TRANSPORT
ISSN 1648-4142 print / ISSN 1648-3480 online
2012 Volume 27(4): 345–350
doi:10.3846/16484142.2012.720278

# SHIPS LEAVING A PORT UNDER EMERGENCY CONDITIONS

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*Submitted 28 November 2011; accepted 9 January 2012*

**Abstract.** Emergency conditions in a port request special precaution measures taken by ships when in the majority of cases they necessitate leaving port waters in the shortest time. Good management, awareness and timely actions can help with avoiding difficulties encountered by ships under emergency conditions at ports. The conducted research suggested in the article has been based on investigation into ship maneuverability considering complicated weather conditions, theoretical methods for the feasibility of ship maneuverability referring to difficult conditions, experimental tests using the calibrated Simulator and evaluation of real ships under similar conditions. The results of the presented research could be used for analyzing the situation in different ports with different ships regarding practical preparation for vessels to leave the port under emergency conditions without any delay.

**Keywords:** seaport, ship, emergency conditions, ship maneuverability, ship steering under complicate conditions.

## 1. Introduction

Emergency conditions in ports request precaution measures taken by ships and in many cases a prompt leave of port waters (James Molinary Ltd. 2011). Weather conditions can change when approaching or departing a port, and thus it is necessary to take into account external forces like wind, waves, current, shallow water, etc. (BS 6349-4:2000).

In the event of the ship calling at the port and in case of emergency, it is necessary to leave the port frequently with no chance of receiving attendance from the port, i.e. pilot or tug assistance etc. In that case, the captain is fully responsible for a safe departure of the ship from the port as soon as possible (Baublys 1997; Paulauskas *et al.* 2008; Peckham 2001). The ships approaching the port, in most instances, should consider weather or other dangerous conditions so that to avoid potential emergency situations. In the cases of emergency situations at the port during ship berthing, the vessel has no possibilities of hesitation, and therefore the ship master must consider all possible actions that could guarantee safe departure from the port or terminal area (Strem 2004; Criteria for Movements… 1995). The cargo terminals used for storing dangerous and hazardous goods are mainly built close to port entrances, because these places have greater depth (BS 6349-1:2000; Somanathan *et al.* 2009; Strubbe 1987).

A theoretical study and methodology for calculating the preparation of ship maneuverability combining external (wind, waves, current, shallow water effect, etc.) and internal (ship propeller and ruder, thrusters) forces having an impact on the ship and achieved employing theoretical methods, simulator testing, a subsequent evaluation of differences, the analysis of real conditions (real ships and environmental conditions), practical solutions and possibilities are the key subjects of research presented in the article.

Good knowledge about the possibilities of ship maneuverability and the impact of natural conditions on the opportunities of ship maneuvers are based on research results presented in the article and can be used for ensuring the safety of ships leaving the port or terminal area in the shortest time so that to avoid complicated emergency situations (Figs 1 and 2).

## 2. Emergency Situations in Ports (Explosions and Fire on Terminals, Attacks on Ships, Sudden Weather Changes)

Emergency situations in ports are related to explosions or fires on terminals, especially on those storing oil, gas or chemical products, when staying alongside is impossible due to the moored ships that must leave the port as fast as possible. Terrorist attacks and other potential dangers toward ships very often prompt a necessity for speedy departure from the port in the shortest time (Paulauskas 1999; Paulauskas *et al.* 2008; Paulauskas, V., Paulauskas, D. 2009).

**Fig. 1**. Jetties at the oil terminal in the Port of Ventspils (Latvia)


**Fig. 2**. Jetties at the oil terminal in the Port of Kalundborg (Denmark)

Assistance for ships, port pilots and port tugs is limited in emergency situations because of urgent necessity to leave the port for many ships at the same time. Tug assistance is needed to solve the problems of port emergency etc.

Although pilot assistance in emergency situations could be provided, yet sometimes there are not enough pilots and frequently the shipmaster is the only person who takes full responsibility for safely leaving from a terminal or port taking into consideration ship maneuverability and environmental conditions.

