho \left(\frac{n}{60}\right)^2 \times D_p^4 \ , \tag{1}$$

where ρ – density of water; n – rotation per minute; D_p - propeller's diameter; K_p – the screw breaker coefficient on the mooring, which could be found by the formula:

$$K_p = \sqrt[3]{(\theta \times Z)} \times \left(0{,}225 \times sin^2 \frac{H}{D_в} + 0{,}098 \times sin \frac{H}{D_в}\right), \tag{2}$$

where θ – screw disk ratio; Z – the number of blades; $\frac{H}{D_в}$ – stepper ratio of the screw.

Screw Disc Area could be defined as

$$A_d = \frac{\pi \times D_в^2}{4}. \tag{3}$$

To account for the influence of the case, need calculate the coefficient of strengthening of the screw, C_{yy}, depending on the area of the submersible part of the Middle-Spanmost $S_\otimes$:

$$S_\otimes = B \times T \times \beta_\otimes, \tag{4}$$

where $\beta_\otimes$ - the completeness coefficient of the Middle-Schandout

Then can find the reinforcement coefficient of the screw:

$$C_{yy} = 0{,}508 + 0{,}106 \frac{S_\otimes}{A_d}. \tag{5}$$

Finally, the calculated maximum strength of the breakers in the rear is equal to:

$$P_{max}^{cal} = P_m \times C_{yy}. \tag{6}$$

The second hierarchy is the force from the towing device. The main characteristic of the towers is the thrust on the forward. At the same time, if two tugs are used, the forward tug is the following condition:

$$P_{t_1} = R_c + R_{t_2}, \tag{7}$$

where R_c – the resistance of the vessel; R_{t_2} – The resistance of the aft tug.

Then the differential equation of the system of the ship - tugs in the process of braking will be:

$$m_{t+v} \frac{dV}{dT} = -\left[(C_v + C_t) \times V^2 + P_{t_2}\right], \tag{8}$$

where m_{t+v} – tug mass and towed vessel with an attached mass;
C_v, C_t – hydrodynamic coefficients of the vessel and forward tug;
V – speed of the system;
P_{t_2} – traction on the tug's hook.

The solution of the differential equation of the system relative to the brake path and the power of the aft tug is:

$$\frac{m_{t+v} \times V^2}{2(R_c + R_{t_1})} ln\, ln\, \left(1 + \frac{P_{t_1}}{P_{t_2}}\right), \tag{9}$$

$$P_t = \frac{P_{t_1}}{e^{\left(\frac{2S_{add} \times P_{t_1}}{m_{t+v} \times V_t^2}\right) - 1}}. \tag{10}$$

The nominal traction of tug is calculated by its engine capacity by the following formula:

$$P_{t_{nom}} = 0{,}133 \times P_{ep}, \tag{11}$$

where $P_{t_{nom}}$ – traction on the tug's hook; P_{ep} – engine power.

The force from the thruster is always directed perpendicular to the diametrical plane (DP). Its value can be determined by engine power device by formula (11).

To determine the transverse force on the steering gear, it is necessary to determine the dimensionless coefficients, as well as the shoulder of the specified force. The equation for the moment in the deployed form can be recorded [26]:

$$M_p = R_{py} \times \overline{l_p} = \left(C_{py} \times \rho \times S_p \times V_p^2\right) \times \overline{l_p}, \tag{12}$$

where R_{py} – transverse power on the steering gear; C_{py} – dimensional coefficient; S_p – pole steering area; V_p – the speed of the incident flow on the steering gear; $\overline{l_p}$– Dimensional Steering Shoulder, which can be taken 0,5.

An anchor device perceives horizontal strength, which occurs on anchor equipment at the return of the anchors on the seabed. Such a safe workload (SWL) is the 200 tons world standard for a single deck stopper. This value is considered satisfactory at the wind speed of up to 30 nodes.

