

PREDICTION OF SHIP TURNING MANEUVERS IN CONSTANT WIND AND REGULAR WAVES

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ABSTRACT

A ship usually performs maneuvers under the influence of external forces and moments, such as wind, waves, and current. Therefore, it is important to understand the maneuvering behavior of ships under the action of external forces. This paper discusses the turning maneuvers of an Indonesian ro-ro ferry under the combined influence of constant wind and regular waves using the mathematical modelling group (MMG). The ship's position relative to the wave trough is added to the original MMG model to estimate the exciting forces and moment induced by the waves. The results of a numerical simulation show that the effect of wave height on turning ability is more significant for a small wavelength; this effect decreases as the wavelength increases. The effect of wavelength on the sway force and yaw moment is more significant compared with its effect on the surge force. The ship's initial position relative to the wave trough does not have a significant effect on the turning characteristic and it can be neglected for the present study's subject ship. Overall, the results of the present work compare well with published data.

Keywords: Maneuvering; Turning; Waves; Wind

1. INTRODUCTION

The maneuvering performance of a ship during the initial design stage is typically predicted in calm water conditions. However, ships usually maneuver in the presence of external forces, such as wind, waves, and current. Therefore, it is important to understand the maneuvering behavior of a ship under the combined actions of the environmental forces.

Some mathematical models for predicting the maneuvering of a ship in conditions of wind and waves have been developed by several authors. Fang et al. (2005) used a 6 degree of freedom (6 DOF) nonlinear mathematical model to simulate a ship's turning maneuver in waves by taking into account the effect of the wave encounter frequency on the inertia, damping, and linear hydrodynamic derivative of the forces and moments acting on the ship's hull. A similar approach was used by Zipfel and Maksoud (2011) to determine a ship's maneuvering motion in regular waves. The frequency-dependent hydrodynamic coefficients were transferred to the time-domain using the impulse response function. A unified seakeeping and maneuvering theory with second-order regular waves was proposed by Skejic and Faltinsen (2008) to analyze the behavior of a ship in waves. Here, the wave drift force was estimated using a two-time scale

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model to separate the low-frequency motion (maneuvering motion) and the high-frequency motion (seakeeping motion). The same method for estimating the wave drift force was used by Seo and Kim (2011) to predict ship maneuvering in waves using a combination between the mathematical modelling group (MMG) and seakeeping mathematical model. The second-order wave force was also used by Chroni et al. (2015) to investigate the effect of environmental forces on ship maneuvering with a 4 degree of freedom (4 DOF) mathematical model. Skejic (2013) also used the second-order wave force to simulate ship maneuvering in irregular waves. However, the two-time scale method seems to be inefficient because the solution to the seakeeping motion can be obtained after the maneuvering motion has been solved.

The most practical method for predicting the maneuvering behavior of a ship in the initial design stage may be the MMG model because empirical formulas for estimating the coefficients of the hydrodynamic derivatives have been developed (Yoshimura & Masumoto, 2012). Even the original MMG model is a pure maneuvering motion problem with a 3 DOF mathematical model; some researchers included the roll or heeling effect using a 4 DOF model. Fujiwara et al. (2006) and Paroka et al. (2015) used the MMG model to investigate the steady state equilibrium of a ship maneuvering in wind and waves.

The discrepancy between the MMG model and the previously mentioned methods is the encounter frequency of forces and moments induced by the ship's hull. In cases of long wavelengths in which the length of the wave is larger than the length of the ship, some authors neglected the effect of the encounter frequency on hydrodynamic forces and moments induced by the ship's hull, although it was taken into account for the forces and moments induced by the waves (Munif & Umeda, 2000; Umeda & Hashimoto, 2002). Munif and Umeda (2000) showed that with long waves, the heave and pitch motion may not be significant. Following this assumption, the MMG model seems to be able to predict the turning characteristics of ships in waves. However, it is necessary to add a mathematical equation to the MMG model to describe the ship's position relative to the wave. This is important because the forces and moments induced by the wave depend on the ship's position in the wave surface.

This paper discusses the turning maneuverability of a small Indonesian roro ferry under the combined action of wind and waves using the modified MMG model. The effect of the characteristics of the waves, such as wave height, wavelength, and the initial position of the ship relative to the wave, was investigated. For small ships, these wave characteristics may have a significant effect on the maneuvering performance as indicated by Fang et al. (2005). The wind velocity is assumed to be constant and to be uncorrelated with the wave characteristics.

