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A SIMPLIFIED MANEUVERING PERFORMANCE OF A LARGE CONTAINER SHIP PASSING THROUGH THE SUEZ CANAL

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SUMMARY

In the Suez Canal, it have been consistently reported that ships collided with other ships or inner walls of the Canal, despite the maneuverability of the ships meet the IMO standards. Ship owners are requiring the ship design considering the maneuverability under restricted water, because they thought that those collisions resulted from bad execution in the Canal. In this paper, it is simply tried to evaluate the maneuvering performance to specify the design basis related to the rudder considering the maneuverability of the ship under restricted water such as the Suez Canal. The hydrodynamic coefficients at deep and shallow water are predicted based on the empirical formulae. The bank effects due the walls of the Canal are considered by analyzing the CFD calculation results using the parameters with reference to the empirical formulae. The index as a design basis is developed by evaluating the minimum relative distances between the ship and both walls of the Canal under prescribed environmental conditions.

1 INTRODUCTION

Most of ships in shipyards of South Korea sailing along a planned route in the ocean are large vessels such as container ship, liquefied natural gas carrier (LNGC), very large crude oil carrier (VLCC) et al. It is general that the ships have simplified sailing plan where complex maneuvering behaviors are minimized to secure ship handling safety. Therefore, hull, propeller and rudder design have been conducted by considering typical maneuvering test results such as course keeping ability and turning ability at design speed. For the designed ship, it should be shown whether the maneuverability meet the standards related to the initial turning test, 35° turning test, 10°/10° zigzag test and 20°/20° zigzag test recommended by the International Maritime Organization (IMO) [1]. It have been generally demonstrated using simulation, model test and sea trial. In shipyards, it is frequent that maneuvering performance of a ship is evaluated by simulation, because it is important to confirm whether the ship can meet the IMO standards or not, from the shipbuilding company's point of view. Kijima et al [2] conducted regression analysis based on the model test for various ships and predicted hydrodynamic coefficients of a ship using principal particulars. Based on the research, it is possible to predict maneuverability of a ship using limited information which can be obtained in the initial design stage. Lately, Sung and Park [3] conducted virtual captive model test using the computational fluid dynamics (CFD) and obtained the hydrodynamic coefficients. The maneuvering simulation results using the acquired coefficients are compared with those using coefficients obtained from the model test.

It has been enough to verify the maneuverability of the designed ship using the typical maneuvering test results if the ship has a simple sailing route. However, it is hard to judge the ship handling safety based on the typical test, if complex sailing conditions such as low speed, shallow water and restricted water are additionally included in the sailing plan for financial efficiency and security reasons. It is representative that a large vessel passes through the Suez Canal from Asia to Europe. In the Suez Canal, it have been consistently reported that ships collided with other ships or inner walls of the Canal, despite the maneuverability of the ships meet the IMO standards. Ship owners are requiring the rudder design considering the maneuverability under restricted water, because they thought that those collisions resulted from bad execution in the Canal. However, there is no way like IMO standards to judge the ship handling safety in the canal.

