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STEADY STATE EQUILIBRIUM OF SHIPS MANEUVERING UNDER COMBINED ACTION OF WIND AND WAVE

Daeng Paroka*, Andi Haris Muhammad, Syamsul Asri

Hasanuddin University, Makassar, Indonesia

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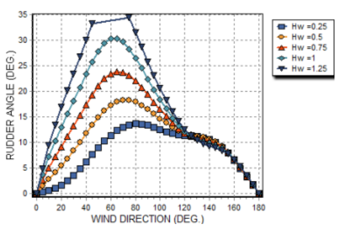
*Corresponding author
dparoka@eng.unhas.ac.id

Graphical abstract



Abstract

Maneuverability is important in ship design stage not only for ship performance but also for safety reason regarding the collision and stability especially in quartering following waves. The International Maritime Organization (IMO) therefore developed maneuvering criteria and collision regulation to ensure the ship safety against collision. This paper discusses maneuvering performance of ship under combined action of wind and wave. The steady state equations of ship maneuvering were numerically solved using the Newton-Rhapson method in order to obtain the drift angle, the rudder angle and the ship forward speed. Results of numerical simulations show that the combined action of wind and wave has significant effect on the drift angle and the rudder angle in the range of wind and wave direction between 20.0 degrees and 120.0 degrees. The ship forward speed significantly changes due to alteration of wind velocity in the wind and wave direction smaller than 40.0 degrees or in the wind and wave direction larger than 140.0 degrees. The wave height has significant effect on the ship forward speed in the wind and wave direction between 20.0 degrees and 80.0 degrees.

Keywords: Steady state equlibrium, maneuvering, wind, wave

Abstrak

Olah-gerak sangat penting pada peringkat awal reka bentuk kapal tidak hanya untuk meningkatkan prestasi kapal tetapi juga untuk alasan keselamatan, khususnya bahaya perlanggaran dan kesetabilan pada arah gelombang quartering-fallowing. Pertumbuhan Maritim Antara Bangsa (IMO) telah membangunkan kriteria dan peraturan keselamatan olah-gerak dalam memastikan keselamatan kapal. Kertas kerja ini membincangkan prestasi olah-gerak kapal akibat pengaruh gabungan angin dan gelombang. Persamaan keseimbangan keadaan mantap olah-gerak kapal diselesaikan secara berangka dengan menggunakan kaedah Newton-Rhapson untuk mendapatkan sudut hanyut, sudut kemudi dan kelajuan kapal. Hasil simulasi menunjukkan bahawa gabungan angin dan gelombang mempunyai pengaruh yang besar pada sudut hanyut dan sudut kemudi pada arah gelombang dan angin antara 20 - 120 darjah. Kelajuan kapal ketara berubah dikeranakan perubahan kelajuan angin pada arah gelombang dan angin lebih kecil dari 40 darjah atau pada arah gelombang dan angin lebih besar dari 140 darjah. Ketinggian gelombang mempunyai pengaruh yang besar pada kelajuan kapal pada arah gelombang dan angin antara 20 - 80 darjah.

Kata kunci: Keseimbangan keadaan mantap, olah gerak, angin, gelombang

1.0 INTRODUCTION

Maneuvering performance is one of the safety criteria for ships operation in order to avoid collision dangerous in seaways. Therefore, the International Maritime Organization (IMO) introduced maneuvering criteria consist of turning ability, zig-zag maneuver and stopping ability as requirements for ships safely operated in seaways[1]. The IMO also developed a collision regulation (COLREG) in order to avoid collision dangerous of ships[2]. The maneuvering criteria and the collision regulation were developed without taking into account effect of wind and wave. The maneuvering test should be conducted in mostly calm water. Therefore, a ship may be in dangerous condition even though the ship complies with the IMO maneuvering criteria and the collision regulation when the ship is operated in wind and wave.

Fujiwara *et al.* [3] investigated the effect of wind and wave on maneuvering performance of a large passenger ship under action of wind and wave. They assumed that the drift angle under combined action of wind and wave is small. The same assumption was used regarding the necessary rudder angle in order to maintain the ship course under combined action of wind and wave. As result, the angle of effective inflow of rudder in the steady state equlibrium was also assumed to be small. Therefore, its effect on the rudder forces and moment were simplified as $\sin\delta\cos\alpha_R \approx \delta^2$ and $\cos\delta\sin\alpha_R \approx \alpha_R$. These assumptions seem to be unacceptable when the ship operates in high wind velocity and large wave height in which the drift angle and the rudder angle may become significant. This phenomena was also comfirmed in their paper. In order to estimate the forces and moment induced by the wave, they used the New Strip Method (NSM) as proposed by Ueno *et al*. [4]. Here, the forces and moment act on the ship hull due to wave depend only on wave height and wave frequency. The ship position relative to the wave surface may have significant effect on the wave forces and moment which is not considered in this method. In order to take into account effect of the ship position relative to the wave, Umeda and Renilson[5] proposed a simplified method to estimate the wave forces and moment acting on ship hull. Umeda and Hashimoto[6] used this method to estimate wave forces and moment including forces and moment induced by the wave acting on ship rudder which was not considered in the previous method. Following the formula are used by Umeda and Hashimoto[6] the effect of ship position relative to the wave surface may be investigated. The effect of ship position relative to the wave surface on the wave forces and moment is important regarding investigation of surf-riding phenomena and ship stability in quartering and following waves. If the yaw motion or ship direction becomes unstable when the ship surfing in the wave down slope, the ship will be turning. This phenomena is known as broaching in which the ship may be in capsizing dangerous.