Good knowledge and awareness taking into account the possibilities of ship maneuverability under adverse external and internal forces can be helpful for a shipmaster in emergency situations. Currents and winds often make the impact of external force on the ship having different characteristic vectors and as a result can be successfully used for implementing the approached tasks.

The oil terminal (Berths 1 and 2) in the Port of Klaipeda has been taken as a case study for ships leaving the port (Fig. 3). In this place, current direction is mainly parallel to quay walls, the wind blows in all directions and a combination of variables like different forces, values and directions, including additional external conditions such as channel parameters can be successfully used under emergency conditions.

The above mentioned emergency conditions request taking into account all possible internal and external factors that potentially affect the ship in order to ensure the safety of the vessel leaving the port in the shortest time. Only a very deep knowledge of possible acting forces, preliminary studies and calculations of ship maneuvering possibilities under specific situations can prevent from complications under such conditions.


**Fig. 3**. Quays at the oil terminal in the Port of Klaipėda

## 3. Theoretical Basis for Ship Maneuverability under Emergency Conditions

For calculating ship maneuverability (forces and moments) when leaving the port under emergency conditions, the following formulas for determining the forces and moments affecting the ship can be used (Paulauskas, V., Paulauskas, D. 2009):

$$X_{in} + X_k + X_\beta + X_p + X_N + X_a + X_{sr} + X_b + X_{sek} + T_x + T_V = 0; \quad (1)$$

$$Y_{in} + Y_k + Y_\beta + Y_p + Y_N + Y_a + Y_{sr} + Y_b + Y_{sek} + T_y + Y_V = 0; \quad (2)$$

$$M_{in} + M_k + M_\beta + M_p + M_N + M_a + M_{sr} + M_b + M_{sek} + M_T + M_V = 0, \quad (3)$$

where: $X_{in}$, $Y_{in}$, $M_{in}$ – inertial forces and moments; $X_k$, $Y_k$, $M_k$ – the force and moment acting on ship hull; $X_\beta$, $Y_\beta$, $M_\beta$ – ship hull as wing force and moment; $X_p$, $Y_p$, $M_p$ – the force and moment of the ship helm (ruder); $X_N$, $Y_N$, $M_N$ – the force and moment produced by ship thrusters; $X_a$, $Y_a$, $M_a$ – aerodynamic forces and moments; $X_{sr}$, $Y_{sr}$, $M_{sr}$ – the force and moment generated by currents; $X_b$, $Y_b$, $M_b$ – the force and moment produced by waves; $X_{sek}$, $Y_{sek}$, $M_{sek}$ – the force and moment of shallow effects; $T_x$, $T_y$, $M_T$ – the force and moments produced by the ship propeller; $X_V$, $Y_V$, $M_V$ – the force and moment created by tugs.

In many cases, ship propulsion equipment generates the force required for a ship moving in $X$ direction (ahead or astern) at least in port conditions and depending on wind and current activity. The main problem of ship emergency unmooring is moving in $Y$ direction (abeam) and steering, which means the ship must have enough power for steering in requested $Y$ direction (abeam) and overall ship control (Strem 2004).

Considering the above tasks, to ensure the movement and operation of the ship leaving the quay, the above Formulas (2) and (3) can be used for calculations

(Paulauskas 1999) in the following way:

$$\left(V+\lambda_{22}\right)\frac{dv}{dt}\cdot\sin\beta+Y_k+Y_\beta+Y_p+Y_N+$$
$$Y_a+Y_{sr}+Y_b+Y_{sek}+T_y+Y_V=0; \quad (4)$$
$$\left(I+\lambda_{66}\right)\frac{d\omega}{dt}\cdot\sin\beta\cdot\cos\beta+M_k+$$
$$M_\beta+M_p+M_N+M_a+M_{sr}+$$
$$M_b+M_{sek}+M_T+M_V=0, \quad (5)$$

where: $V$ – ship weight (displacement); $\lambda_{22}$ – added water mass in $Y$ direction; $\frac{dv}{dt}$ – ship acceleration; $\beta$ – ship drift angle; $I$ – the moment of the inertia of the ship hull; $\lambda_{66}$ – the added moment; $\frac{d\omega}{dt}$ – ship turning acceleration.