2. RESEARCH METHODOLOGY

To describe the present mathematical model, two coordinate systems are used as shown in Figure 1. The first coordinate system, $o-x_o y_o z_o$, is fixed on the calm water surface and is used to describe the coordinates of the ship's position and wave propagation, respectively. The second coordinate system, $G-xyz$, has its origin on the ship's center of gravity, G , and moves with the ship's motion. The symbols u , v , and r indicate the surge, sway, and yaw velocities, respectively. The drift angle is designated by β , and δ is used for the rudder angle. The propeller thrust is indicated by T_j and the heading angle is indicated by ψ . The angle of the wave direction ψ_w is assumed to be the same as the wind angle.

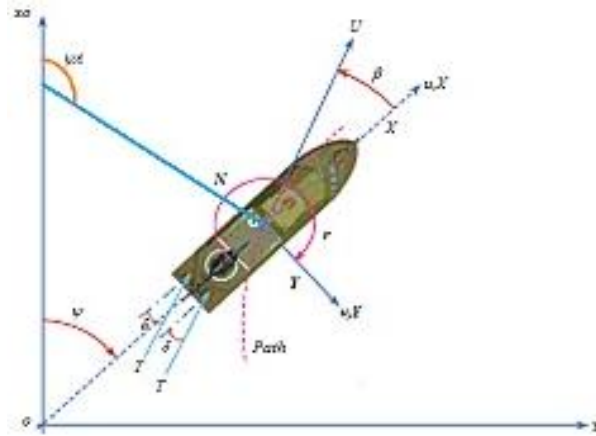


Figure 1 The coordinate systems

According to Newton's second law of motion and following the MMG model, the equation for a ship maneuvering in the combined action of wind and wave according to Fujiwara et al. (2006) is written as:

$$\ddot{\xi}_G = u \cos \chi - v \sin \chi \quad (1)$$

$$(m + m_x)(\dot{u} - vr) = X_H + X_P + X_R + X_A + X_W \quad (2)$$

$$(m + m_y)(\dot{v} - ur) = Y_H + Y_R + Y_A + Y_W \quad (3)$$

$$(I_{zz} + J_{zz})\dot{r} = N_H + N_R + N_A + N_W - x_G(Y_H + Y_R + Y_A + Y_W) \quad (4)$$

Here, m , m_x , and m_y indicate the ship's mass, the added mass in the surge, and the added mass in the sway, respectively, while \dot{u} , \dot{v} , and \dot{r} are the surge, the sway, and the yaw accelerations, respectively. The subscripts H , P , R , A , and W indicate the hull, propeller, rudder, wind, and the wave forces and moments in the surge, sway, and yaw directions. Equation 1 is added to the MMG model (Equations 2 to 4) to take into account the effect of the ship's position relative to the wave surface on the wave forces and moments. This equation was used by Fang et al. (2005) and Umeda and Hashimoto (2002) to estimate the wave forces and moments acting on a ship's hull. Integration of Equation 1 over time results in the relative position of a ship's center of gravity relative to the wave trough. Therefore, Equations 1 to 4 can be solved at the same time without separating the seakeeping and maneuvering motions. The symbol χ in Equation 1 indicates the angle of the wave encounter relative to the ship heading angle.

The forces and moments of the hull in Equations 2 to 4 are empirically estimated using the polynomial regression of the nondimensional hydrodynamic derivatives (Yoshimura, 2005; Yoshimura & Masumoto, 2012). The ship's resistance is estimated using a method developed by Holtrop and Mennen (1982). The propeller thrust is estimated using the equation proposed by Kijima et al. (1990). The thrust coefficient as a function of the advance coefficient are estimated based on statistical data of the open water test for B series propeller (Carlton, 2007). The rudder forces and moments are calculated using a formula proposed by Kijima et al. (1990) for a twin propeller and twin rudder.

