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Maneuverability of Ships with Small Draught in Steady Wind

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Abstract

Wind force and moment may force a ship to drastically decrease its speed and use a large drift angle as well as a large rudder angle in order to maintain its course. Ships with a small draught might have more risk in maneuvering to its point of view compared with a ship with a larger draught. This paper discusses maneuverability of a ship with a small draught in steady wind. The effect of wind on ship speed, drift angle, and rudder angle are investigated in a steady state condition. Five different ratios of wind velocity to ship speed from 1.0 to 20.0 are used in the simulation. The variation in wind direction is examined from 0° to 180°. Results of the numerical simulation show that the wind has a significant effect on the reduction in ship speed with a wind direction less than 100°. The drift angle increases due to increasing wind velocity in the same wind direction. Wind direction also has a significant effect on the drift angle especially when the wind direction is less than 140°. The same phenomenon was found for the rudder angle. The necessary rudder angle is greater than the maximum rudder angle of the ship when the wind direction is 60° with a wind velocity to ship speed ratio of 20 or more.

Abstrak

Kemampuan Manuver Kapal dengan Sarat Kecil pada Kecepatan Angin Konstan. Gaya dan momen yang ditimbulkan oleh angin dapat mengakibatkan kecepatan operasi kapal berkurang secara drastis, sudut geser yang besar serta sudut kemudi yang besar untuk mempertahankan arah gerak kapal. Kapal dengan sarat yang kecil mempunyai kemungkinan yang lebih besar untuk mengalami masalah manuvering tersebut dibandingkan dengan kapal dengan sarat yang besar. Tulisan ini membahas performa manuvering kapal dengan sarat kecil pada kondisi angin dengan kecepatan konstan. Lima perbandingan kecepatan angin dan kecepatan kapal tersebut, yaitu 1,0, 5,0, 10,0, 15,0 dan 20,0 digunakan untuk simulasi. Arah data angin terhadap kapal divariasikan mulai dari 0° sampai 180°. Sudut geser kapal bertambah besar dengan bertambahnya kecepatan angin. Arah angin juga mempunyai pengaruh yang signifikan terhadap sudut geser khususnya pada sudut datang angin lebih kecil dari 140°. Fenomena yang sama terjadi pada kasus sudut kemudi. Sudut kemudi yang diperlukan untuk mempertahankan arah gerak kapal maksimum terjadi pada sudut datang angin 60° untuk perbandingan kecepatan angin dan kecepatan kapal (v/c) sama dengan atau lebih besar dari 20.0.

Keywords: drift angle, maneuverability, rudder angle, ship speed, wind

1. Introduction

Maneuverability is one of the most important issues regarding performance of ships in seaways. Consequently, the International Maritime Organization (IMO) has recommended certain requirements for ship maneuverability [1]. Collisions may occur due to poor maneuvering performance when a ship operates in heavy weather. High wind velocity can exert a large force and moment, resulting in a lack of navigational control, particularly for ships with a large wind age area, such as large passenger ships, pure car carriers (PCCs), and roll-on roll-off (ro-ro) passenger ferries. Ship speed may also significantly decrease because of resistance forces created by the wind mainly through head wind conditions and significant drift velocity. When the ship speed decreases, the propeller torque increases, causing an increasing operational cost due to higher fuel consumption.

Research regarding the maneuvering performance of ships under wind and wave action is ongoing. Fujiwara *et al.* [2] investigated the maneuvering performance of a large passenger ship operating in heavy seas and found that the ship's speed drastically decreased in a certain wind direction at high wind velocities and the delivery horse power (DHP) increased more than 200% when the wind velocity was higher than 25 m/s due to increasing engine torque. Stability of yaw motion regarding controllability of a ship in a seaway has been investigated by Yasukawa *et al*. [3] and Spyrou [4] for a PCCs. They showed that the yaw motion of a PCC may stabilize without a rudder controller for a certain wind velocity and direction, and the stability of yaw motion may improve by increasing the rudder controller. They used a non dimensional wind velocity by ship speed with a maximum value of 5.0 and assumed that reduction of ship speed in case of low wind velocity was negligible.