In this paper, it is tried to construct an evaluation method of the maneuvering performance to specify the design basis related to the rudder considering the maneuverability of the ship under restricted water such as the Suez Canal. First of all, a large container ship was chosen to investigate the maneuvering behavior under the restricted water, because there are in great demand for container ships passing through the Suez Canal. And, the hydrodynamic coefficients at deep and shallow water are predicted based on the empirical formulae proposed by Kijima et al [2, 4] and added mass and added mass moment of inertia are predicted based on the empirical formulae suggested by Hooft and Pieffers [5] and Meijing [6]. Rudder lift and drag coefficients are predicted based on the empirical formulae proposed by Fujii and Tsuda [7, 8]. In case of propeller thrust coefficients, they are obtained from the model test results for previous project in the Daewoo Shipbuilding and Marine Engineering Co., Ltd. (DSME). Environmental conditions for the Suez Canal are determined with reference to the sailing directions published by the National Geospatial-Intelligence Agency [9]. Maximum wind speed which is allowed for sailing ship in the Canal is 10.0 knots. The wind load coefficients of the large container ship are predicted using the empirical formulae proposed by Fujiwara [10] and irregular wind speeds are generated using Frøya spectrum proposed by Anderson and Løvseth [11]. The effect of the canal flow on the ship can be considered in the maneuvering equations of motion using the Hwang's method [12]. The bank effects due the walls of the Canal are considered by analyzing the CFD calculation results using the parameters with reference to the empirical formulae proposed by Norbin [13]. To specify the design basis of maneuverability under the prescribed condition, it is assumed that the ship passes through along the virtual waypoints in the straight canal with same cross section. Rudders have to be controlled for the ship to go straight following the way points, because there are irregular winds, canal flows and bank effects. In the Suez Canal, it is prohibited to operate the autonomous navigation system. Therefore, the ship has to be controlled by a seafarer. To consider the control characteristics of the human seafarer, the fuzzy control proposed by Hasegawa [14] is applied. The maneuvering performance as a design basis is evaluated by calculating the minimum relative distances between the ship and both walls of the Canal under prescribed environmental conditions. The minimum distances for 3 hours obtained according to the wind directions. Four points, which are bow and stern end points in the port and starboard side of the ship, are decided as the reference points for the evaluation. For the reference points, the ship is assumed as a rectangle whose length is same with the length between perpendiculars and width is same with the breadth. Using the evaluated results, it is anticipated that the ship handling safety can be qualitatively compared under the given environmental conditions. In the future, it is possible to be developed as minimum requirement to ensure the performance of a ship which has to pass through any restricted water, after the values for ships in the collision accident are statistically investigated.

2 MODEL SHIP AND MANEUVERING EQUATIONS OF MOTION

As shown in Fig. 1, a large container ship with twin propellers and rudders was chosen in order to calculate the maneuvering behavior of the ship in the Suez Canal. Table 1 shows the principal particulars of the container ship. LCG indicates the distance of the longitudinal center of gravity from midship. In this study, maneuvering equations of motion as shown in equation (1) are solved to evaluate the maneuvering performance of the ship. In equation (1), m indicates the mass of the ship, and I_{zz} means the mass moment of inertia. u, v are the longitudinal and transverse speeds, and r is the rotational angular velocity. $\dot{u}$, $\dot{v}$ indicate the time derivatives of longitudinal and transverse speed. $\dot{r}$ is the time derivatives of angular velocity. X, Y is the longitudinal and transverse forces acting on the ship, and N is the yaw moment.

Figure 1. A model of the large container ship with twin propellers and rudders

Table 1. Principal particulars of the container ship

Item	Magnitude
Length overall [m]	About 400.0
Length between perpendiculars [m]	About 375.0
Breadth [m]	59.0
Draft [m]	16.0
Block coefficient [-]	0.700
LCG [m]	7.00
Propeller diameter [m]	9.50
Pitch at 0.7R [m]	6.700
Rudder area [m^2]	60.00
Aspect ratio [-]	1.50

$$\begin{aligned} m(\dot{u} - vr) &= X \\ m(\dot{v} + ur) &= Y \\ I_{zz}\dot{r} &= N \end{aligned} \tag{1}$$

Fig. 2 shows the coordinate system of this research. x_g, y_g indicates the global coordinate axis, δ is the rudder deflection angle. U means the ship speed. Ψ, Ψ_{wind}, $\Psi_{canal\ flow}$ are the heading angle of the ship, incident angle of wind and canal flow, respectively. V_{wind}, $V_{canal\ flow}$ are the speed of wind and canal flow.

The forces and moment acting on the ship can be expressed as equation (2). The subscript “H” indicates the hull of the ship, and “C” means the canal flow. The meaning of “H(C)” is that canal flow load acting on the hull is considered during the calculation of hydrodynamic loads acting on the hull [12]. “P”, “R”, “W” and “B” indicate loads due to the propellers, rudders, wind and bank effect.