The forces and moments induced by the waves are estimated using formula proposed by Umeda and Hashimoto (2002). A correction factor, which depends on the block coefficient, is used to estimate the wave force in the surge direction (Ito et al., 2014). The equation for estimating the wave force in the surge and sway directions, as well as the wave moment in the yaw direction are shown in Equations 5 to 7.

$$X_W = -\alpha \rho g \zeta_W k \cos \chi \int_{AE}^{FE} C_1(x) S(x) e^{-kd(x)/2} \times \sin(k(\xi_G + x \cos \chi)) dx \tag{5}$$

$$Y_W = \rho g \zeta_W k \sin \chi \int_{AE}^{FE} C_1(x) S(x) e^{-kd(x)/2} \times \sin(k(\xi_G + x \cos \chi)) dx + \zeta_W \omega \omega_e \sin \chi \int_{AE}^{FE} \rho S_y(x) e^{-kd(x)/2} \times \sin(k(\xi_G + x \cos \chi)) dx - \zeta_W \omega u \sin \chi \times [\rho S_y(x) e^{-kd(x)/2} \cos(k(\xi_G + x \cos \chi))]_{AE}^{FE} + (1 + a_H) \frac{\rho}{2} A_R f_\alpha \varepsilon_R (1 - w_p) u \sqrt{1 + \kappa_p \frac{8K_T}{\pi J^2} v_{WR}} \tag{6}$$

$$N_W = \rho g \zeta_W \sin \chi \int_{AE}^{FE} C_1(x) S(x) e^{-kd(x)/2} \times x \sin(k(\xi_G + x \cos \chi)) dx + \zeta_W \omega \omega_e \times \sin \chi \int_{AE}^{FE} \rho S_y(x) e^{-kd(x)/2} x \sin(k(\xi_G + x \cos \chi)) dx + \zeta_W \omega u \sin \chi \int_{AE}^{FE} \rho S_y(x) e^{-kd(x)/2} \times \cos(k(\xi_G + x \cos \chi)) dx - \zeta_W \omega u \sin \chi \times [\rho S_y(x) e^{-kd(x)/2} x \cos(k(\xi_G + x \cos \chi))]_{AE}^{FE} + (x_R + a_H x_H) \frac{\rho}{2} A_R f_\alpha \varepsilon_R (1 - w_p) u \sqrt{1 + \kappa_p \frac{8K_T}{\pi J^2} v_{WR}} \tag{7}$$

Here, α is the correction factor dependent on the block coefficient, and ζ_W , k , $S(x)$, and $d(x)$ are the wave amplitude, wave number, area, and draught of section at a longitudinal distance x from the midship, respectively. The symbols ω , ω_e , and $S_y(x)$ indicate the wave frequency, wave encounter frequency, and added mass of section in the sway direction, while x_R , x_H , a_H , and A_R are the longitudinal position of the rudder from the midship, the longitudinal position of the center of the interaction force between the hull and the rudder, the interaction factor between the hull and the rudder, and a the rudder area, respectively. The rudder coefficient is indicated by f_α and the effective propeller wake fraction is designated by w_p . The symbols ε_R , κ_p , J , and K_T are the wake ratio between propeller and rudder, the interaction factor between propeller and rudder, the advance coefficient, and the thrust coefficient, respectively. $C_1(x)$ and v_{WR} are calculated using Equation 8 and Equation 9, respectively.

$$C_1(x) = \frac{\sin(k \sin \chi \cdot B(x)/2)}{(k \sin \chi \cdot B(x)/2)} \tag{8}$$

$$v_{WR} = \zeta_W \omega \sin \chi \exp(-kz_R) \cos(2\pi \xi_G/\lambda + kx_R \cos \chi) \tag{9}$$

Here, $B(x)$, z_R , and λ are the breadth of section, the center of the rudder from the baseline, and the wavelength, respectively.

The wind forces and moments in the surge, sway, and yaw directions are calculated using the empirical formula proposed by Fujiwara et al. (2006). The angle of wind attack is determined by the wind direction and the ship heading angle. The wave angle is assumed to be the same as the wind angle.

2.1. Ship Data

The ship used in the numerical simulation is an Indonesian ro-ro ferry with the principle dimensions shown in Table 1. The dimensions of the propeller and the rudder are shown in Table 2.