Ship movement in $Y$ direction during an unmooring operation is usually very slow because the ship encounters stiff resistance in $Y$ direction (abeam); in such cases, considering many situations, inertial forces and moments cannot be taken into account.

The total ship hull resistance $R_y$ can be calculated as follows:

$$R_y=C_y\frac{\rho}{2}L\cdot T\cdot\gamma\cdot v_y^2, \quad (6)$$

where: $C_y$ – a hydrodynamic factor that could be calculated on the basis of ship theory methods; $\rho$ – water density making 1000 kg/m$^3$ for fresh water; $L$ – ship length between perpendiculars; $T$ – ship average draft; $\gamma$ – a square coefficient of underwater hull projection on the diametric square of the ship in most cases could be taken as 0.95 to 1.0 depending on the construction of ship hull; $v_y$ – calculated ship speed in $Y$ direction.

The resulted wind force $Y_a$ can be calculated as follows:

$$Y_a=C_a\frac{\rho_1}{2}S_x\cdot v_a^2\cdot\sin q_a, \quad (7)$$

where: $C_a$ – an aerodynamic coefficient (in most cases could be taken as 1.0 to 1.3); $\rho_1$ – air density (for calculation purposes can be taken as 1.25 kg/m$^3$); $S_x$ – the space of projection onto a diametrical plane (DP) of the wind surface area of the vessel; $v_a$ – wind velocity; $q_a$ – wind course angle.

Current related force $Y_{sr}$ can be calculated as follows (Paulauskas, V., Paulauskas, D. 2009):

$$Y_{sr}=C_y\frac{\rho}{2}L\cdot T\cdot\gamma\cdot v_c^2\cdot\sin q_c, \quad (8)$$

where: $v_c$ – current velocity affecting the ship; $q_c$ – current course angle.

If the current sets directly against ship course at an angle, ship motion can involve 'wing effect' ($Y_\beta$) calculated as follows (Paulauskas, V., Paulauskas, D. 2009):

$$Y_\beta=C_\beta\frac{\rho}{2}L\cdot T\cdot\gamma\cdot\left(v_c-v_x\right)\cdot\cos q_c, \quad (9)$$

where: $v_x$ – ship speed above water ('–' if the ship sails against the current); $C_\beta$ – a hydrodynamic wing coefficient for practical angles up to 30 degrees can be calculated as follows:

$$C_\beta=\sin q_c. \quad (10)$$

Propulsion force $T_y$ is defined as the difference between ship DP and propeller screw. The angle between ship DP and propeller screw $q_y$ averages up to 3 degrees. $T_y$ can be calculated as follows:

$$T_y=K_1'\cdot\rho\cdot n_p^2\cdot D_p^4\left(1-t''\right)\sin q_y, \quad (11)$$

where: $K_1'$ – the coefficient of propeller force (accepted in calculations as 0.2); $n_p$ – propeller revolutions, rps (revolutions per sec); $D_p$ – the diameter of the ship propeller; $t''$ – the coefficient of propeller propulsion (in most cases could be used as 0.2); $q_y$ – angle between ship DP and propeller screw.

The force of the ship helm (ruder) in $Y$ direction can be expressed as follows:

$$Y_p=C_y'\frac{\rho}{2}S_h\cdot v_h^2, \quad (12)$$

where: $C_y'$ – a hydrodynamic coefficient of the ship rudder (in case of ship movement can be accepted up to 1.0); $S_h$ – the square of the rudder plate; $v_h$ – the velocity of the propeller screw on the ship rudder plate can be calculated as follows:

$$v_h=1.6\cdot D_p\cdot n_p^2. \quad (13)$$

Thruster force values can be taken directly from thruster application (manual).