The yaw motion may also become unstable under action of strong wind as found by Yasukawa *et al.* [7] Here the steady state equilibrium of ship maneuver under action of wind was investigated for different wind direction. The nonlinear hull forces and moment, rudder forces and moment as well as the wind exciting forces and moment were linearized by assuming that the surge velocity, the sway velocity and the yaw rate is very small so that the higher order term in the nonlinear 3 DOF of maneuvering equation is negligible small. The ship is also assumed to be able to maintain her forward speed under action of wind. It means that effect added resistance induced by the wind velocity to the ship speed can be neglected. This assumption is different with the results obtained by Fujiwara *et al*. [3] in which the ship speed may significantly decrease due to increase the wind velocity in a certain wind direction. The same result was published by Paroka *et al*. [8],[9] regarding the effect of wind on steady state equilibrium of a ro-ro ship.

In order to precisely predict the steady state equilibrium of ship maneuver under combined action of wind and wave, a free running model experiment shoul be conducted in order to validate the proposed mathematical models. However, the steady state equilibrium is very difficult to obtain with model experiment because ship responses to the forces and moments induced by the wind and the wave are very sensitive. The other method is to develop a mathematical model by taking into account the ship speed as well as the significant alteration of the drift angle and the rudder angle due to wind and wave. This means that effect of nonlinear part in the 3 DOF maneuvering equation should be maintained mainly in high wind velocity and large wave height in which the steady state equilibrium occurs in large drift angle and rudder angle with smaller ship speed.

This paper discusses the steady state equilibrium of a ship maneuver under combined action of wind and wave. This steady state equlibrium consists of the drift angle, the rudder angle and the ship speed for several different wind velocity and wave height with its direction from head to following wind and wave. The result of this research can be used to estimate ship operability in a certain seaway condition especially regarding the maximum rudder angle of real ships of 35 degrees. The ship speed obtained for each wind velocity and wave height as well as the angle of wind and wave direction may be used to estimate the real fuel consumption. This information is important in reason of optimum ship route regarding not only in operational cost but also in safety operation point of view. The yaw motion stability in the obtained steady state equilibrium can be investigated in advance as performed by Yasukawa *et al.* [7] and Spyrou[10] for ships under action of steady wind. The results of this research can also be used to investigate maneuver stability under combined action of wind and wave which has never been investigated by the other reserchers.

2.0 3 DOF MANEUVERING EQUATION

The ship maneuvering is generally modelled using three degree of freedom mathematic equation consists of surge, sway and yaw motions. The 3 DOF mathematical equation can be upgraded to be 4 DOF model by taking into account the roll motion effect. The 3 DOF mathematic equation is developed using the global and local coordinate systems shown in Figure 1. The global coordinate system is set to be fixed relative to the earth with origin of O with the horizontal axis designated by x_o dan the vertical axis indicated by y_o. The origin of the local coordinate system is located on the ship center of gravity with the horizontal axis of x and the vertical axis is designated by y. Here, X and Y are the resultant of forces acting on ship in surge and sway direction, respectively. N indicates the resultant of moments in yaw direction. U and β are the ship speed and the drift angle, respectively. u, v and r are the surge, sway and yaw rate, respectively. The rudder angle of the ship in Figure 1 is designated by δ for both the rudder in starboard and in portside, respectively. The heading angle is measured based on the global coordinate system which is indicated by ψ.

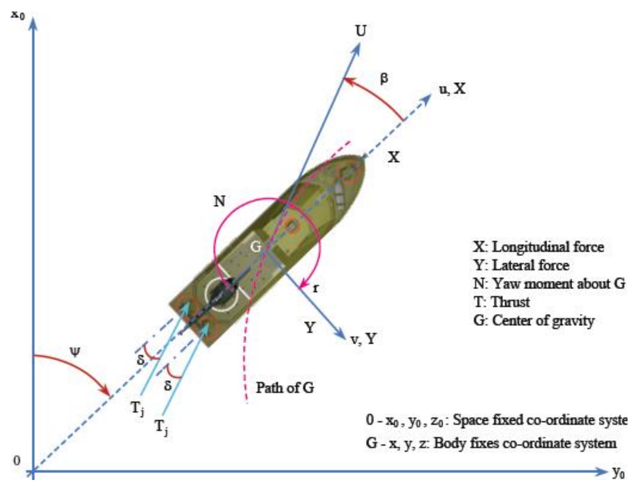


Figure 1 The coordinate system uses to developed the 3 DOF maneuvering equation

The maneuvering equation for 3 DOF system using the MMG model as proposed by Hirano, *et al*. [11] and Kijima, *et al*. [12] based on the coordinate systems shown in Figure 1 can be written as follows:

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

Here, m, Izz and x_G indicate the ship mass, the inertia of ship mass in yaw direction and the longitudinal center of gravity, respectively. $\dot{u}$, $\dot{v}$ and $\dot{r}$ indicate the surge, sway and yaw accelleration, repectively. The resultant of forces and moment acting on ship in the right hand side of the equation (1) consists of hull forces and moment, propeller forces, rudder forces and moment as well as wind and wave forces and moments, respectively. The resultant of forces and moment in the equation (1) can be written as the following equation:

$$
\begin{aligned}
X &= X_H + X_P + X_R + X_A + X_W \\
Y &= Y_H + Y_P + Y_R + Y_A + Y_W \\
N &= N_H + N_P + N_R + N_A + N_W
\end{aligned}
\quad (2)
$$