Table 1 Principle dimensions of the subject ship

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
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 area 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 dimensions

Items	Dimension
Number of propellers	2
Number of propeller blades (Z)	4
Propeller diameter (D_P)	1.10 m
Propeller revolution (n)	8.58 rps
Transverse position propeller (y_P)	± 2.55 m
Longitude position propeller (x_P)	15.50 m
Rudder area (A_R)	2.08 m ²
Rudder coefficient (f_A)	2.10
Transverse rudder position (y_R)	± 2.55 m
Longitude rudder position (x_R)	15.75 m

3. RESULTS

The numerical results of the turning maneuver simulation for a wave height of 0.50 m and 0.75 m are shown for a wavelength that is the same as the ship's length (Figure 2a) and for a wavelength of 50.0 m (Figure 2b). The wind velocity for all wave characteristics is 6.75 m/s (Beaufort scale 4). The turning diameter decreases as the wave height increases. The distance between the first and the second turning circles is longer for a larger wave height. A similar result is obtained for a larger wavelength. The distance of the turning circles movement becomes smaller as the wavelength increases. These results show that the wave height has a more significant effect on the ship turning maneuver for a shorter wavelength compared with a longer wavelength.

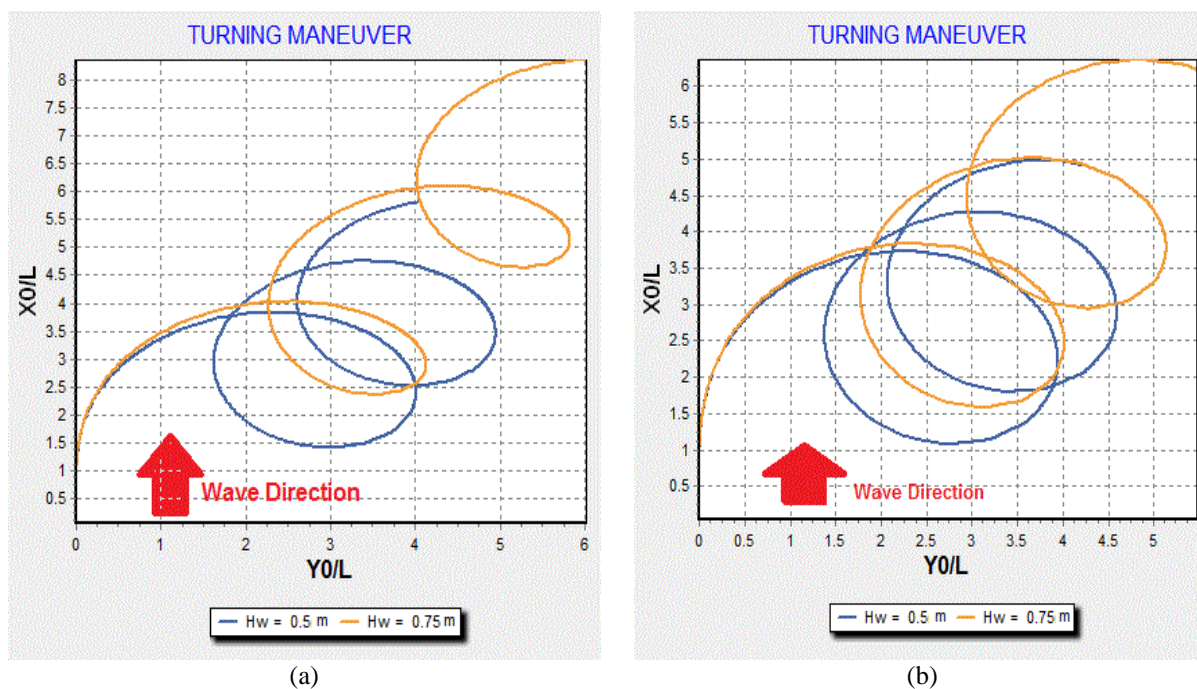


Figure 2 Trajectory of the turning circle: (a) Wavelength is the same as the ship's length; and (b) Wave length is 50.00 meters

The surge and sway velocities of the ship during the turning simulation are shown in Figure 3a for a wavelength that is the same as the ship's length for a wave height of 0.50 m and 0.75 m. The results for a wavelength of 50.0 m with the same wave heights are shown in Figure 3b. The yaw rates for a wavelength that is the same as the ship's length for the same wave heights are shown in Figure 3c, while Figure 3d shows the results for a wavelength of 50.0 m. The surge and sway velocities oscillate depending on the angle of the wave encounter relative to the ship heading angle. The minimum velocity occurs when there is a heading wave in which the angle of the wave encounter is 0.0 degrees, while the maximum velocity occurs in a following wave in which the angle of the wave encounter is 180.0 degrees. The oscillation of the surge, sway, and yaw motions also occur in all conditions of wave height and wavelength. These are purely affected by the ship's position relative to the wave. The oscillation of the surge velocity becomes significant in heading and following waves, while the oscillation of the sway velocity becomes significant in beam seas. Therefore, the phase between the surge and sway motions becomes 90.0 degrees as shown in Figures 3a and 3b.