The research mentioned above used large ships with a large wind age area and large draught. The sway forces due to wind and wave can be neglected by the hydrodynamic force of the ship hull induced by the drift motion. In the case of ships with a small draught, such as small ro-ro ferries for interisland transportation with limited distance, the effect of sway motion could be more significant than that of a ship with a large draught. However, with small-draught ships, the sway force in drifting conditions may decrease if the underwater portion of the ship's hull has a small lateral projection. Nevertheless, these ships will have a high drift velocity and the ship velocity will significantly decrease in heavy wind conditions. The large drift velocity or drift angle caused by the wind can reduce course stability. A ship with unstable yaw motion could be in danger when operating in heavy seas. For example, capsizing has been investigated in following and quartering waves [5]. The maneuvering performance of a ship with a small draught without the effect of wind and waves has been investigated by Khanfir [6]. Even when the turning diameter and overshoot angle comply with the maneuvering criteria of the IMO, the turning diameter and the overshoot angle may be large due to the large drift angle and drift velocity.

This paper discusses the effect of wind on the maneuvering performance of ships with a small draught and large wind age area. These ship types are used for short-distance interisland transportation, river transportation, and inland transportation in many countries. Course stability in this regard is important because instability of yaw motion may occur due to a large wind force in the sway direction. The necessary rudder angle in order to maintain the course might be more than the maximum rudder angle of the ship in strong wind. This means that the ship course cannot be controlled by rudder forces and moment. Consequently, the reduction of ship speed could be more significant than that of larger ships with a large draught, especially in head-wind conditions. These factors are important with respect to safety and operability as well as economical aspects of ship operation in seaways.

2. Methods

Mathematical modeling of ship maneuverability under wind action. Ship maneuverability is usually modeled with three degrees of freedom in mathematical equations: surge, sway, and yaw motions. The Mathematic Modeling Group (MMG) formulation proposed by Hirano *et al*. [7] and Kijima *et al*. [8] was used to govern the maneuvering mathematic model. Here, two coordinate systems are necessary for ship movement. The first one is the local coordinates located in the ship's center of gravity. This coordinate system is used to describe the ship motions in the surge, sway, and yaw directions. The second system is the global coordinate system, which is used to identify the effect of ship motions on ship position (trajectory) and ship heading angle (ship course).

Figure 1 shows the coordinate system for a ship with twin propellers and twin rudders. Here, U, u, and v are ship speed, surge velocity, and sway velocity, respectively; r is the yaw rate, and β is the drift angle. The ship heading angle is noted by ψ, and the rudder angle is indicated by δ. The mathematical equations for the three degrees of freedom for ship motion in maneuvering are as follows [8]:

$$\mathrm{m}(\mathrm{u} - vr) = X \tag{1}$$

$$\mathrm{m}(v - ur) = Y \tag{2}$$

$$\mathrm{I_{zz}}\mathrm{r} = N - x_G Y \tag{3}$$

where m is the ship mass, I_{zz} is the inertia of the ship mass in the yaw direction, $\mathring{u}$ and $\mathring{v}$ indicate the acceleration of ship in surge and sway directions, respectively, x_G is the longitudinal position of the ship's center of gravity from the midship section, and X, Y, and N are the resultant forces and moments induced by the ship hull, propeller, and rudder and wind acting on the ship, respectively. The hull forces and moment can be estimated using the formulas proposed by Yoshimura and Sakurai [9] as follows equation (4), (5), and (6).