Finally, ship force in $Y$ direction (abeam) can be expressed as follows:

$$C_y\frac{\rho}{2}L\cdot T\cdot\gamma\cdot v_y^2+C_a\frac{\rho_1}{2}S_x\cdot v_a^2\cdot\sin q_a+$$
$$C_y\frac{\rho}{2}L\cdot T\cdot\gamma\cdot v_c^2\cdot\sin q_c+$$
$$C_\beta\frac{\rho}{2}L\cdot T\cdot\gamma\left(v_c-v_x\right)^2\cos q_c=$$
$$K_1'\cdot\rho\cdot n_p^2\cdot D_p^4\left(1-t''\right)\sin q_y+Y_N+Y_p. \quad (14)$$

Using Formula (14), the speed of the ship moving in $Y$ direction (abeam) can be arranged as follows:

$$v_y=\sqrt{a+b+c+d+e+f}, \quad (15)$$

where:

$$a=\frac{C_a\cdot\rho_1\cdot S_x\cdot v_a^2\cdot\sin q_a}{C_y\cdot\rho\cdot L\cdot T\cdot\gamma};$$
$$b=v_c^2\cdot\sin q_c;$$
$$c=\frac{C_\beta\left(v_c-v_x\right)^2\cos q_c}{C_y};$$
$$d=\frac{2\cdot K_1'\cdot n_p^2\cdot D_p^4\left(1-t''\right)\sin q_y}{C_y\cdot\rho\cdot L\cdot T\cdot\gamma};$$
$$e=\frac{C_{yh}\cdot S_h\cdot v_p^2}{C_y\cdot L\cdot T\cdot\gamma};$$
$$f=\frac{2\cdot Y_N}{C_Y\cdot\rho\cdot L\cdot T\cdot\gamma}.$$

The latter formula expresses ship speed in $Y$ direction (abeam) during mooring or unmooring to or from the quay and can be used for calculating ship speed in emergency situations. The last formula did not include tug bollard pull and the inertial force of the ship because inertial forces are insignificant in comparison to other possible forces at very low speed. Tug forces can also be taken into account and Formula (15) may, in such a case, include tug force involved in creating ship speed in $Y$ direction (abeam) (if tugs are used). If using tugs, Formula (15) could be written as follows:

$$v_y = \sqrt{a+b+c+d+e+f+g}, \tag{16}$$

where:

$$a = \frac{C_a \cdot \rho_1 \cdot S_x \cdot v_a^2 \cdot \sin q_a}{C_y \cdot \rho \cdot L \cdot T \cdot \gamma};$$

$$b = v_c^2 \cdot \sin q_c;$$

$$c = \frac{C_\beta \left(v_c - v_x\right)^2 \cos q_c}{C_y};$$

$$d = \frac{2 \cdot K_1' \cdot n_p^2 \cdot D_p^4 \left(1 - t''\right) \sin q_{sr}}{C_y \cdot \rho \cdot L \cdot T \cdot \gamma};$$

$$e = \frac{C_{yh} \cdot S_h \cdot v_p^2}{C_y \cdot L \cdot T \cdot \gamma};$$

$$f = \frac{2 \cdot Y_N}{C_Y \cdot \rho \cdot L \cdot T \cdot \gamma};$$

$$g = \frac{2T_T \left(\cos\alpha_T + \cos\beta_T\right)}{C_y \cdot \rho \cdot L \cdot T \cdot \gamma},$$

where: $T_T$ – horizontal pull power of tugs in the direction perpendicular to ship DP; $\alpha_T$ – a vertical angle of the tug line from the ship to the tug; $\beta_T$ – a horizontal angle of the tug line from the ship to the tug.

Horizontal force $F'$ as produced by ship motion at speed $v_y$ in $Y$ direction (abeam) could be calculated as follows:

$$F' = C_y \cdot \frac{\rho}{2} \cdot L \cdot T \cdot \gamma \cdot v_y. \tag{17}$$