3. *The algorithm for selecting the total towing power to normalize the velocity speed of the vessel*

In order to develop reasonable recommendations on the action of navigators in case of failure of the controls, we will draw up the energy balance of the control forces. In this case, it is necessary to balance along the axis along the DP and perpendicular to it:

$$m_x \frac{dV_x}{dT} + kV_x^2 \leq P_e + \sum_{i=1}^{2} P_{a_i} + \sum_{j=1}^{n} P_{x_{t_j}} + R_{e_x}, \tag{13}$$

where R_{e_x} – the total force from external influences along the X axis.

$$m_y \frac{dV_y}{dT} + kV_y^2 \leq R_{py} + P_{thr} + \sum_{j=1}^{n} P_{y_{t_j}} + R_{e_y}, \tag{14}$$

where R_{e_y} – the total force from external influences along the Y axis.

At the disposal of the navigator there is an opportunity to determine the mode of movement of the vessel, and only after that to make a choice of towing support and the mode of use of control devices.

The energy balance method also allows solving the inverse problem of analyzing the causes of an accident. To do this, using equation (13), the towing power and the holding force of the anchor device determine the speed along the X axis, at which they can stop the movement of the ship. By comparing the actual speed and the calculated speed, you can determine the cause of the accident.

To assess the importance of each of the components of the controls, we will determine its weight in the overall balance of power. The balance of forces along the Y axis does not make sense when assigning the number of tugs, since the means on the ship create transverse forces, the magnitude of which is incommensurable with the thrust force of the tugs and propeller. The main task, in case of emergencies, is to stop the movement of the vessel along the X axis.

The weight of each force can be determined by formulas. For screw break force:

$$B_{br_s} = P_e \Big/ \left(P_e + \sum_{i=1}^{2} P_{a_i} + \sum_{j=1}^{n} P_{x_{t_j}} + R_{e_x} \right). \tag{15}$$

For the force from the anchor device:

$$B_{br_a} = \sum_{i=1}^{2} P_{a_i} \Big/ \left(P_e + \sum_{i=1}^{2} P_{a_i} + \sum_{j=1}^{n} P_{x_{t_j}} + R_{e_x} \right). \tag{16}$$

For power from tugs:

$$B_{br_t} = \sum_{j=1}^{n} P_{x_{t_j}} \Big/ \left(P_e + \sum_{i=1}^{2} P_{a_i} + \sum_{j=1}^{n} P_{x_{t_j}} + R_{e_x} \right). \tag{17}$$

For force from external influences:

$$B_{br_{e_x}} = R_{e_x} \Big/ \left(P_e + \sum_{i=1}^{2} P_{a_i} + \sum_{j=1}^{n} P_{x_{t_j}} + R_{e_x} \right). \tag{18}$$

For trouble-free control in case of failure of the main engine, the force from the tugs and the anchor device must stop the movement of the vessel at the current speed. In the absence of external influences, the necessary force can be determined from the condition:

$$\sum_{i=1}^{2} P_{a_i} + \sum_{j=1}^{n} P_{x_{t_j}} \geq k V_x^2, \tag{19}$$

Knowing the holding force of the ship's anchor, it is possible to determine the required total power of the tugs required for trouble-free maneuvering:

$$\sum_{j=1}^{n} P_{x_{t_j}} \geq k V_x^2 - \sum_{i=1}^{2} P_{a_i}, \tag{20}$$

The first step in creating a safe maneuvering model is to make its verbal-informational description. It includes the following actions: description of the external environment with parameters that make it possible to quantify its impact on the functioning of the system; establishing links between the system and the external environment; description of the elemental composition of the system and its subsystems, as well as the hierarchical structure; establishment of functional direct, reverse, and local links between the elements and the control object.

The analysis of the control forces, made according to the formulas (15) – (18) shows that the force from the screw has the greatest weight. For this reason, ensuring guaranteed safety of maneuvering can be done by fully compensating the propeller stop force with towing support.