$$\mathrm{X_H} = \tfrac{\rho}{2} LTU^2 (X'_{H0} + X'_{\beta\beta}\beta^2 + (X'_{\beta rr} - m'_y)\beta r' + X'_{rr} r'^2 + X'_{\beta\beta\beta r}\beta^3 r' + X'_{\beta\beta\beta\beta}\beta^4) \tag{4}$$

$$\mathrm{Y_H} = \tfrac{\rho}{2} LTU^2 (Y'_{\beta}\beta + (Y'_r - m'_x) r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr} r'^3) \tag{5}$$

$$\mathrm{N_H} = \tfrac{\rho}{2} L^2 TU^2 (N'_{\beta}\beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^{2'} + N'_{rrr} r'^3) \tag{6}$$

Here, r’ indicates the non dimensional yaw rate and X'_{H0} is the non dimensional ship resistance. The sub script of each coefficient in the above equations indicates the derivative of the hull force and moment components to the drift angle and yaw rate, respectively.

Following the MMG model proposed by Kijima *et al.* [8], the propeller thrust is estimated based on the thrust coefficient as follows equation (7). The propeller thrust depends upon the thrust deduction factor coefficient t_P, the propeller revolution n, the propeller diameter D_P, and the thrust coefficient K_T as a function of the advance coefficient J. The advance coefficient, including the wake fraction, is also determined in accordance with the MMG model. Here, the thrust coefficient is calculated by a polynomial regression equation based on the experimental data of a B series propeller as follows [10] equation (8). Here, P and D indicate the pitch and diameter of the propeller, respectively, A_E is the expanded blade area, A_0 is the blade area of the propeller, and Z is the blade number. The C_n, S_n, t_n, u_n, and v_n coefficients are obtained from the data shown in [9]. The rudder forces and moment are defined by Kijima *et al.* [8] as a function of a_H, x'_H, and t_R coefficients, rudder normal forces F_N, and the rudder angle δ as follows equation (9), (10), and (11).

The rudder normal force is estimated using the following equation (12) where A_R is the rudder area, U_R is the effective inflow velocity, f_α is the rudder coefficient, and α_R is the angle of effective inflow. The rudder coefficient in equation (12) can be estimated using the equation (13) where Λ is the ratio of rudder height to breadth. The forces and moments acting on the ship hull above the seawater level induced by wind in the surge, sway, and yaw directions are expressed by the following equations (14), (15), and (16) [2].

In these equations, C_{Ax}, C_{AY}, and C_{AN} are the coefficients of wind forces and moments in surge, sway, and yaw directions, respectively, and are functions of the wind direction relative to the ship ψ_A. q_A is the wind pressure, while A_F and A_L indicate the transversal and lateral projection of the wind age area, respectively. The estimation method of wind pressure can be found in [11] and those for the wind force and moment coefficients in [12].

$$\mathrm{X_p} = (1-t_p)n^2 D_p{}^4 K_T(J) \tag{7}$$

$$\mathrm{K_T}(J) = \sum_{n=1}^{39} C_n (J)^{s_n} (P/D)^{t_n} (A_E/A_0)^{u_n} Z^{v_n} \tag{8}$$

$$\mathrm{X_R} = -(1-t_R) F_N \sin\delta \tag{9}$$

$$\mathrm{Y_R} = -(1-a_H) F_N \cos\delta \tag{10}$$

$$\mathrm{N_R} = -(x'_R + a_H x'_H)(1 + lcb/L_{BP}) F_N \cos\delta \tag{11}$$

$$\mathrm{F_N} = \tfrac{\rho}{2} A_R U_R{}^2 f_\alpha \sin\alpha_R \tag{12}$$

$$\mathrm{f}_\alpha = \frac{6.13\Lambda}{2.25+\Lambda} \tag{13}$$

$$\mathrm{X_W} = C_{AX}(\psi_A) q_A A_F \tag{14}$$

$$\mathrm{Y_W} = C_{AY}(\psi_A) q_A A_L \tag{15}$$

$$\mathrm{N_W} = C_{AN}(\psi_A) q_A A_L L_{OA} \tag{16}$$

The maneuvering performance can be investigated in the steady state condition of the ship in a seaway. The steady state condition occurs when the resultant of forces and moments acting on the ship is equal to zero. The ship will have a constant drift velocity and drift angle as well as a constant speed. The ship may also turn with a constant heading angle for a certain rudder angle. Therefore, the total force and moment in a steady state condition for surge, sway, and yaw can be respectively written as follows:

$$\mathrm{X} = X_H + X_p + X_R + X_W = 0 \tag{17}$$

$$\mathrm{Y} = Y_H + Y_R + Y_W = 0 \tag{18}$$

$$\mathrm{N} = N_H + N_R + N_W = 0 \tag{19}$$

Numerical Simulation. The mathematical model as described above was used to investigate the maneuverability of an Indonesian ro-ro passenger ferry with principle dimensions as shown in Table 1. This ship has a small draught and large breadth in order to provide a larger space for vehicles on the main deck. Passenger accommodations are located on the second deck above the vehicle deck, and the navigation deck is located above the passenger deck. Therefore, the ship has a large and tall wind age area.

This ship has two propellers and two rudders with a distance of ±2.55 m between the ship centerline and the centerline of the propellers and rudders. The propeller

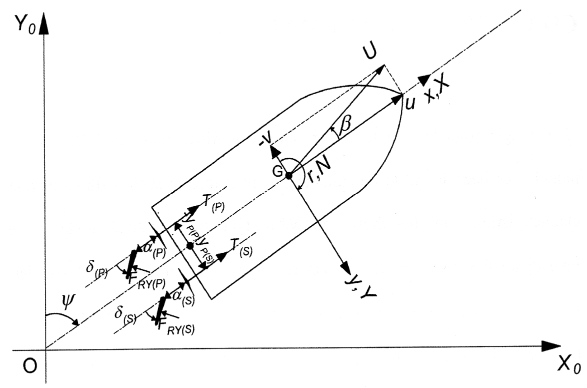

Figure 1. Coordinate System for Ship Maneuvering

has a diameter of 1.10 m with four blades and revolves at 8.87 rps. The rudder height is 1.56 m, and its breadth is 1.33 m. The longitudinal position of the rudder from the mid ship section is 15.75 m.

The forces and moments induced by ship hull were calculated using equations (4)–(6), while the ship resistance was estimated by using the Holtrop method [13]. For simulation purposes, the thrust coefficient of the propeller was estimated for several different ship speeds, using equation (8) to obtain a polynomial equation of the thrust coefficient as a function of the advance coefficient. Using this polynomial equation, the thrust coefficient for any different ship speed can be easily determined. A graphic of the thrust coefficient for different ship speeds is shown in Figure 2, and its polynomial equation is shown in equation (19).

Using equation (7), the propeller thrust force can be estimated for any different ship's forward speed. The wind direction was simulated from 0° (head wind) to 180° (tailwind) with a simulation step of 10°. The wind direction was defined based on the global coordinate system, while the wind direction relative to the ship was based on the local coordinate system. This wind direction can be calculated from the wind direction and the heading angle of the ship. The wind direction relative to the ship may differ with the wind direction defined in the global coordinate system due to the alteration of the ship heading angle during the simulation. Using this relative heading angle, the wind forces and moments acting on ro-ro ferries can be estimated from the equations (14)–(16).

The maneuvering characteristics of the ro-ro ferry, such as the ship speed, drift angle, and rudder angle, can be investigated in a steady state condition by solving equations (17)–(19). The ship speed is obtained from the numerical simulation by solving equation (17) and equation (18) without considering the yaw moment effect. The drift angle can be obtained by substitution the equation (19) into equation (18) to obtain a new equation as a function of drift angle and the ratio of wind velocity to ship speed. By defining the ratio of wind velocity and ship speed, the equation can be solved for the drift angle in each wind direction by using the Newton–Rhapson method. Finally, the necessary rudder angle to maintain the ship's course can be calculated from one of the steady state equations.