An alteration in surge velocity when the ship is in following waves and heading waves significantly increases as the wave height increases. However, the effect of wave height on the alteration in surge velocity decreases as the wavelengths increase. The same trend is also obtained for the sway velocity. The yaw rate is more sensitive to the alteration in wave direction compared with the surge and sway velocities. This is because the yaw moment exists even in beam seas depend on the position of longitudinal center of gravity. The minimum yaw rate will occur in following and heading waves, although this condition appears in a very short time in case of a turning maneuver.

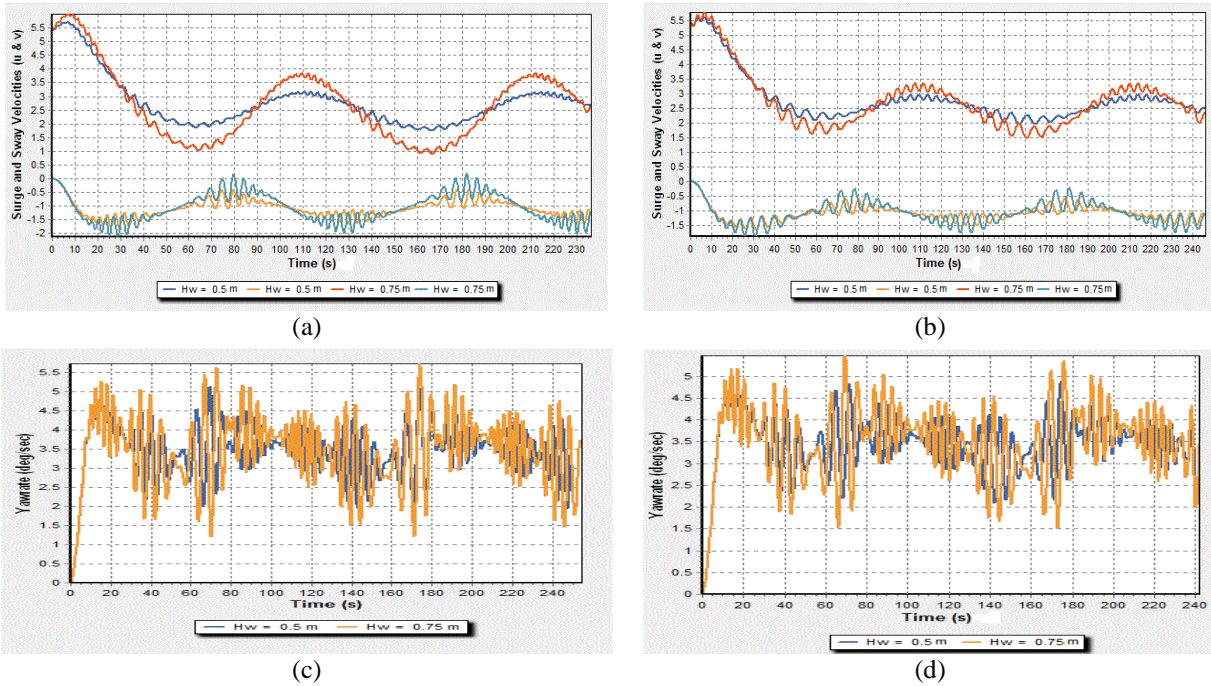


Figure 3 Ship motion during a turning maneuver: (a) Surge and sway velocities for wavelength the same as ship's length; (b) Surge and sway velocities for wave length of 50.00 meters; (c) Yaw rate for wavelength the same as ship's length; (d) Yaw rate for wavelength of 50.00 meters

Figures 4a to 4f show the nondimensional forces and moments in the surge, sway, and yaw directions at two different wave heights and two different wavelengths. The figures on the left are for a wavelength that is the same as the ship's length, and the figures on the right are the forces and moments for a wavelength of 50.0 m. The effect of wavelength on the force in the surge direction is not significant compared with its effect on the force in the sway direction and on the moment in the yaw direction. Therefore, the characteristic of turning trajectory significantly changes as the wavelength increases for the same wave height. The wave height significantly affects the forces and moments for a wavelength of 50.0 m. However, the effect of wave height on the forces and moments tends to decrease as the wavelength increases. Similar to the sway velocity, the force in the sway direction is negligibly small in heading and following waves, although it reaches its maximum in beam seas. The same trend is obtained for the surge force when the angle of the wave encounter is 90.0 degrees and 270.0 degrees (beam waves). The minimum value of the yaw moment occurs in cases of heading and following waves. The yaw moment is still significant in a beam wave because of the effect of the longitudinal center of buoyancy.