Subscripts H, P, R, A and W in the equation (2) indicate the ship hull, the propeller, the rudder, the wind and the wave forces and moments in surge, sway and yaw direction, respectively. The forces and moment induced by ship hull are estimated using empirical formula as function of the hull hydrodynamics derivatives as proposed by Yoshimura and Sakurai[13]. The ship will move forward with constant speed, drift angle, rudder angle and heading angle in steady state equilibrium. This means that the yaw rate becomes zero in the steady state equilibrium. Therefore the forces and moment induced by ship hull can be simplified by removing the yaw rate components from the equation. Finally the hull forces and moment can be written as follows:

$$
\begin{aligned}
X_H &= \tfrac{\rho}{2}LTU^2\left(X'_{HO} + X'_{\beta\beta}\beta^2 + X'_{\beta\beta\beta\beta}\beta^4\right) \\
Y_H &= \tfrac{\rho}{2}LTU^2\left(Y'_{\beta}\beta + Y'_{\beta\beta\beta}\beta^3\right) \\
N_H &= \tfrac{\rho}{2}L^2TU^2\left(N'_{\beta}\beta + N'_{\beta\beta\beta}\beta^3\right)
\end{aligned}
\quad (3)
$$

where L is the ship length between perpendicular, T is the ship draught and U indicates the ship forward speed.

The propeller force and moment for ships with twin propeller are estimated using the formula proposed by Kijima, *et al.* [12] as the following equation:

$$
\begin{aligned}
X_P &= \left(1 - t_{P(S)}\right)n^2 D_p{}^4 K_{T(S)}(J) + \left(1 - t_{P(P)}\right)n^2 D_p{}^4 K_{T(P)}(J) \\
N_P &= y_{P(S)}\left(1 - t_{P(S)}\right)n^2 D_p{}^4 K_{T(S)}(J) \\
&\quad + y_{P(P)}\left(1 - t_{P(P)}\right)n^2 D_p{}^4 K_{T(P)}(J)
\end{aligned}
\quad (4)
$$

where t_p is the thrust deduction factor of propeller, n is propeller revolution, D_P is the propeller diameter and K_T is the thrust coefficient of propeller as function of the advance coefficient, J. The distance of the propeller from the ship centerline is indicated by y_P. Subscripts S and P in the equation (4) indicate starboard and portside. The advance coefficient, J, in this equation is estimated by using the equation as follow:

$$
J = \frac{u(1 - w_p)}{nD_p} \quad (5)
$$

where w_p is the effective wake friction of propeller which is obtained by using the following equation[14]:

$$
w_p = w_{p0}exp(-4.0\beta^2) \quad (6)
$$

with w_{p0} is the wake friction of propeller.

The rudder forces and moment for ship with twin rudder in the equation (2) can be estimated using the formula proposed by Kijima, *et al*. [12] as follows:

$$\begin{aligned} X_R &= -(1-t_{R(S)})\left(F_{RN(S)}\sin\delta_{(S)} + F_{RN(P)}\sin\delta_{(P)}\right) \\ Y_R &= -(1+a_H)\left(F_{RN(S)}\cos\delta_{(S)} + F_{RN(P)}\cos\delta_{(P)}\right) \\ N_R &= -(x_R + x_H a_H)\left(1 + l_{CB}/L_{pp}\right)\left(F_{RN(S)}\cos\delta_{(S)} + F_{RN(P)}\cos\delta_{(P)}\right) \end{aligned} \tag{7}$$

where t_R, a_H, x_R and x_H are the interactiton coefficient between hull and rudder, the longitudinal position of the rudder and the longitudinal position of the center of interaction force between hull and rudder, respectively. The normal rudder force, F_{RN}, in this equation can be estimated using the following equation:

$$F_{RN} = \tfrac{1}{2}\rho f_A A_R U_R{}^2 \sin\alpha_R \tag{8}$$

with

$$f_A = \frac{6.13\Lambda}{(2.25+\Lambda)} \tag{9}$$

$$U_R{}^2 = (1-w_R)^2[1+\eta_P k\{2-(2-k)s\}s/(1-s)^2]U^2 \tag{10}$$

$$\alpha_R = \delta - \gamma_E\beta \tag{11}$$

where Λ is the rudder aspect ratio, A_R is the rudder area. This formula is used to estimate the normal force of both starboard and portside rudders, respectively.

The wind forces and moment in surge, sway and yaw direction are estimated using formula proposed by Fujiwara, *et al*. [3], [14] as function of wind pressure, windage area as well as the coefficients of wind forces and moment as follows:

$$\begin{aligned} X_A &= C_{AX}(\psi_A) q_A A_F \\ Y_A &= C_{AY}(\psi_A) q_A A_L \\ N_A &= C_{AN}(\psi_A) q_A A_L L_{OA} \end{aligned} \tag{12}$$

Here, C_{AX} indicates the coefficient of wind force in surge direction, C_{AY} is the coefficient of wind force in sway direction and C_{AN} is the cofficient of wind moment in yaw direction. These coefficients depend on the geometry of windage area as well as the wind direction relative to the ship. A_F, A_L and L_{OA} are the frontal projected area, the lateral projected area and the ship length over all, respectively. ψ_A is the wind direction relative to the ship. This relative wind direction can be obtained using the following equation:

$$\psi_A = \tan^{-1}\left[\frac{U_T\cos\psi + U\cos\beta}{U_T\sin\psi - U\cos\beta}\right] \tag{13}$$

where U_T is the wind velocity and ψ is the angle of wind direction with reference of the global coordinate system. The wind pressure, q_A in the equation (12) is calculated by using the equation proposed by Fujiwara, *et al*. [3] as follow:

$$q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi+\beta) \tag{14}$$

where q_T is the wind pressure due to elevation of the center of windage area and q_S is the wind pressure induced by the wind velocity without the elevation effect.