The numerical simulation was performed for three different wind velocities: 10 m/s, 20 m/s, and 30 m/s. The maximum realistic wind velocity along the route of the ro-ro ferry based on the data of *Badan Metereologi, Klimatologi dan Geofisika* (BMKG) is 20 m/s [14]. However, a numerical simulation at higher wind velocities is necessary in order to analyze the maximum maneuverability of the ship.

Tabel 1. Principle Dimensions of the Ro-Ro Ferry

Items	Dimension
Length overall (L_{OA})	36.40 m
Length between perpendicular (L_{BP})	31.50 m
Breadth (B)	8.70 m
Height (H)	2.65 m
Draught (T)	1.65 m
Ship speed (V_S)	10.5 knots
Block coefficient (C_B)	0.63
Midship coefficient (C_M)	0.986
Waterline coefficient (C_W)	0.886
Prismatic coefficient (C_P)	0.804
Lateral windage area (A_L)	36.40 m^2
Transverse windage area (A_F)	93.61 m^2
Lateral area of superstructure (A_{OD})	187.21 m^2
Center of windage area (C)	–0.558 m
Vertical center of A_L (H_C)	0.720 m
Vertical center of A_{OD} (H_L)	4.930 m
Height of transverse area (H_{BR})	10.73 m

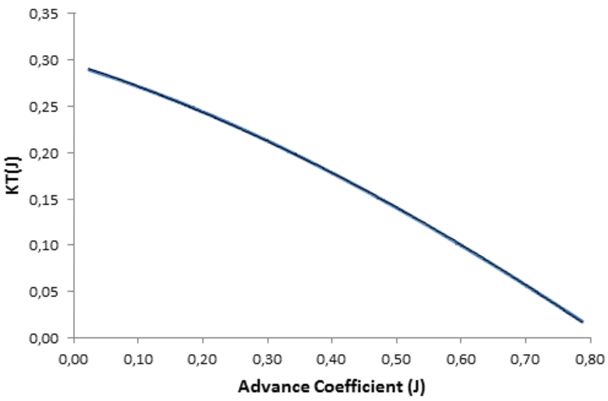

Figure 2. Thrust Coefficient as a Function of the Advance Coefficient

$$K_T(J) = 0.2989 - 0.2545J - 0.1273J^2 \qquad (20)$$

$$J = \frac{u(1-w)}{nD_P} \qquad (21)$$

3. Results and Discussion

The numerical simulation of the ship speed at four different wind velocities and with a wind direction from 0° to 180° is shown in Figure 3. The ship speed significantly decreased with an increasing wind speed when the wind direction was less than 100°. With a wind direction greater than 100°, wind speed had no significant effect on ship speed. The results show that the effect of wind on ship speed needs to be considered with a head wind, i.e., when the wind direction relative to the ship is less than 100°.

With a head wind, the wind velocity relative to the ship was higher than the actual wind velocity because it includes the ship speed. The wind pressure on the wind age area was calculated using the wind velocity relative to the ship. As a result, wind forces in the surge and sway directions significantly increased. The drift angle increased due to the large wind forces in the sway direction.

With a tailwind, the wind velocity relative to the ship was less than the actual wind velocity because it appeared to be reduced by the ship speed. As a consequence, the ship speed did not change drastically due to the wind. The other factor that affects the wind effect on the ship speed is the geometry of the wind age area. This relates to the force and moment coefficients of the wind and the wind direction relative to the ship. The wind force and moment coefficients of the subject ship for the different wind directions are shown in Figure 4.