In this regard, it is proposed to use the following algorithm for selecting the total towing power by normalizing the speed of the vessel during marine operations.

1. Calculate the area of the wetted surface:

$$\Omega = D^{2/3} \times \left(4{,}854 + 0{,}492 \times \frac{B}{T_m}\right), \tag{21}$$

where D – the displacement; B – the width of the vessel; T_m – average draft.

2. Calculate the drag coefficient K

$$K = 5880\_0{,}654 \times \Omega \times \sqrt{\frac{B}{T_m}}. \tag{22}$$

3. Determine the force of hydrodynamic resistance kV_x^2.

The magnitude of the resistance force determines the total power of the tugs, which are necessary to stop the movement of the vessel.

Conclusions and further research prospects

The analysis of the accident rate during moorings in ports showed that the main cause of the accident is the lack of mooring lines submitted to the tugs. They occur due to insufficient control by the pilot or captain of the proper organization of the management of the work of tugs.

The proposed method for choosing the number of tugs according to the maximum thrust force of the ship's propeller allows us to speak about the creation of adequate reserve control forces that create the prerequisites for safe maneuvering. If the propeller stop is not enough, then anchors can be used, the holding force of which will reduce the braking distance and stop time, which is of paramount importance in the conditions of the operating water area. However, for its use it is necessary to perform preliminary calculations.

The scientific result of solving the second auxiliary problem is the development of a formalized model for the choice of towing support by the force balance method. The results obtained can be used to select reasonable restrictions for maritime operations in the port when compiling the “Compulsory Regulations for the Port” and standardizing the provision of various types of vessels with tugs, considering the power of their main power plant, weather conditions and the size of the operating water area.

REFERENCES

1. Aydin, C.; Karabulut, U.C.; Ünal, U.O.; Sariöz, K. Practical computational procedures for predicting steering and braking forces of escort tugs. Gemive Deniz Teknol. 2017, 21, 21–36. https://doi.org/10.1016/j.oceaneng.2018.08.021
2. Piaggio, B.; Viviani, M.; Martelli, M.; Figari, M. Z-Drive Escort Tug manoeuvrability model and simulation. Ocean Eng. 2019, 191, 106461. https://doi.org/10.1016/j.oceaneng.2019.106461
3. Çakır, E.; Fıs ̧kın, R.; Bayazit, O. *An Analysis of Accidents Occurred on Tugboats*; Dokuz Eylül University, Maritime Faculty: Izmir, Turkey, 2017; pp. 1–13.
4. Kornacki, J.; Galor, W. Analysis of Ships Turn Manoeuvres in Port Water Area. *Int. J. Mar. Navig. Saf. Sea Transp.* 2007, *1*, 95–100.
5. Kang, L.; Meng, Q.; Tan, K.C. Tugboat scheduling under ship arrival and tugging process time uncertainty. *Transp. Res. Part E Logist. Transp. Rev.* 2020, *144*, 215–230. https://doi.org/10.1016/j.tre.2020.102125
6. Paulauskas, V. *Ships Entering the Ports*; N.I.M.S Publish House: Riga, Latvia, 2013; 240p, ISBN 9984-679-71-3.