The wave exciting forces and moment in surge, sway and yaw direction may be estimated by using formula used by Umeda and Hashimoto[6] as shown in the equations (15) – (17). The Froude-Krylov part of the forces and moment induced by the wave have been validated by model experiment[5]. The wave force in surge direction has been improved by Ito, *et al.* [15] by adding a correction factor, α, based on model experiment for several different ship types.

$$X_W = -\alpha\rho g\zeta_W k\cos\chi\int_{AE}^{FE} C_1(x)\,S(x)e^{-kd(x)/2} \times \sin\left(k(\xi_G + x\cos\chi)\right)dx \tag{15}$$

$$\begin{aligned} Y_W &= \rho g\zeta_W k\sin\chi\int_{AE}^{FE} C_1(x)\,S(x)e^{-kd(x)/2} \\ &\times \sin\left(k(\xi_G + x\cos\chi)\right)dx + \zeta_W\omega\omega_e \\ &\sin\chi\int_{AE}^{FE}\rho\,S_y(x)e^{-kd(x)/2}\times\sin\left(k(\xi_G + x\cos\chi)\right)dx \\ &-\zeta_W\omega u\sin\chi\times\left[\rho S_y(x)e^{-kd(x)/2}\cos\left(k(\xi_G + x\cos\chi)\right)\right]_{AE}^{FE} \\ &+(1+a_H)\tfrac{\rho}{2}A_R f_\alpha\varepsilon_R(1-w_p)u\sqrt{1+\kappa_P\frac{8K_T}{\pi J^2}}\,v_{WR} \end{aligned} \tag{16}$$

$$\begin{aligned} N_W &= \rho g\zeta_W\sin\chi\int_{AE}^{FE} C_1(x)\,S(x)e^{-kd(x)/2} \\ &\times x\sin\left(k(\xi_G + x\cos\chi)\right)dx + \zeta_W\omega\omega_e \\ &\times\sin\chi\int_{AE}^{FE}\rho\,S_y(x)e^{-kd(x)/2}x\sin\left(k(\xi_G + x\cos\chi)\right)dx \\ &+\zeta_W\omega u\sin\chi\int_{AE}^{FE}\rho\,S_y(x)e^{-kd(x)/2} \\ &\times\cos\left(k(\xi_G + x\cos\chi)\right)dx - \zeta_W\omega u\sin\chi \\ &\times\left[\rho S_y(x)e^{-kd(x)/2}x\cos\left(k(\xi_G + x\cos\chi)\right)\right]_{AE}^{FE} \\ &+(x_R + a_H x_H)\frac{\rho}{2}A_R f_\alpha\varepsilon_R(1-w_p)u\sqrt{1+\kappa_P\frac{8K_T}{\pi J^2}}\,v_{WR} \end{aligned} \tag{17}$$

where ζ_W is the wave amplitude, χ is the angle of wave direction which is assumed to be the same as the wind direction, ω is the wave frequency and ω_e is the wave encounter frequency. $S(x)$ and $d(x)$ indicate the area and the draught of section at longitudinal distance, x, from the origin of local coordinate system, respectively. Here, k is the wave number, ξ_G is the location of the ship center of gravity based on the global coordinate system and $S_y(x)$ is the ship added mass in sway direction. AE and FE are the ship after perpendicular and fore pendicular, respectively. $C_1(x)$ and v_{WR} in the equations (15) – (17) are estimated using the equations as follows:

$$C_1(x) = \frac{\sin(k\sin\chi\,.\,B(x)/2)}{(k\sin\chi\,.\,B(x)/2)} \tag{18}$$

$$v_{WR} = \zeta_W\omega\sin\chi\,exp(-kz_R)\cos(2\pi\,\xi_G/\lambda + kx_R\cos\chi) \tag{19}$$

where z_R and x_R are the vertical center of rudder and the longitudinal position of rudder, respectively. $B(x)$ indicates the breadth of ship section at the longitudinal distance, x and λ is the wave length. The correction of the Froude-Krylov force, α, in surge direction as shown in the equation (15) is dependent of the block coefficient, C_b, which can be estimated by using the equations as follows[15]:

$$\alpha = 1.46\, C_b - 0.05 \text{ if } C_b > 0.9 \tag{20}$$

$$\alpha = 1.06\, C_b - 0.05 \text{ if } C_b < 0.9 \tag{21}$$

3.0 RESULTS AND DISCUSSION

The above maneuvering mathematical models are used to investigate the steady state equilibrium of a ro-ro ferry with principles dimension shown in Table 1. The subject ship has propulsion system with twin propeller with twin rudder. The propeller and the rudder configuration and its dimensions are shown in Tabel 2.

Table 1 The principle dimension of 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 knot
Block coefficient (C_B)	0.63
Midship coefficient (C_M)	0.986
Waterline coefficient (C_W)	0.886
Lateral projected windage area (A_L)	36.40 m^2
Transverse projected windage area (A_F)	93.61 m^2
Lateral projected area of superstructure (A_{OD})	187.21 m^2
Center of windage are from midship (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 projected area (H_{BR})	10.73 m

Table 2 Propeller and rudder geometry

Items	Dimension
Number of propeller	2
Propeller blade (Z)	4
Propeller diameter (D_P)	1.10 m
Propeller revolution (n)	8.58 rps
Transverse position propeller (y_P)	±2.55 m
Long. position propeller (x_P)	15.50 m
Rudder area (A_R)	2.08 m^2
Transverse rudder position (y_R)	±2.55 m
Long. Rudder position (x_R)	15.75 m

The coefficients of hydrodynamic derivative for estimating hull forces and moment in surge, sway and yaw direction are estimated by using the empirical formula proposed by Yoshimura, *et al.* [13]. The Holtrop method is used in order to obtain the ship resistance in calm water.