Here, the coefficient of wind force in the surge direction is greater than that in the sway and yaw directions. Therefore, the surge force due to wind can significantly

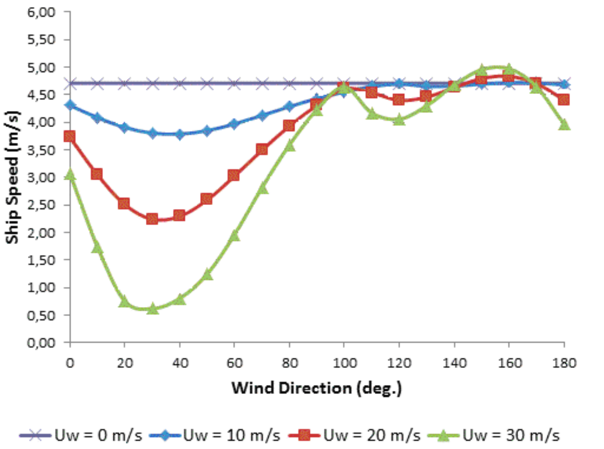

Figure 3. Ship Speed with Varying Wind Velocity and Direction

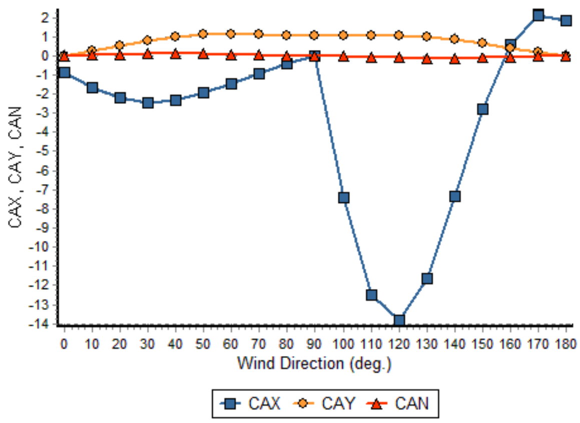

Figure 4. Coefficients of Wind Force and Moment

increase when the wind pressure increases. The coefficient of wind moment in the yaw direction is less than that in the sway direction. Even though the highest value for the wind force coefficient in the surge direction occurs at 120°, the reduction in ship speed in this wind direction is less than that at a wind direction less than 100°. This is because the ship speed reduces the relative wind velocity in this wind direction to less than the actual wind velocity.

The calculated drift angles in a steady state condition are shown in Figure 5. Here, the drift angle was estimated for five different ratios of wind velocity to wind speed: 1.0, 5.0, 10.0, 15.0, and 20.0. These ratios were determined based on the numerical results of the estimated ship speed as shown in Figure 3. For a wind velocity of 30 m/s, the ship speed declines to about 0.60 m/s when the wind direction is 40°, giving a wind velocity to ship speed ratio greater than 20. However, this is not a realistic sea condition based on the weather information obtained from BMKG. The horizontal axis in this figure is the wind direction and the vertical axis is the drift angle in.

The drift angle is strongly affected by the wind velocity and direction. In cases of heavy wind, the drift angle is greater than 20° in a wind direction ranging from 20° to 120°.

This coincides with a reduction in ship speed in windy conditions when the significant effect of wind occurs in a similar wind direction. The ship drifts to the opposite direction when the wind direction is 140° or more. This indicates that the yaw moment induced by the wind is the dominant force affecting the drift angle compared with the surge and sway forces. However, the drift angle in a tailwind is less than that in a head wind.

The same drift angle trend due to the alteration of wind direction occurs with a large passenger ship [2]. The maximum drift angle occurs in a wind direction ranging from 20° to 140°. However, for the same wind velocity, the drift angle of a ship with a small draught is greater than that for a ship with a deep draught. This means that the ship draught has a significant effect on the drift angle caused by the wind. The drift velocity of a ship with a small draught is greater than that of a ship with a deep draught because the sway force resulting from the ship's hull is less than that induced by the wind.

As a result, the drift velocity of a ship with a small draught is less than that of a ship with a large draught and the speed of a ship with a small draught is therefore less than that of a ship with a large draught. The ratio of wind velocity to ship speed for a ship with a small draught is 20, and for the same wind velocity that ratio for a ship with a large draught is 3 [2].