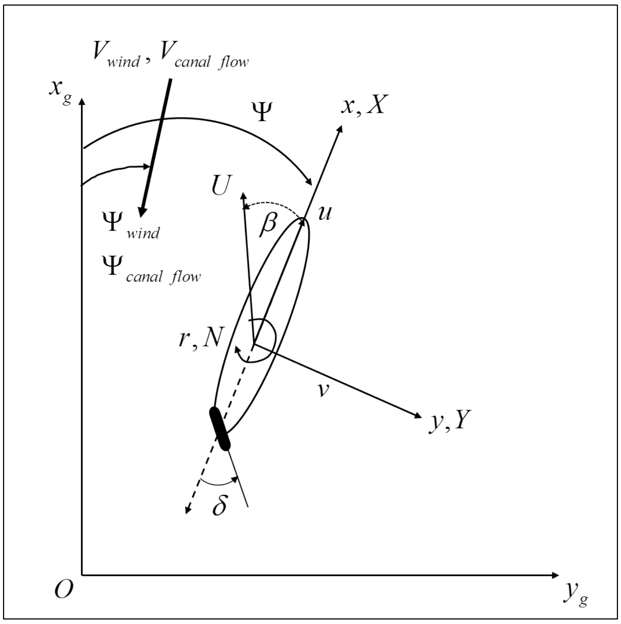

Figure 2. Coordinate system

$$\begin{aligned} X &= X_{H(C)} + X_P + X_R + X_W + X_B \\ Y &= Y_{H(C)} + Y_R + Y_W + Y_B \\ N &= N_{H(C)} + N_R + N_W + N_B \end{aligned} \qquad (2)$$

Because the design of a ship is not confirmed in the initial design stage, it is impossible to acquire the detailed information, accurately. All hydrodynamic coefficients, added mass and added mass moment of inertia, and rudder lift coefficients are predicted using the empirical formulae to consider the limitation on the initial design stages [2, 4, 5, 6, 7, 8]. However, resistance coefficient and information related to propeller thrust are obtained from model test results for previous projects. Hydrodynamic loads are written as shown in equation (3). m_x , m_y indicate the added mass along the longitudinal direction and transverse direction. J_{zz} is the added mass moment of inertia. T means the draft of the ship. x_G indicates the LCG as defined in Table 1.

$$\begin{aligned} X_{H(C)} &= -m_x\dot{u} + (m_y + X_{vr})vr + \left(\frac{1}{2}\rho \cdot L_{pp} \cdot T \cdot U^2\right) \cdot X_{uu}\cos^2\beta \\ Y_{H(C)} &= -m_y\dot{v} + m_x ur + Y_H(v', r') \\ N_{H(C)} &= -J_{zz}\dot{r} + N_H(v', r') + x_G \cdot Y_H(v', r') \end{aligned}$$

where,

$$\begin{aligned} Y_H(v', r') &= \left(\frac{1}{2}\rho \cdot L_{pp} \cdot T \cdot U^2\right) \\ &\cdot \left(Y_v' \cdot v' + Y_r \cdot r' + Y_{vv}' \cdot v'|v'| + Y_{rr}' \cdot r'|r'| + Y_{vvr}' \cdot v'v'r' + Y_{vrr}' \cdot v'r'r'\right) \\ N_H(v', r') &= \left(\frac{1}{2}\rho \cdot L_{pp}{}^2 \cdot T \cdot U^2\right) \\ &\cdot \left(N_v' \cdot v' + N_r \cdot r' + N_{vv}' \cdot v'|v'| + N_{rr}' \cdot r'|r'| + N_{vvr}' \cdot v'v'r' + N_{vrr}' \cdot v'r'r'\right) \end{aligned}$$

$$\beta = \frac{-v}{\sqrt{u^2 + v^2}},\ v' = v/U,\ r' = r \cdot L_{pp}/U$$

$$X_{vr} = \frac{\partial^2 X}{\partial v \partial r},\ X_{uu} = \frac{\partial^2 X}{\partial u \partial u},\ Y_v = \frac{\partial Y}{\partial v}, Y_r = \frac{\partial Y}{\partial r},\ Y_{vv} = \frac{\partial^2 Y}{\partial^2 v},\ Y_{rr} = \frac{\partial^2 Y}{\partial^2 r},$$

$$Y_{vvr} = \frac{\partial^3 Y}{\partial^2 v \partial r}, Y_{vrr} = \frac{\partial^3 Y}{\partial v \partial^2 r}, N_v = \frac{\partial N}{\partial v}, N_r = \frac{\partial N}{\partial r},\ N_{vv} = \frac{\partial^2 N}{\partial^2 v},$$

$$N_{rr} = \frac{\partial^2 N}{\partial^2 r},\ N_{vvr} = \frac{\partial^3 N}{\partial^2 v \partial r}, N_{vrr} = \frac{\partial^3 N}{\partial v \partial^2 r}$$

