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CRUISING PERFORMANCE OF INDONESIAN RO-RO FERRIES UNDER ACTION OF WIND AND WAVES

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SUMMARY

The ro-ro ferries play an important role in Indonesian sea transportation. Therefore, performance of the Indonesian ro-ro ferries in operation become important in technical and economical point of view. This paper discuss effect of wind and wave to the ship speed, drift and rudder angle in order to maintain the ship direction. The wind velocities of 5 m/s, 10 m/s, 15 m/s, 20 m/s and 25 m/s with variation of direction from 0 degree (head wind) to 180 degrees (following wind) are used to investigate its effect on ship speed, drift angle and rudder angle. The wave is assumed to be fully developed due to wind. Therefore the wave parameters are determined using wind and wave correlation as defined in Beaufort scale. These environment parameters are used to numerically solve the maneuvering equation based on MMG model by using the Newton-Rhapson method.

Results of the numeric simulation show that the wind effect to the drift angle become significant in the wind and wave direction less than 80.0 degrees. In this range of wind and wave direction, effect of wave height is neglected small. The 0 effect of wave on the drift angle tends to be increase in range of wind and direction from 80.0 degrees up to 180.0 degrees. The encessary rudder angle is dominantly affected by the wind in the wind and wave direction of 40.0 degrees or larger. The wave effect becomes significant in the wind and wave direction is smaller that 100.0 degrees. The ship speed is significantly affected by the wind velocity compared with the effect of wave height. The effect of wave height to the ship speed occurs in the range of wind and wave direction from 20.0 degrees up to 100.0 degrees.

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NOMENCLATURE

A_E	Propeller blade expanded area (m^2)
A_R	Rudder area (m^2)
A_0	Area of propeller blade (m^2)
a_H	Interaction factor of hull and rudder
$B(x)$	breadth of section (m)
D_P	Propeller diameter (m)
$d(x)$	Draught of section (m)
I_{zz}	Moment of inertia in yaw (kN m rad^{-1})
J	Advance coefficient
K_T	Thrust coefficient of propeller
k	Wave number
m	Ship mass (ton)
N	Moment resultant in yaw (kN m)
N_A	Wind moment in yaw (kN m)
N_H	Hull moment in yaw (kN m)
N_P	Moment of propeller in yaw (kN m)
N_R	Rudder moment in yaw (kN m)
N_W	Wave moment in yaw (kN)
n	Propeller revolution (rps)
P	Propeller pitch
r	Yaw rate (rad s^{-1})
$\dot{r}$	Angle acceleration in yaw (rad s^{-2})
$S(x)$	Sectional area (m^2)
$m(x)$	Added mass of section in sway (kN)
u	Surge velocity (m s^{-1})
$\dot{u}$	Surge acceration (m s^{-2})
v	Sway velocity (m s^{-1})
$\dot{v}$	Sway acceleration (m s^{-2})
w_p	Wake friction of propeller
X	Forces resultant in surge (kN)
X_A	Wind force in surge (kN)
X_H	Hull force in surge (kN)
X_P	Propeller thrust (kN)
X_R	Rudder force in surge (kN)
X_W	Wave force in surge (kN)
x_G	Longitudinal center of gravity (m)
x_H	Position of Hull-rudder interaction (m)
x_R	Longitudinal position of rudder (m)
Y	Forces resultant in sway (kN)
Y_A	Wind force in sway (kN)
Y_H	Hull force in sway (kN)
Y_P	Propeller thrust in sway (kN)
Y_R	Rudder force in sway (kN)
Y_W	Wave force in sway (kN)
Z	Number of propeller blade
z_R	Vertical center of gravity of rudder (m)
ε_R	Wake ratio of propeller and hull
κ_P	Interaction of propeller and rudder
ρ	Density of water (kg m^{-3})
ω	Wave frequency (rad s^{-1})
ω_e	Wave encounter frequency (rad s^{-1})
ζ_W	Wave amplitude (m)
ξ_G	Ship trajectory (m)
χ	Wind and wave direction (rad)
λ	Wave length (m)

1. INTRODUCTION

As an archipelago country with distance between the islands quite short, interisland transportation becomes the most important transportation system in Indonesia.

Recently, there are more than 100 routes of interisland transportation have be operated with more than 150 ro-ro ferries. Therefore, safety and economic aspects in operation of the Indonesian ro-ro ferries become important in order to ensure effectively of the interisland transportation. With the last two decades, more 600 accidents of ships occurred in Indonesian seaways and 15 percent of the accidents are due to collision [1]. The last accident is collision between a ro-ro ferry KMP Bahuna Jaya and a tanker MV Norgas Chantika in Sunda strait.