The thrust coefficient of propeller changes due to alteration of the propeller submergence as result of ship motion and the ship position relative to the wave surface[16]. In cases of wave lenght are much larger than the ship length, the effect of ship position relative to the wave surface on the propeller submergence can be neglected especially for quite small wave amplitude[17]. Therefore the thrust coefficient is assumed to be independent of wave effect. The thrust coefficient of propeller, therefore can be assumed to be the same as the thrust coefficient in calm water which can be estimated by using polynomial regression based on the statistical data of open water test for B series propeller[18]. Here, the thrust coefficient is estimated for several different surge velocity in order to obtain the quadratic polynomial of the thrust coefficient as function of the advance coefficient. The obtained thrust coefficient is shown in Figure 2 and its polynomial equation is shown in the equation (22), respectively.

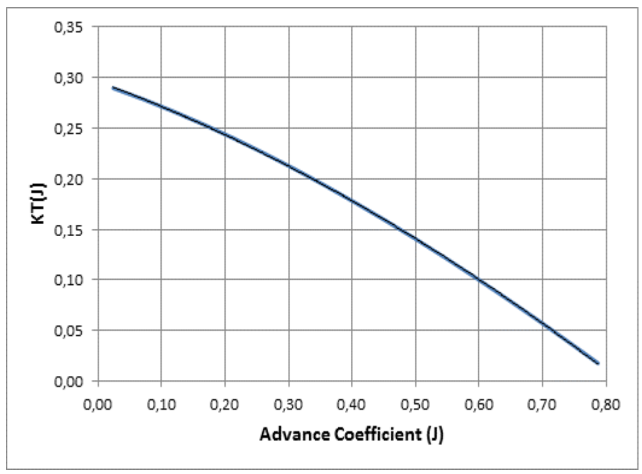


Figure 2 The thrust coefficient for several different ship speed as function of the advance coefficient

$$K_T(J) = 0.2989 - 0.2545J - 0.1273J^2 \tag{22}$$

The coefficients of wind forces and moment for surge, sway and yaw in the equation (12) are estimated using the methodology proposed by Fujiwara *et al.* [3]. Those coefficients are estimated in several wind direction from 0.0 degrees up to 180.0 degrees. The 0.0 degrees of wind direction means that the wind comes from ship bow (head wind) and the 180.0 degrees of wind direction means the following wind. The coefficients obtained for each angle of wind direction are shown in Figure 3. Here, CAX means the wind force coefficient in surge direction, CAY is the coeffcient for sway direction and CAN indicates the coefficient of wind moment in yaw direction. These coefficients are dependent on the superstructure configuration and ship principles dimension.

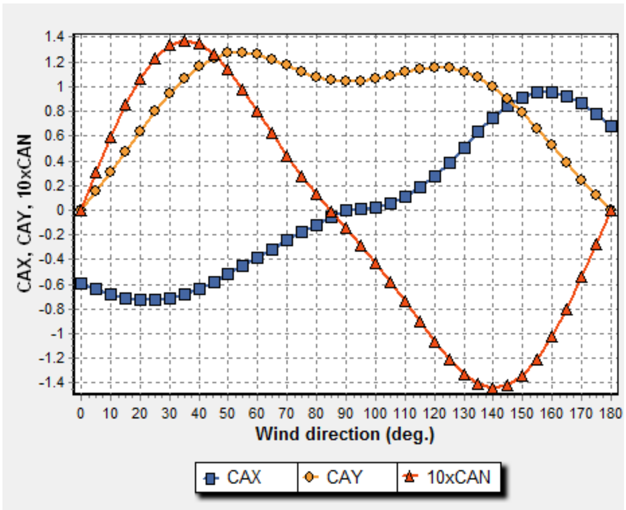


Figure 3 The wind forces and moment coefficients for several different wind direction

The wave direction is assumed to be the same as the wind direction. The ship added mass in sway direction is estimated using the Frank-Closed Fit method combined with 2D strip theory for each ship section in order to obtain the total added mass with numerical integral.

The steady state equilibrium under action of combined wind and wave occurs when the resultant of forces and moment acting on ship hull becomes zero. It means that the ship moving in wind and wave with constant ship speed, drift angle and rudder angle in order to maintain the ship direction. The left side of the equation (1) therefore become zero. Subtitution of the resultant forces and moment shown in the equation (2) into the equation (1), the equation of steady state equilibrium under combined action of wind and wave therefore can be written as follows:

$$X_H + X_P + X_R + X_A + X_W = 0$$
$$Y_H + Y_P + Y_R + Y_A + Y_W = 0 \qquad (23)$$
$$N_H + N_P + N_R + N_A + N_W = 0$$

As the yaw rate in the steady state equilibrium is the same as zero as result of the constant ship direction, the components forces and moment in the equation (23) are independent of the yaw rate. The hull forces and moment depend only on the drift angle which can be estimated by using the equation (3). The propeller force in surge direction is calculated by using the equation (4) and the rudder forces and moment are estimated by using the equation (7). The wind forces and moment are estimated by using the equation (12) and the wave forces and moment are estimated by using the equations (15) – (17). The equation (23) are numerically solved by using the Newton-Rhapson method in order to obtain the ship forward speed, the drift angle and the rudder angle for each wind and wave direction. In order to investigate effect of wind, wave and combined wind and wave, the numerical simulation are conducted for wind constant and several different wave height. Here, the wind velocity is 20.0 m/s with the wave heights of 0.5 meters, 1.0 meters, 1.5 meters, 2.0 meters and 2.5 meters with constant wave length of 80.0 meters. The second simulation is for several different wind velocity in constant wave height. The wave height is 2.0 meters with wave stippness of 0.025 and the wind velocities are 5.0 m/s, 10.0 m/s, 15.0 m/s and 20.0 m/s. The forces and moment induced by the wave in the equation (23) are dependent of the ship position relative to the wave.