(3)

3 PREDICTION OF ENVIRONMENTAL LOADS SUCH AS WIND, CANAL FLOW AND BANK EFFECT

The cross section of the Suez Canal is defined with reference to the cross sectional area proposed by the National Economic Development as shown in the Fig. 3. Actual cross section is not only same along the canal but also it is not straight. In this research, the geographical characteristics are simplified, even if actual cross section is not always identical. The canal section has two sloped walls whose angles are same at both sides. The width of the bottom is 121 m, and the width of the canal at mean water level is 313 m. And, the depth of the canal is 24m. It is assumed that virtual way points are located at the center of the width at mean water level. Because it is not wide enough to allow two-way passage, two convoys are scheduled to transit the Canal on a typical day, one southbound and northbound. Therefore, a ship always tries to move straight near center in the Suez Canal. Because the draft of the container ship is 16 m, the relative distances between the two reference points at starboard side and bank wall have to be larger than 64.0 m to prevent from colliding with the wall. Likewise, the relative distances between the two reference points at port side and bank wall have to be larger than 64.0 m, as well. Accordingly, the values can be regarded as indices which should be kept to a minimum. The values are defined as C_{STBD} and C_{PORT}.

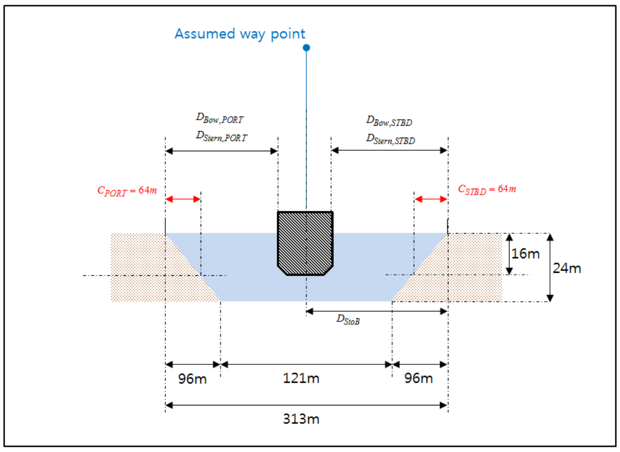

Figure 3. Design section of the Suez Canal

To consider the wind loads acting on the hull, wind load coefficients are obtained from the empirical formulae proposed by Fujiwara [10]. The values to predict the coefficients are shown in Table 2. The maximum allowed wind speed for sailing in the Suez Canal is 10.0 knots. HBR indicates the height to top of superstructure, C is the distance from midship section to center of the superstructure. H_C is the height to center of lateral projected area, AOD is the lateral projected are of superstructure. CBR is the distance from midship section to center of the superstructure. A_T , A_L are the transverse and lateral projected area, respectively.

To generate irregular wind speeds acting on the hull, Frøya spectrum proposed by Anderson and Løvseth is used. The spectral density function is shown in equation (4). U_0 is the 1-hour mean wind speed at 10 m in units of m/s, and z is the height above sea level in units of m. n is 0.468.

The spectral density considering the geographical characteristics of the Suez Canal is shown in Fig. 4. Fig. 5 shows the generated random wind speed based on the acquired spectral density function.

Table 2. Inputs of the large container ship to predict wind load coefficients proposed by Fujiwara (2001)

Item	Magnitude
Design wind speed [$knots$]	10.0
HBR [m]	43.0
C [m]	9.75
H_C [m]	24.7
AOD [m^2]	11445
CBR [m]	14.75
A_T [m^2]	17338.4
A_L [m^2]	3114.4

$$S_U(f) = 320 \cdot \frac{(\frac{U_0}{10})^2 (\frac{z}{10})^{0.45}}{(1+\tilde{f}^n)^{\frac{5}{3n}}} \tag{4}$$

$$(where, \tilde{f} = 172 \cdot (\frac{z}{10})^{\frac{2}{3}} \cdot (\frac{U_0}{10})^{-0.75})$$