Horizontal ship speed and/or force in $Y$ direction (abeam) alone are not enough to take the final decision because the ship should be steering well enough. For assessing the possibilities of ship steering, the calculation of moments is necessary. If the moments generated by the ship propeller and tugs (a ship moving back, in the majority of cases, does not use the rudder) are longer than the other moments, the ship is able to steer, and the moment can be formulated as follows:

$$M_\beta + M_p + M_N + M_a + M_{sr} + M_V = 0. \tag{18}$$

In that particular case, when for unmooring operations or leaving the quay, horizontal pull power perpendicular to the direction of ship DP is required, Formula (18) can be successfully applied:

$$T_T = \frac{Y_a \cdot x_a' + T_y \cdot x_p' - Y_\beta \cdot x_0'}{x_T' \cdot \sin q_T}, \tag{19}$$

where: $x_a'$ – the distance from the aerodynamic center to the pivot point of the ship, which in case of the ship moving back, is located about 0.3 $L$ to the stern of the ship midship section; $x_p'$ – the distance from the ship propeller to the pivot point of the ship; $x_0'$ – the distance from the point adding force to the ship hull to the pivot point of the ship accepting the hull as a 'wing'; $x_T'$ – the distance from the fixing point of the tug line to the pivot point of the ship; $q_T$ – the angle of the course in tug pulling.

In case when the horizontal pulling force of the tug in the direction perpendicular to ship DP is enough, the ship could be steering.

The simulations of ship movement on the basis of a theoretical methodology and real ship characteristics could explain ship movement under different conditions and find optimal possible solutions to emergency conditions (Köse *et al.* 2003; Hensen 1999).

At the same time, it is necessary to take in account that frequently the moments created by the ship hull, wind and current have different directions and do not have maximum values. In such a case, even a small tug or boat, like a pilot bout, could be very useful for following the right ship direction moving away from the quay wall (Thiers, Janssens 1998).

## 4. A Case Study on Ship Unmooring Calculations and Testing under Emergency Conditions

As a case study on ship unmooring under emergency conditions, PANAMAX type tanker unmooring from Quay 1 at Klaipėda port and leaving the port was taken. For unmooring operations, the main parameters of the ship include length – 220 m, width – 32.3 m, draft – 12.5 m, depth in a maneuvering place – 14 m, wind perpendicular to the quay wall – 15 m/s, the current alongside the quay wall – 0.5 m/s and a tug the pull force of which reaches 300 kN.

With reference to the aforementioned conditions, calculations were made on the account of varying currents and wind parameters in the mentioned directions. Ship unberthing and maneuvering leaving the port under emergency situation was tested applying the calibrated visual simulator SimFlex Navigator (2010). Sailing parameters of similar ships were checked in the same location under analogous conditions using navigational system E-Sea Fix (E-Sea Fix… 2003). Calculation and testing results are presented in Figs 4–11.

The calculation results of horizontal force $F'$ produced by PANAMAX tanker moving at speed $v_y$ in $Y$ direction (abeam) at the rate of 0.2 m/s are presented in Fig. 6.

The calculation results, presented in Figs 6 and 7 and received applying Formulas (16), (17) and (19), testing results obtained employing the simulator and presented in Figs 8 and 9 as well as experimental results got using similar types of real ships under the same environmental conditions and presented in Fig. 7 show that the correlation between all obtained results, including the same situations and conditions, is good enough and makes differences less than 15%. The above mentioned results indicate that with reference to carefully prepared