The necessary rudder angles to maintain the ship's direction in a seaway for five different wind velocities and ship speeds with wind directions from 0° to 180° are shown in Figure 6. In order to maintain the ship's course when the ship cruises in windy conditions, the rudder angle increases when the wind velocity increases.

Figure 6 shows that the necessary rudder angle is greater than the maximum rudder angle of the ship (±35°) when the ratio of wind velocity to ship speed is 20 or more. This means that the rudder cannot control the ship's course or heading angle. As with the drift angle, the rudder angle should also be in the opposite direction in the case of a tailwind. The necessary rudder angle in a tailwind is also less than that for a head wind for the same wind velocity.

This result trends differently with ships with larger draughts, especially for large passenger ships [2]. The maximum necessary rudder angle for a ship with a large draught occurs with a wind direction of 140°. The difference between the drift angle and the necessary rudder angle for a ship with a large draught is greater than 5° [2] and [3]. However, for a ship with a small draught, this difference is less than 5°. The necessary rudder angle for a ship with a small draught is greater than that for a ship with a deep draught. These results show that rudder performance to control the ship direction against the wind effect tends to be less for a ship with a small draught. This is because the yaw moment induced by the rudder is partially neglected by the drift motion of the ship with significant drift velocity. An investigation of maneuvering performance of a ship with a small draught, particularly with respect to course stability, is an essential future study.

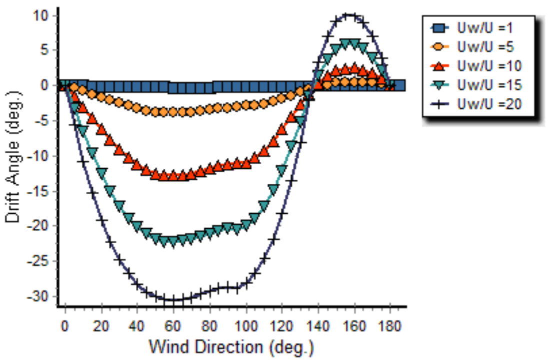

Figure 5. Drift Angles in a Steady State Condition

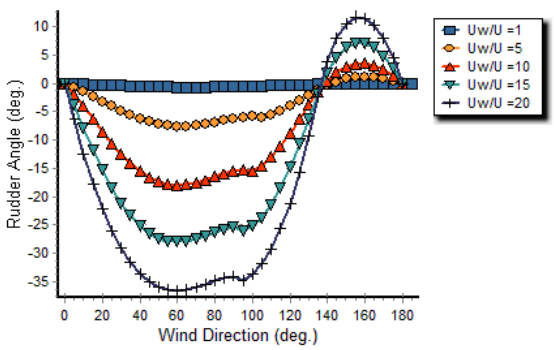

Figure 6. Rudder Angles in a Steady State Condition

4. Conclusions

Maneuvering performance of an Indonesian ro-ro ferry was investigated using numerical simulations for three different wind velocities and wind directions ranging from 0° to 180°. Our results lead to the following conclusions: (1) The ship's speed drastically decreases when the wind direction is less than 100^0. The maximum reduction in ship speed occurs when the wind direction is 30°. The wind velocity and direction significantly effect ship speed reduction. Therefore, ship operators should avoid head wind conditions. (2) The drift angle and the rudder angle significantly affected by the wind velocity and direction. The maximum drift angle occurs in a wind direction of 60°. The drift angle significantly increases when the wind velocity increases. (3) In order to maintain the ship's direction in a steady state condition, the rudder angle must coincide with the drift angle. However, the necessary rudder angle is greater than the drift angle. The ship cannot be controlled by rudder action when the ratio of wind velocity to the ship's speed is greater than 20, especially with a wind direction of 60°. The maximum rudder angle is 35° while the necessary rudder angle is more than 35°.

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