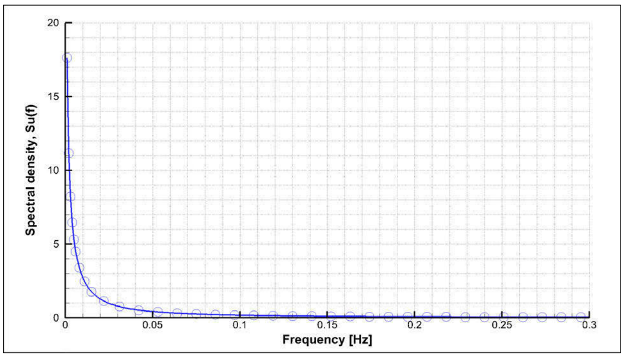

Figure 4. Spectral density of Froya Spectrum

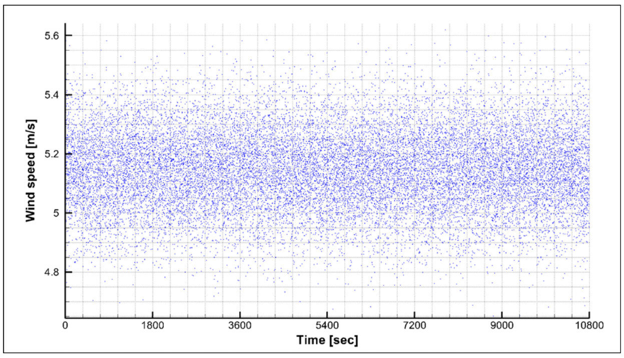

Figure 5. Generated random wind speed

In the canal, there can be canal flow according to the change of the water level in both ends of the Suez Canal. However, it is ignored in this research. Namely, still water condition is only considered.

Bank effect between hull and wall in the canal are obtained from CFD calculation. The loads due to bank effect can be acquired as follows. First of all, X , Y forces and N moment are calculated under the certain conditions with bank wall and they are marked as $X_{w/\ walls}$, $Y_{w/\ walls}$ and $N_{w/\ walls}$, as shown in Table 3. And the forces and moment, which are marked as $X_{w/o\ walls}$, $Y_{w/o\ walls}$ and $N_{w/o\ walls}$, are calculated under same conditions without bank walls. The differences between the values with bank walls and the values without bank walls are regarded as the loads due to the bank walls. And, they are marked as X_B , Y_B and N_B , as shown in equation (5). In this research, the the effect of X_B is ignored to simplify the analysis for the maneuvering performance in the Suez Canal.

Test matrix for CFD calculation written as shown in Table 3. According to the formulae proposed by Norbin, depth, inflow speed and distance from wall to hull are important parameters. With reference to other research conducted by Ch'ng [15], it is aimed to investigate the effect due to the inflow speed and distance from wall to hull. In Table 3, D_{StoB} indicates the distance from the center line of the ship to the wall in the starboard side. In the empirical formulae proposed by Norbin, it was constructed for the wall in starboard side, only. However, there are two sloped walls in the Suez Canal. Accordingly, the parameter of the CFD calculation is modified with reference to the parameters proposed by Ch'ng [15].

Table 3. CFD calculation matrix to estimate the bank effect on the hull

Depth [m]	Inflow speed [knots]	D_{StoB} [m]
24	5.5, 7.5, 9.5	91.25
		104.3
		130.4
		156.5

In the CFD calculation, it is assumed that there is uniform flow with prescribed speed. In addition, it is assumed that there is no free surface effect acting on the hull. The meaning of no free surface indicates the submerged body is only affected by the canal flow. Namely, there are no waves induced by the hull. Of course, the disturbed free surface and generated waves affect the calculated forces and moment. In reality, the free surface effect is significantly related to the ship speed. Because the magnitude of the values which are induced by the ship moving with low speed may be small, it can be ignored. Fig. 6 shows an example of the pressure distribution on the ship bottom obtained by the CFD calculation. In the figure, there are four solid lines. The solid lines at the top and bottom are the boundaries in the Suez Canal at mean water level. The two lines in the middle show the boundaries at bottom in the Canal. Due to the wall effect acting on the ship bottom, the asymmetric pressure distribution can be observed. Accordingly, as the ship approaches on the wall, the calculated yaw moment have to increase. In the CFD calculation, the scale factor is 39.551, the number of meshes ar about 200 million. The Star CCM+ is used to calculate the bank effect as a CFD tool. A Reynolds-Averaged Navier Stokes (RANS) model with K-epsilon turbulence model is used for simulation.