The results of numerical simulation for constant wave height of 2.0 meters with several wind velocities are shown in Figure 4 for the drift angle and that for the ship forward speed in Figure 5. Here the wave slope is 0.025 or the wave length is 80.0 meters.

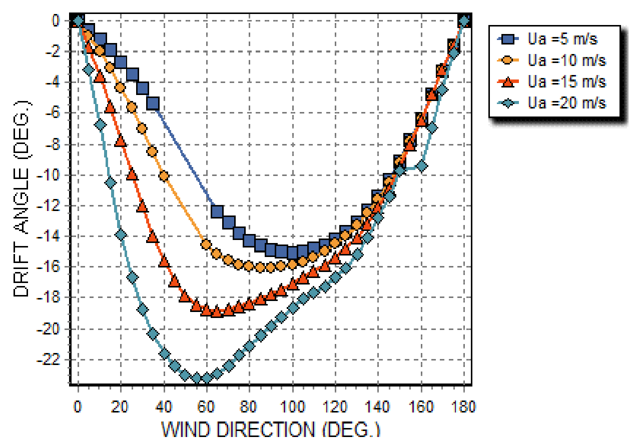


Figure 4 The drift angle for several wind velocity with wave height of 2.0 meters and wave slope of 0.025

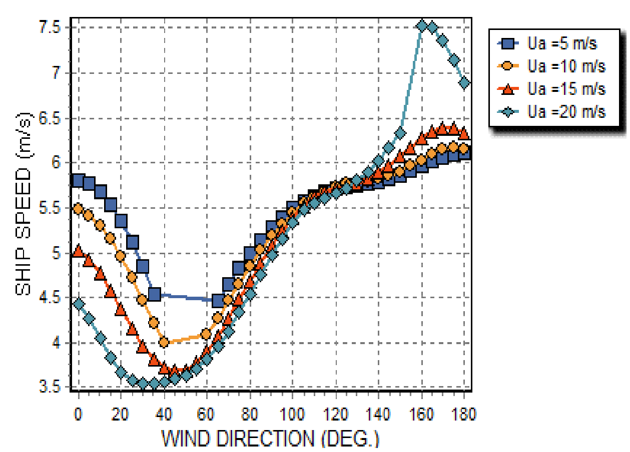


Figure 5 The ship forward speed for several wind velocity with wave height of 2.0 meters and the wave slope of 0.025

The wind velocity has significant effect on the drift angle when the wind and wave direction is smaller than 120.0 degrees or mostly in head wind to the beam wind condition. In cases of quartering following wind and wave, the drift angle does not significantly change due to alteration of the wind velocity. The angle of wind and wave direction with maximum drift angle tends to decreases when the wind velocity increases. This phenomena coincides with the alteration of ship forward speed as shown in Figure 5. It means that the large drift angle occurs as result of significant reduction of the ship forward speed when the wind direction is smaller than 80.0 degrees. Here,the ship forward speed decreases due to increase the wind and wave direction. The reduction of ship forward speed occurs due to increase the wind resistance when the wind velocity increases as well as due to increase the drift velocity as the wind force in sway direction increases when the wind velocity increases in the wind and wave direction larger than zero.

The ship forward speed is higher than the ship normal speed in cases of following wind and waves. The engine torque decreases as the propeller thrust decreases due to increase of the ship forward speed. This means that the engine revolution may be reduced in order to operate the ship with normal speed. When the wind velocity is higher than the ship normal speed, the drift angle does not significantly change due to alteration of the wind velocity. The ship forward speed does not significantly decrease when the wind velocity increases in the range of wind and wave direction from 60.0 degrees to 120.0 degrees. However, the drift angle significantly increases due to increase the wind velocity in these angle of wind and wave direction. This means that the drift velocity due to wind force in sway direction is reduced by increasing the ship forward speed due to positive force induced by the wind in surge direction.

The necessary rudder angle in order to maintain the ship heading angle for several different of wind velocities with constant wave height of 2.0 meters is shown in Figure 6. The necessary rudder angle in order to maintain the heading angle tends to decrease when the wind velocity increases in the angle of wave and wind direction is smaller than 60.0 degrees but it tends to increase in larger angle of wave and wind direction. The rudder should be rotated to the starbord direction when the angle of wave and wind direction is larger than 115.0 degrees for the wind velocity of 5.0 m/s. In cases of following wave, the yaw moment excited by the wave may induce yaw motion toward starboard. Therefore the rudder should be rotated to the portside or negative rudder angle in order to maintain the ship direction. When the wind velocity increases, effect of the yaw moment induced by the wind becomes more dominant compared with the effect of the wave exciting yaw moment. As results, the necessary rudder angle becomes positive for all wind direction.

In order to investigate the effect of wave, the numerical simulation are also conducted for several different wave height with constant wind velocity. The drift angle, the rudder angle and the ship forward speed in the steady state equilibrium are shown in Figures 7 – 9. Here, the wave length is assumed to be constant. Therefore, the wave slope changes due to different wave height. The wind velocity within these numerical simulations is determined to be 20.0 m/s as the highest wind velocity in the investigation of wind effect.