7. Paulauskas, V.; Paulauskas, D. Research on work methods for tugs in ports. *Transport* 2011, *26*, 310–314. https://doi.org/10.3846/16484142.2011.623825
8. Toma, A.; Oncica, V.; Atodiresei, D. The study of ships behavior during port maneuvering with tugs. *Mircea Cel Batran Nav. Acad. Sci. Bull.* 2016, *19*, 109–115.
9. *Tugs and Tows—A Practical Safety and Operational Guide*; The Shipowners' Mutual Protection and Indemnity Association: London, UK; Singapore, 2015; 88p.
10. Baldauf, M.; Benedict, K.; Fischer, S.; Motz, F.; Schröder-Hinrichs, J.-U. Collision avoidance systems in air and maritime traffic. *Proc. Imeche* 2011, *225*, 333–343. https://doi.org/10.1177/1748006X11408973
11. Abhijit, S. Hazards Identification and Safety Management Practices for Major Hazards in Routine Ship Towage Operation in Indian Coastal Waters. Ph.D. Thesis, University of Petroleum and Energy Studies (UPES), Dehradun, India, 2021. Available online: http://hdl.handle.net/10603/183139. (accessed on 01 May 2022).
12. Yıldırım, U.; Bas ̧ar, E.; Ug ̆urlu, Ö. Assessment of collisions and grounding accidents with human factors analysis and classification system (HFACS) and statistical methods. *Saf. Sci.* 2019, *119*, 412–425. https://doi.org/10.1016/j.ssci.2017.09.022
13. Zalewski, P.; Montewka, J. Navigation Safety Assessment in an Entrance Channel, Based on Real Experiments; Guedes-Soares & Kolev Maritime Industry, Ocean Engineering and Coastal Resources: Varna, Bulgaria, 2007; pp. 1113–1117.
14. I. Surinov. Information support of operator activity in organizing the tug service / I. Surinov, V. Shemonayev, Yu. Kazak. // Shipping & Navigation. – 2021. – №32. – Pp. 95–102. https://doi.org/10.31653/2306-5761.32.2021.95-102
15. Klaipeda Seaport Manuel, Maps and Charts; LMSA: Klaipeda, Lithuania, 2020; 60p.
16. Fitriadhy, A.; Yasukawa, H.; AMaimun, A. Theoretical and experimental analysis of a slack towline motion on tug-towed ship during turning. Ocean Eng. 2015, 25–32. https://doi.org/10.1016/j.oceaneng.2015.03.008
17. Strem, K. Ship‘s Handling; FORCE Technology: Lyngby, Denmark, 2004; 130p.
18. Weintrit, A. Initial description of pilotage and tug services in the context of e-navigation. J. Mar. Sci. Eng. 2020, 8, 116.
19. Figuero, A.; Sande, J.; Peña, E.; Alvarello, A.; Rabuñal, J.R.; Maciñeira, E. Operational thresholds of moored ships at the oil terminal of inner port of A Coruña (Spain). Ocean Eng. 2019, 172, 599–613. https://doi.org/10.3390/jmse8020116
20. Quy, M.N.; Łazuga, K.; Gucma, L.; Vrijling, J.K.; van Gelder, P.H.A.J.M. Towards generalized ship's manoeuvre models based on real time simulation results in port approach areas. Ocean Eng. 2020, 209, 107476. https://doi.org/10.1016/j.oceaneng.2020.107476
21. Coldwell, T.G. Marine traffic behaviour in restricted waters. J. Navig. 1983, 36, 430–444. https://doi.org/10.1017/S0373463300039783
22. Huang, Y.; Chen, L.; Chen, P.; Negenborn, R.R.; van Gelder, P.H.A.J.M. Ship collision avoidance methods: State-of-the-art. Saf. Sci. 2020, 121, 451–473. https://doi.org/10.1016/j.ssci.2019.09.018
23. Kristensen, H.O.; Lützen, M. Project no. Emissionsbeslutningsstøttesystem Work Package 2; Report no. 04; Technical University of Denmark; University of Southern Denmark: Odense, Denmark, 2013.
24. Wei, X.; Jia, S.; Meng, Q.; Tan, K.C. Tugboat scheduling for container ports. Transp. Res. Part E Logist. Transp. Rev. 2020, 142, 102071. https://doi.org/10.1016/j.tre.2020.102071
25. Li, J.; Zhang, X.; Yang, B.; Wang, N. Vessel traffic scheduling optimization for restricted channel in ports. Comput. Ind. Eng. 2021, 152. https://doi.org/10.1016/j.oceaneng.2018.03.073