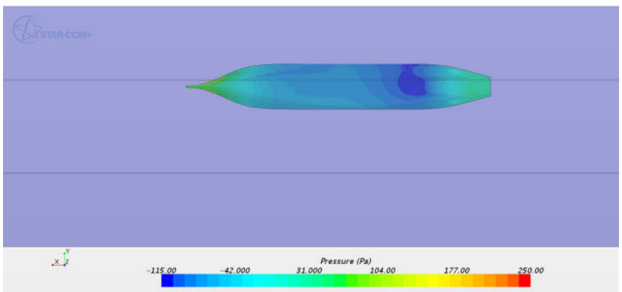

Figure 6. An example of the pressure distribution on the ship bottom obtained by the CFD calculation

To consider the Y forces and N moments due to the banks, the heading angle of the ship is ignored, because the deviation of the heading angle is small. Of course, the effect of heading angle is very significant. In this study, it is only aimed to construct the evaluation method of the maneuvering performance of the ship in the Suez Canal.
Fig.7 and 8 show the calculated Y forces and N moments using CFD at 5.5, 7.5 and 9.5 knots. In the figures, the black squares, blue circles and red diamonds indicate the results at 5.5, 7.5 and 9.5 knots. In the calculation, the heading angle of the ship is zero. The acquired Y forces and N moment have increased, as the ship speed increases. Likewise, Y forces and N moment have increased, as the location of ship goes near bank.

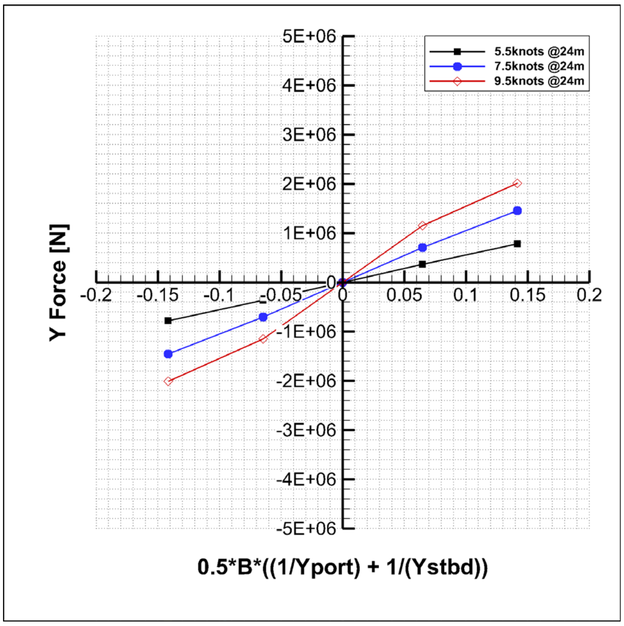

Figure 7. Calculated Y forces according to the ship location in the Suez Canal

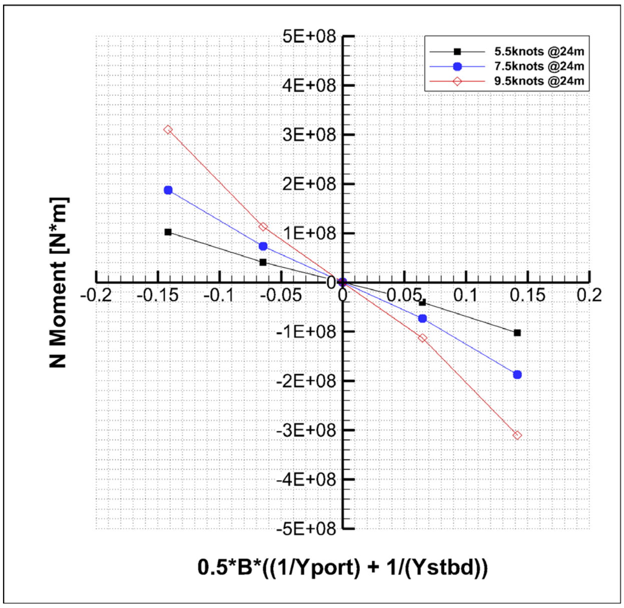

Figure 8. Calculated Y forces according to the ship location in the Suez Canal

4 ESTIMATION OF MANEUVERING PERFORMANCE PASSING THROUGH THE CANAL

As mentioned, the minimum distances between the four reference points and port/starboard banks under the prescribed environmental conditions are acquired as shown in Fig.9. The red solid line indicates minimum value of C_{STBD} and C_{PORT}. And the red dashed line indicates the maximum value of C_{STBD} and C_{PORT}.