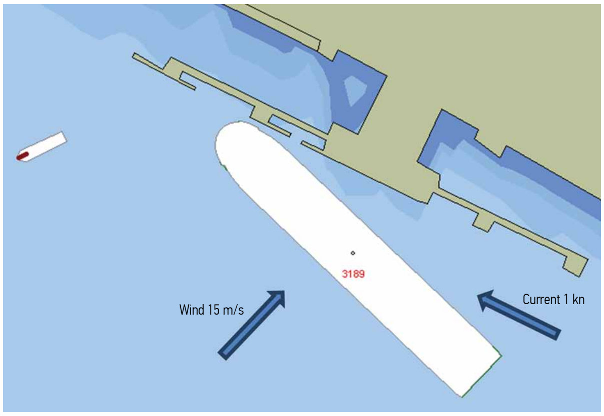


**Fig. 4.** Scheme for ship maneuvering and external forces (wind and current)

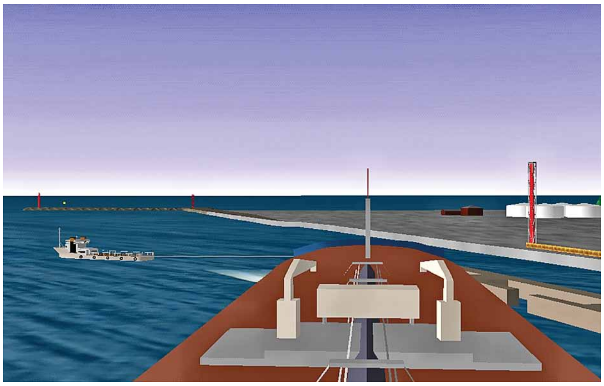

**Fig. 5.** Visual picture of ship unberthing and maneuvering

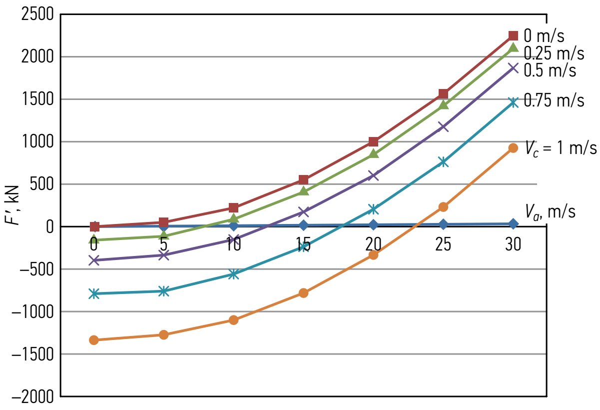


**Fig. 6.** Horizontal force $F'$ produced by PANAMAX tanker moving at speed $v_y$ in $Y$ direction (abeam) at the rate of 0.2 m/s) depending on the velocity of the current and wind ($F'$ '+' – the ship moving towards the quay wall; $F'$ '–' – the ship leaving the quay wall)

research related to ship maneuvering, knowledge of ship control and thoroughly explored ship maneuvering characteristics and possibilities along with environmental conditions in situ, the vessels could leave a terminal or port under emergency conditions without tug assistance or merely with minimum pull power used for ship steering assistance.

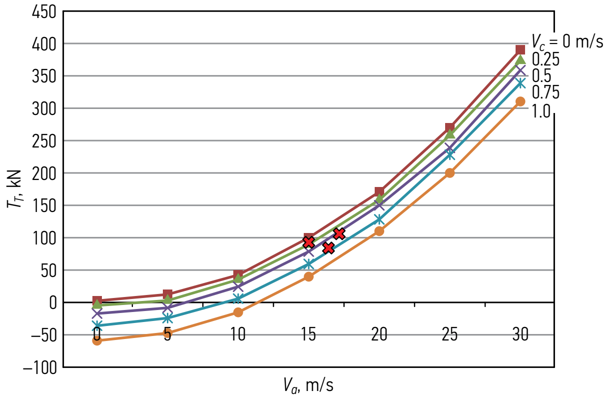


**Fig. 7.** The force required for tug pulling in the direction perpendicular to the DP of PANAMAX tanker turning left ('–') and right ('+'); ✖ – the experimental results were obtained using similar ships under the same environmental conditions (wind – 15 m/s, current – 1 kn)