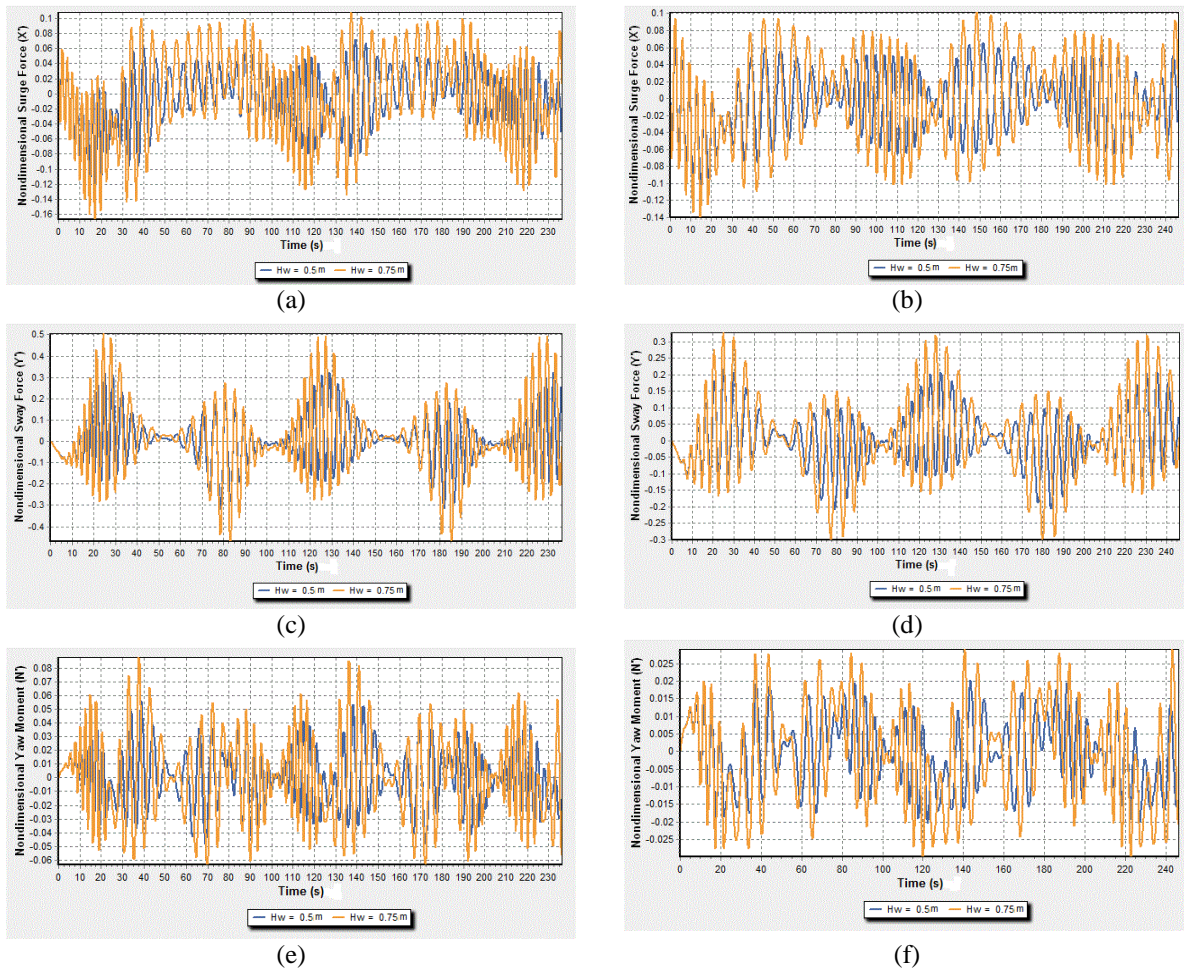


Figure 4 Resultant forces and moments acting on a ship hull during a turning maneuver: (a) Surge force for wavelength the same as the ship's length; (b) Surge force for wavelength of 50.00 meters; (c) Sway force for wavelength the same as the ship's length; (d) Sway force for wavelength of 50.00 meters; (e) Yaw moment for wavelength the same as the ship's length; (f) Yaw moment for wavelength of 50.00 meters