26. O’zoga, B.; Montewka, J. Towards a decision support system for maritime navigation on heavily trafficked basins. Ocean Eng. 2018, 159, 88–97.
27. Olba, X.B.; Daamen, W.; Hoogendoorn, S.P. State-of-the-art of port simulation models for risk and capacity assessment based on the vessel navigational behavior through the nautical infrastructure. J. Traffic Transp. Eng. 2018, 5, 335–345.
28. Paulauskas, V.; Paulauskas, D.; Wijffels, J. Ship safety in open ports. Transport 2009, 24, 113–120. https://doi.org/10.3846/1648-4142.2009.24.113-120
29. Szlapczynski, R.; Szlapczynska, J. Review of ship safety domains: Models and applications. Ocean Eng. 2017, 145, 277–289. https://doi.org/10.1016/j.oceaneng.2017.09.020
30. Gucma, L. The risk assessment of ships maneuvering on the waterways based on generalized simulation data. In Safety and Security Engineering II. WIT Transactions on the Built Environment; WIT Press: Southampton, UK, 2007; Volume 94, pp. 58–69.
31. Perera, L.P.; Soares, C.G. Collision risk detection and quantification in ship navigation with integrated bridge systems. Ocean Eng. 2015, 109, 344–354. https://doi.org/10.1016/j.oceaneng.2015.08.016
32. Theirs, G.F.; Jansses, G.K. A Port Simulation Model as a Performance Decision Instrument. Simulation 1998, 71, 117–125. https://doi.org/10.1177/003754979807100206
33. Gil, M.; Montewka, J.; Krata, P.; Hinz, T.; Hirdaris, S. Determination of the dynamic critical maneuvering area in an encounter between two vessels: Operation with negligible environmental disruption. Ocean Eng. 2020, 213, 1–12. https://doi.org/10.1016/j.oceaneng.2020.107709
34. Haseltalab, A.; Negenborn, R.R. Model predictive maneuvering control and energy management for all-electric autonomous ships. Appl. Energy 2020, 251, 12–25. https://doi.org/10.1016/j.apenergy.2019.113308
35. Kurowski, M.; Kockritz, O.; Korte, H. Full-state Manoeuvre Planning System for Marine Vehicles. Ifac Proc. Osaka Vol. 2013, 46, 144–149. https://doi.org/10.3182/20130918-4-JP-3022.00022
36. Liu, S.; Wang, C.; Zhang, A. A method of path planning on safe depth for unmanned surface vehicles based on hydrodynamic analysis. Appl. Sci. 2019, 9, 3228. https://doi.org/10.3390/app9163228
37. Orc, Y.H.; Zhang, A.; Tian, W.; Zhang, J.; Hou, Z. Multi-Ship Collision Avoidance Decision-Making Based on Collision Risk Index. J. Mar. Sci. Eng. 2020, 8, 640. https://doi.org/10.3390/jmse8090640
38. Paulauskas, V. Navigational risk assessment of ships. Transport 2006, 21, 12–18. https://doi.org/10.3846/16484142.2006.9638034
39. Taimuri, G.; Matusiak, J.; Mikkola, T.; Kujala, P.; Hirdaris, S. A 6-DoF maneuvering model for the rapid estimation of hydrody-namic actions in deep and shallow waters. Ocean Eng. 2020. https://doi.org/10.1007/s12206-008-0309-9
40. Lee, C.-K.; Lee, S.-G. Investigation of ship maneuvering with hydrodynamic effects between ship and bank. J. Mech. Sci. Technol. 2008, 22, 1230–1236. https://doi.org/10.1007/s12206-008-0309-9
41. Paulauskas, V.; Lukauskas, V.; Plac˘iene, B. Ships leaving a port under emergency conditions. Transport 2012, 27, 345–350. https://doi.org/10.3846/16484142.2012.720278
42. Paulauskas, V.; Paulauskas, D.; Wijffels, J. Ships mooring in Complicated Conditions and possible solutions. In Proceedings of the 12th International Conference ‘Transport Means”; Technologija: Kaunas, Lithuania, 2008; pp. 67–70. https://doi.org/10.1016/j.trpro.2016.05.128