**Fig. 8.** PANAMAX tanker assisted by one tug and leaving the berth

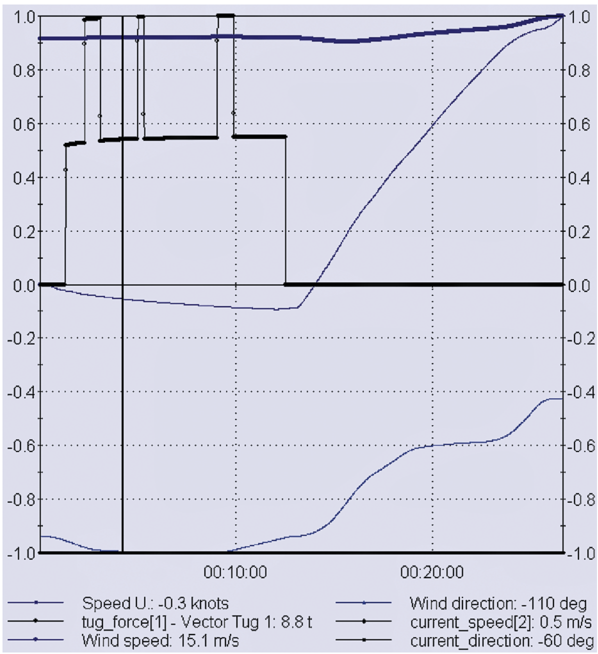


**Fig. 9.** PANAMAX tanker, tug movement and environmental parameters considering position details presented in Fig. 8

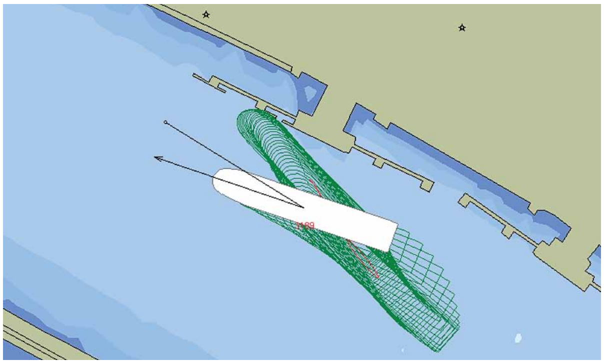

**Fig. 10.** PANAMAX tanker moving inside the port channel after unberthing with no tug assistance

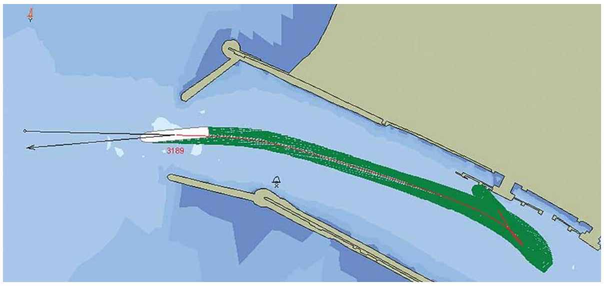

**Fig. 11.** The trajectory of PANAMAX tanker unberthing and leaving the port

The above presented calculation programs created on the introduced methodology can be successfully used by ship masters and operators to make preliminary calculations of restrictions on ship possibilities under emergency conditions. Ship masters and crews should be trained employing full mission simulators to improve knowledge of ship crew and operators under emergency conditions leaving terminals and ports (Criteria for Movements… 1995). At the same time, every ship master should carefully use such information and consider each specific situation taking into account personal experience and knowledge.

During day-to-day operation, every ship master must maintain and collect information and knowledge about ship maneuverability and related characteristics.

## 5. Conclusions

1. Emergency conditions in ports and terminals are very rare but when necessary, every ship master must take all possible actions to ensure the safety of the ship leaving a terminal and port using the available resources and possibilities.
2. External forces created by the wind, currents, etc. and internal forces created by the helm, propeller, thrusters, etc. and having impacts on the ship could be evaluated using the combinations of these forces for safe ship maneuvers and departures from the terminal and port in case of emergency situations.
3. The methodology presented in the article has been verified with reference to real ships and calibrated full mission simulators and have shown a good correlation between the theory and practice.
4. The methodology presented in the article can be used for evaluating potential ship possibilities of leaving the port under emergency situations as well as for researching potential possibilities of ships and ports thus providing preliminary calculations of ship unmooring possibilities under specific environmental impact without external assistance.
5. Researchers could use the presented methodology for ports, channels and other waterways to study the advantages and disadvantages of particular waterways and to improve these factors before physical construction works are started.
6. In-depth investigations into ship possibilities as shown in this article are important for ship design, building and operation.
7. Ship crew training employing full mission simulators in regard of emergency terminal and port leaving situations is very important and recommended for developing a ship crew training program.

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