4. DISCUSSION

The obtained turning trajectory for two different wave heights and wavelengths are similar to the results found in previous studies (Fang et al., 2005; Seo & Kim, 2011; Skejck, 2013; Chroni et al., 2015). The turning circle becomes smaller as the wave height increases for both a wavelength that is the same as the ship's length and a wavelength of 50.0 m. The turning circle for a shorter wavelength is larger than for a larger wavelength. This indicates that the drift motion significantly increases when the wave height increases and decreases as the wavelength increases. Figure 3 shows that the surge velocity is minimum in beam seas, which produces a maximum sway velocity. The yaw moment tends to increase when the wave slope increases. As result, the turning motion for a large wave slope is faster than with a small wave slope. These turning motion characteristics also induce a longer distance of movement between the first turning circle and the second turning circle as shown in Figure 2.

Fang et al. (2005) showed that the oscillations of both the surge and sway velocities depend on the angle of the wave encounter relative to the ship heading angle. The same results are obtained in the present study. A more significant amplitude of oscillation of the surge and sway velocities has also been identified in the transition from following waves to beam seas and from beam waves to heading waves and so on. This phenomenon did not appear in a study conducted

by Fang et al. (2005). Skjick (2013) had similar results as this study for a ship turning in irregular waves. This phenomenon may depend on the wave characteristics compared with the ship geometry. Thus, it may not occur in cases of large ships compared with the wave height, although it may be seen in small ships even for a small wave height as seen in this study. Figures 3a and 3b show that the oscillation due to the transition from following waves to beam waves and so on decreases when the wavelength increases. It may disappear for smaller wave slopes.

The initial position of a ship relative to the wave does not have a significant effect on the turning maneuvers of a ship in waves. The same results were obtained by Fang et al. (2005), although they stated that the effect of the initial position relative to the wave may be significant for small ships. This effect is not obtained in the present study. The initial position of a ship relative to the wave surface does not significantly affect the forces and moments induced by the wave during a turning maneuver. The initial position only makes the changing phase of the forces and moments. Therefore, its effect on the turning maneuver becomes negligibly small.

The subject ship cannot perform a turning maneuver in a wave height of 1.0 m when the wavelength is the same as the ship's length or is smaller. The numerical simulation can be conducted for a wave height of 1.0 m when the wavelength is longer than the ship. However, the turning circle becomes very small and it seems to be unrealistic from a practical point of view. The very small turning circle occurs due to the large drift motion with a small surge velocity in beam seas up to heading waves during the turning simulation. The large drift motion may occur due to the small draught of the subject ship so that the hydrodynamic damping force in the sway direction becomes smaller compared with a ship with a larger draught. This was shown by Chroni et al. (2015) using a wavelength that was half the ship's length, a wave height of 5.50 m, and a wind velocity of 19.0 m/s (Beaufort scale 8). The subject ship used in their simulation was larger than that used in the present study. These facts show that the required weather conditions to perform a sea trial of small ships should be smaller than that in the guidance of the International Maritime Organization (IMO, 2002).

5. CONCLUSION

The mathematical model for predicting a ship's turning maneuver in constant wind and regular waves has been developed based on the 3 DOF of the MMG model. In order to directly calculate wave forces and moment, an equation to describe the ship's position relative to the wave profile as a function of the surge and sway velocities, as well as the heading angle has been included in the MMG model. The present mathematical model can be simultaneously solved to obtain the maneuvering characteristics. Based on the numerical results for a small Indonesian roro ferry, some conclusions can be made as follows: (1) The effect of the wave height on a ship's turning maneuver is more significant for a short wavelength. This effect decreases as the wavelength increases; (2) The sway force and yaw moment of a wave significantly decrease when the wavelength increases. Alteration of the surge force due to an increasing wavelength is smaller compared with the sway force and yaw moment. This means that the drift motion may have an important role on ship maneuvering for short wavelengths; (3) The initial position of a ship relative to the wave does not have a significant effect on the ship's turning maneuver; its effect can be neglected in the subject ship of the present study.

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