If the ship approaches to the bank in starboard side, the calculated relative distances between two reference points in starboard side and bank in starboard side decrease. Otherwise, the calculated relative distances between two reference points in port side and bank in port side increase. If the distances are less than 64.0 m, it indicates the ship collide with the bank. At that time, the relative distances in opposite direction become 249.0 m.

The black line with squares shows the minimum distances for the bow reference point in starboard to the starboard side wall. And the black line with circles shows the minimum distances for the stern reference point in starboard to the starboard side wall. The blue line with empty squares shows the minimum distances for the bow reference point in port to the port side wall. And the blue line with empty circles shows the minimum distances for the stern reference point in port to the port side wall. To mark the acquired values on the same plot, infinitesimal values and overlarge values are marked as 64.0 m and 249.0 m, respectively. As mentioned, if the calculated values are lower than 64.0 m, it means the ship collided with a bank wall. At that time, the calculated values for the opposite direction are larger than 249.0 m.

Because the cross section of the Canal is symmetric, the obtained polar chart is symmetric as well. The relative distance for bow reference points are insignificantly different with that for stern reference points. Based on the acquired polar chart, the ship cannot be safely operated under the wind for 60, 90, 270 and 300 deg. In other conditions, the ship can move without colliding with the bank walls. Based on the results, it is possible to evaluate the maneuvering performance of the ship in the Suez Canal, qualitatively.

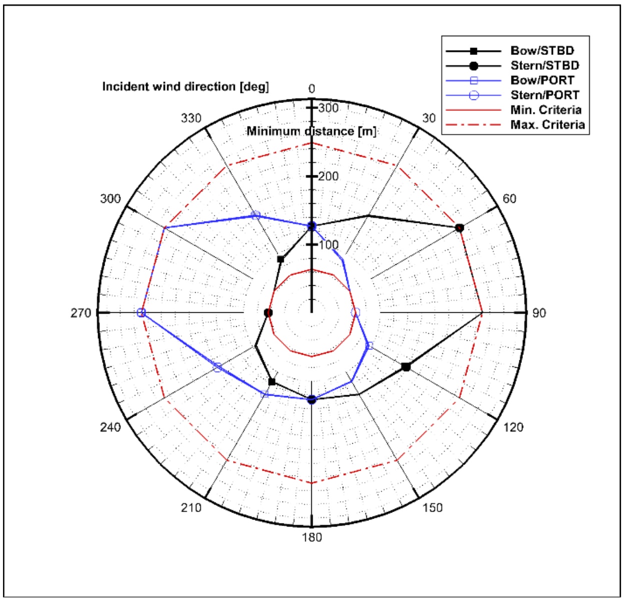

Figure 9. Minimum distances between the ship with 7.5 knots and banks along the Suez Canal under the maximum wind speed

5 CONCLUSIONS

In this paper, it is tried to construct an evaluation method of the maneuvering performance of the ship in the Suez Canal. The hydrodynamic coefficients for the container ship at deep and shallow water are predicted and added mass and added mass moment of inertia are predicted based on the empirical formulae. The maximum environmental conditions for the Suez Canal are determined with reference to the sailing directions. The wind load coefficients of the large container ship are predicted using the empirical formulae and irregular wind speeds are generated using Frøya spectrum. The bank effects due the walls of the Canal are considered by analyzing the CFD calculation results. To specify the design basis of maneuverability under the prescribed condition, the minimum relative distances between the ship and both walls of the Canal are calculated under prescribed environmental conditions.

Based on the results, it can be concluded that the container ship cannot sail in the Suez Canal when the maximum wind comes from 60, 90, 270 and 300 deg.

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