43. Bitner-Gregerse, E.M.; Soares, C.G.; Vantorre, M. Adverse weather conditions for ship manoeuvrability. Transp. Res. Procedia 2016, 14, 1631–1640. https://doi.org/10.1016/j.trpro.2016.05.128
44. Jurdzin´ski,M.ProcessesofaFreelyDriftingVessel.Int.J.Mar.Navig.Saf.SeaTransp.2020,14,687–693. https://doi.org/10.2478/v10040-008-0021-y
45. Tomczak, A. Safety evaluation of ship's maneuvers carried out on the basis of integrated navigational system (INS) indications. J. Konbin 2008, 4, 247–266. https://doi.org/10.2478/v10040-008-0021-y
46. Rolf, J.B.; Asbjørn, G. Maritime navigation accidents and risk indicators: An exploratory statistical analysis using AIS data and accident reports. Reliab. Eng. Syst. Saf. 2018, 176, 174–186.
47. Li, L.; Yuan, Z.; Gao, Y. Wash wave effects on ships moored in ports. Appl. Ocean Res. 2018, 77, 89–105. https://doi.org/10.1016/j.apor.2018.06.001
48. Yan, Q. A model for estimating the risk degrees of collisions. J. Wuhan Univ. Technol. 2002, 26, 74–76.
49. Fan, S.; Zhang, J.; Blanco-Davis, E.; Yang, Z.; Wang, J.; Yan, X. Effects of seafarers' emotion on human performance using bridge simulation. Ocean Eng. 2018, 170, 111–119. https://doi.org/10.1016/j.oceaneng.2018.10.021
50. Wu, B.; Yan, X.; Wang, Y.; Soares, C.G. An evidential reasoning-based cream to human reliability analysis in maritime accident process. Risk Anal. 2017, 37, 1936–1957. https://doi.org/10.1111/risa.12757

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ФОРМАЛІЗОВАНА МОДЕЛЬ ВИБОРУ БУКСИРНОГО ЗАБЕЗПЕЧЕННЯ МЕТОДОМ БАЛАНСУ КЕРУЮЧИХ СИЛ

Портові буксири є важливим елементом портової діяльності та питань безпеки судноплавства. Портові буксири забезпечують безпеку великих суден під час їх заходу, маневрування, швартування та відшвартування, і мають величезне значення під час інших портових операцій. У той же час оптимізація кількості портових буксирів і типу буксирів також важлива з точки зору безпеки навігації в порту та економічної точки зору. Методи розрахунку та оцінки оптимального запиту на роботу буксирів в портів є дуже важливими для забезпечення безпеки навігації порту та суден під час виконання основних суднових операцій у порту.

Найбільш небезпечними є ситуації раптового виходу з ладу електропостачання при маневруванні судна в замкнутій акваторії портів, коли буксири стають єдиним засобом контролю, який може запобігти аварії. Це спостерігається при русі судна в зоні з небезпечними ділянками водного шляху, заході в порт і виході з нього, а також при виконанні швартових робіт. До процесу ведення судна додатково залучаються лінійні та/або портові лоцмани, а також буксири для супроводу, супроводу або при виконанні швартовних операцій судна. У іноземних портах також дуже напружені умови управління командами через мовні бар'єри та необхідність синергетичної взаємодії окремих незалежних екіпажів суден без попередньої підготовки до відповідальної місії.

У цій роботі зосереджено увагу на покращенні можливостей буксира та зниженні навігаційних ризиків у районах портів методом балансування сил розвантаження. Таке зниження ризиків у портах є важливою проблемою для подолання, оскільки правильне і правильне використання портових буксирів може значно покращити ситуацію в них.

Ключові слова: *буксири, аврійні ситуації, маневрування акваторією порту, енергетичний баланс керуючих сил.*