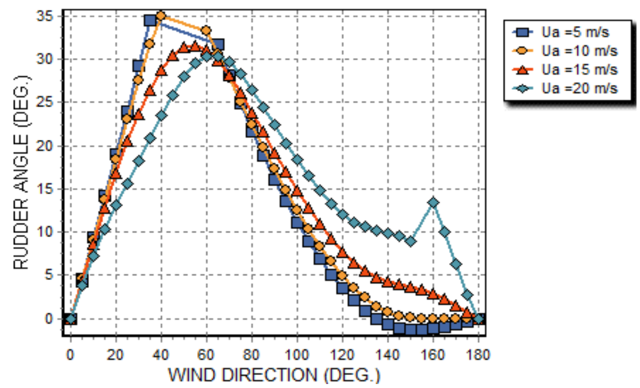


Figure 6 The necessary rudder angle in the steady state equilibrium for several wind velocity with wave height of 2.0 meters. Here the wave slope is 0.025

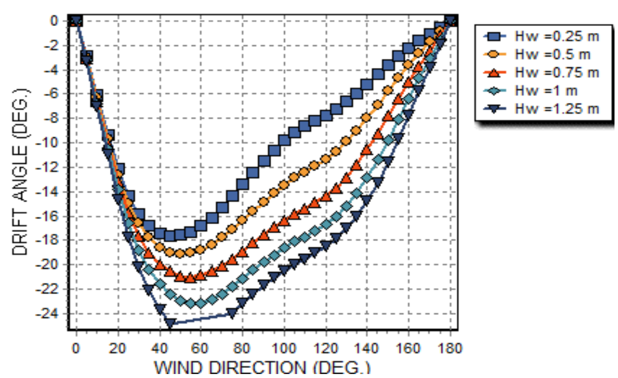


Figure 7 The drift angle for several different wave amplitude with wind velocity of 20.0 m/s. The wave length is 80.0 meters

The wave forces and moment have no effect on the drift angle when the angle of wave and wind direction is smaller than 20.0 degrees. The drift angle increases due to increase the wave amplitude in the angle of wave and wind direction larger than 20.0 degrees. Therefore, it can be concluded that the wave exciting forces and moment have significant effect on the drift angle when the angle of wave and wind direction is larger than 20.0 degrees. This results is different with variation of drift angle for several different wind velocities shown in Figure 4 in which the wind effect to the drift angle becomes significant in the angle of wave and wind direction smaller than 120.0 degrees. In cases of head wind (the angle of wave and wind direction are smaller than 120.0 degrees), the wind forces especially in sway direction reduces the surge velocity due to resistance induced by the wind on the ship windage area. The wind force in the sway direction increases the sway velocity. As result, the drift angle increases. The wave force in sway and the yaw moment in the angle of wave and wind direction smaller than 20.0 degrees may be smaller than those induced by the wind. The wave force in surge has also quite small effect on reduction of the ship forward speed. Therefore, the drift angle does not significantly change due to variation of the wave amplitude.

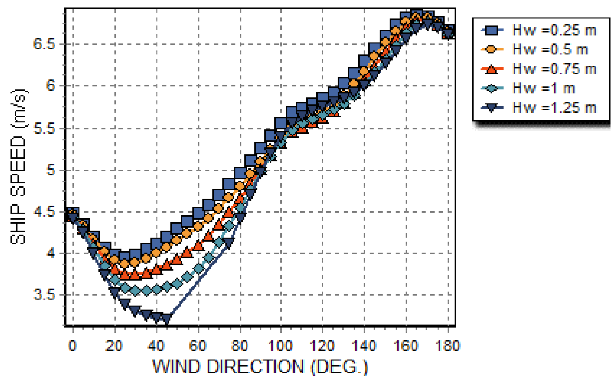


Figure 8 The ship forward speed for several wave amplitude with wind velocity of 20.0 m/s. Here the wave length is 80.0 meters

Figure 8 shows that the wave forces and moment have significant effect on the ship forward speed when the angle of wave and wind direction is larger than 20.0 degrees and it is smaller than 100.0 degrees. The ship forward speed tends to increase due to increase the angle of wave and wind direction when this angle is larger than 40.0 degrees. The ship forward speed also becomes higher than the ship normal speed in calm water if the angle of wave and wind direction is larger than 100.0 degrees or in cases of quartering following wind and waves. However, the ship forward speed does not significantly changes due to alteration of the wave amplitude within this range of wave and wind direction.

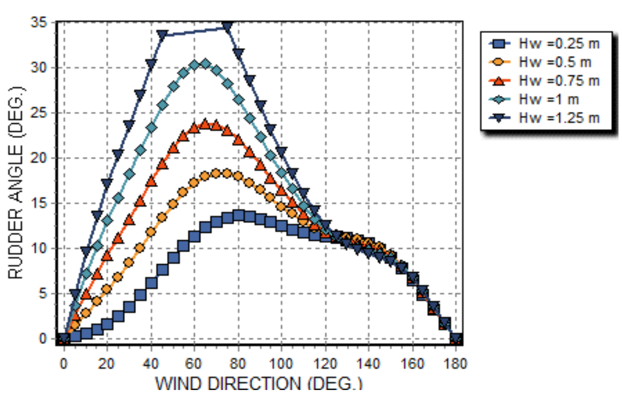


Figure 9 The rudder angle for several different wave amplitude with wind velocity of 20.0 m/s. Here the wave length is 80.0 meters

The rudder angle in the steady state equilibrium is not affected by the wave forces and moment when the angle of wave and wind direction is larger than 120.0 degrees as shown in Figure 9. Oppositely, the wave has significant effect on the rudder angle in the angle of wave and wind direction smaller than 120.0 degrees. The rudder angle is larger than the maximum rudder angle of real ship when the wave amplitude is 1.25 meters or larger in the angle of wave and wind direction ranged from 45.0 degrees up to 75.0 degrees. This range of exceeding the maximum rudder angle may be different for larger wave amplitude. The rudder cannot control the ship when the necessary rudder angle exceeds the maximum possible rudder angle. This means that the yaw motion becomes unstable. Even the necessary rudder angle is still smaller than the maximum rudder angle, the steady state equilibrium may become unstable depend on the characteristics of ship hydrodynamics, rudder forces and moment as well as the external forces and moment acting on ship hull. Therefore, the stability of the steady state equilibrium under combined action of wind and wave is important to analyze in the future.

4.0 CONCLUSION

The steady state equilibrium of ship maneuver under combined action of wind and wave has been investigated by using numerical simulation for the angle of wave and wind direction ranged from 0.0 degree (head wave and wind) up to 180.0 degrees (following wave and wind). Base on the obtained drift angle, ship forward speed and rudder angle in the steady state equilibrium, its can be concluded that the wind has significant effect on the drift angle in the angle of wave and wind direction smaller than 120.0 degrees. It significant effect on the rudder angle occurs when the angle of wave and wind direction is larger than 20.0 degrees.

The wave effect on the drift angle becomes significant when the angle of wave and wind direction is larger than 20.0 degrees, while it significantly affects the rudder angle in the angle of wave and wind direction smaller than 120.0 degrees. The necessary rudder angle exceeds the maximum rudder angle of real ship if the wave amplitude is larger than 1.25 meters or the wave height is larger than 2.50 meters.

The ship forward speed is significantly affected by the wind velocity in the angle of wave and wind direction smaller than 40.0 degrees as well as the angle is larger than 140.0 degrees. Effect of wave on the ship forward speed is only significant in the range of wave and wind direction from 20.0 degrees up to 100.0 degrees. The wave and wind reduces the ship forward speed in cases of head wave and wind but it increases the ship forward speed in cases of following wave and wind.

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References

[1] IMO. 1972. *Collision Regulation (COLREG)*. IMO. London.

[2] IMO. 2002. *Maritime Safety Committee on Ship Maneuverability of International Maritime Organization (IMO), MSC 76/23, Resolution MSC 137(36)*. IMO. London.

[3] T. Fujiwara, M. Ueno, Y. Ikeda. 2006. Cruising Performance of a Large Passenger Ship in Heavy Sea. *Proceeding of the Sixteenth International Offshore and Polar Engineering Conference*. San Francisco, California, USA. 304-311.

[4] M. Ueno, T. Nimura, H. Miyazaki, K. Nonaka. 2000. Steady Wave Forces and Moment Acting on Ships in Maneuvering Motion in Short Waves (in Japanese). *Journal Sociecty of Naval Architects of Japan*. 188: 163-172.

[5] N. Umeda, M.R. Renilson. 1992. Wave Forces on a Ship Running in Quartering Seas – A Simplified Calculation Method. *The 11th Australian Fluid Mechanics Conference*. University of Tasmania, Hobart, Australia. 14 – 18 December 1992. 363-366.

[6] N. Umeda, H. Hashimoto. 2002. Qualitative Aspects of Nonlonear Ship Motions in Following and Quartering Seas with High Forward Velocity. *Journal of Marine Science and Technology*.6(3): 111-121.

[7] H. Yasukawa, T. Hirano, Y. Nakayama, K. K. Koh. 2012. Course Stability and Yaw Motion of a Ship in Steady Wind. *Journal of Marine Science and Technology*.17(3): 291-304.

[8] D. Paroka, A.H. Muhammad, S. Asri. 2014. Maneuvering Performance of Indonesian Ro-Ro Ferries under Action of Wind. *Proceedings of The International Conference on High Performance of Marine Vehicles (HPMV)*. Shanghai, China. 10 – 13 April 2014. E17-1-E17-10.

[9] D. Paroka, A. H. Muhammad, S. Asri. 2014. Maneuverability of Ships with Small Draught in Steady Wind. *Jurnal Makara Seri Technology* (Acccepted for publication).

[10] K. Spyrou. 1995. Yaw Stability of Ships in Wind. *Journal of Ship Research*. 41(1): 21-30.

[11] M. Hirano, J. Takashina. 1982. A Calculation of Ship Turning Motion Taking Coupling Effect due to Heel into Consideration. *Journal of the West Japan Society of Naval Architects*. 59: 71-78.

[12] K. Kijima, T. Katsuno, Y. Nakiri, Y. Furukawa. 1990. On the Maneuvering Performance of a Ship with the Parameter of Loading Condition. *Journal Society of Naval Architects of Japan* 168: 141-148.

[13] Y. Yoshimura, H. Sakurai. 1988. Mathematical Model for the Maneuvering Ship Motion in Shallow Water. *Journal of Kansai Society of Naval Architects of Japan*. 211: 115-126.

[14] T. Fujiwara, M. Ueno, Y. Ikeda. 2006. Cruising Performance of Ships with Large Superstructures in Heavy Sea – 1st report : Added Resistance Induced by Wind (in Japanese). *Journal of Japan Society of Naval Architects and Ocean Engineers*. 2: 243-255.

[15] Y. Ito, N. Umeda, H. Kubo. 2014. Hydrodynamic Aspects on Vulnerability Criteria for Surf-Riding of Ships. *Jurnal Teknologi (Science and Engineering)*. 66(2): 127-132.

[16] International Towing Tank Conference (ITTC). 2008. Recommended Procedures and Guidlines: Testing and Extrapolation Methods, Propulsion, Performance, Predicting Powering Margins. *The Specialist Committee on Powering Performance Prediction of 25th ITTC*. September 2008. 1-9.

[17] K. Zelazny. 2014. A Simplified Method for Calculating Propeller Thrust Decrease for a Ship Sailing on a Given Shipping Lane. *Polish Maritime Research*. 21: 27-33.

[18] J. Carlton. 2007. *Marine Propellers and Propulsions Second Edition*. London: Elsevier Ltd.