Collision accidents may occur due to poor maneuverability under disturbance of wind and waves in seaways. The International Maritime Organization (IMO) therefore developed maneuverability criteria for ships in operation [2]. When the ship operating in heavy weather, the ship course or the ship direction may not be controlled by the rudder due to large yaw moment induced by wind and wave. Instability of yaw motion can bring the ship into beam seas condition and capsizes due to large roll angle. This phenomenon has been investigated by Umeda, et. al [3] and Spyrou [4].

Yasukawa, et. al [5] investigated the yaw motion stability of pure car carrier (PCC) due to wind. They found that the yaw motion becomes unstable when the ship operating in high wind velocity. The drift angle and the rudder angle of the ship in order to maintain the ship course increases when the wind velocity increases. The significant effect of wind to the maneuvering performance of PCC occurs in the wind direction smaller than 90 degrees (in head wind). The same results were presented by Fujiwara, et. al [6] for large passenger ship and Paroka, et. al [7] for an Indonesian ro-ro ferry. Collision accident may also occur due to instability of yaw motion and large drift motion especially for crowded ship routes.

The ship speed may also significantly decreases due to wind and wave resistances depends on the wind velocity and direction as well as the wave parameters and direction relative to the ship [5], [6], [7]. Reduction of the ship speed will increases fuel consumption due to longer operation time as well as increasing the engine torque. Fujiwara et. al [6] show that the engine torque of ships increases due to decreasing the ship speed for constant propeller revolution. This means that a ship with poor maneuverability are going to have higher operation cost when operating in heavy weather.

This paper discusses regarding maneuvering performance of Indonesian Ro-Ro ferries due to wind and waves. The drift angle and the rudder angle in order to maintain the ship courses are investigated for several wind velocity and wave height. The alteration of ship speed due to wind and wave effects is also investigated. This is important for ship master or ship operator to understand characteristics of ship maneuverability especially when operating in heavy weather. The real fuel consumption may also be estimated based on the ship speed in a certain wind velocity and wave characteristic including the wind and wave direction relative to the ship. This paper may also provide basic information in order to avoid collision accident or ship grounding.

2. MODELLING OF SHIPS MANEUVERING

The ship maneuvering is usually modeled using three degree of freedom equation consist of surge, sway and yaw. In order to consider the ship transverse stability due to ship maneuver, the maneuvering is modeled using four degree of freedom equation including the roll motion equation [7]. The maneuvering equation is developed using the global and local coordinate systems. The global coordinate system was determined to be fixed relative to the earth. The local coordinate system was in the ship center of gravity and moving with ship. The coordinate systems for three degree of freedom equation are shown in Figure 1 as follows:

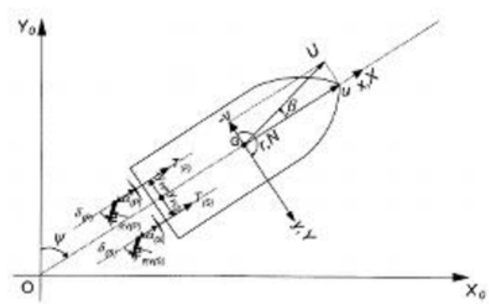

Figure 1. The coordinate systems of ship with three degree of freedom mathematic model

Base on these coordinate systems, the equation of maneuvering using the MMG model as proposed by Hirano, et. al [8] and Kijima, et. al [9] is written as the following equations:

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

Resultant of surge forces, sway forces and yaw moments in the equation (1) consists of hull, propeller, rudder, wind and wave forces and moment which can be written as follows:

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

The hull, propeller, rudder and wind forces and moments in surge, sway and yaw direction are estimated by using the mathematic equation as proposed by Yoshimura and Sakurai [10] for hull, propeller and rudder forces and moments. The wind force and moment is estimated using equation proposed by Fujiwara et. al [6] as used by Paroka, et. al [7] to investigate maneuvering performance of an Indonesian ro-ro ferries under action of steady wind. Fujiwara, et. al [6] estimated the wave force and moment in surge, sway and yaw direction the same as the added resistance induced by the wave. Using this assumption, some part of the wave force and moment is not considered. Therefore, the force and moment induced by wave may underestimate. Umeda, et. al [3] proposed method for estimating the wave force by using strip theory considering the Froude-Krylov force and moment as well as the wave force and moment acting on the rudder. The force and moment induced by wave can be estimated as the following equations:

$$X_W = -\rho g \zeta_W k \cos\chi \int_{AE}^{FE} C_1(x)\, S(x) e^{-kd(x)/2} \times \sin\big(k(\xi_G + x\cos\chi)\big)\, dx \tag{3}$$

$$\begin{aligned} Y_W = {} & \rho g \zeta_W k \sin\chi \int_{AE}^{FE} C_1(x)\, S(x) e^{-kd(x)/2} \\ & \times \sin\big(k(\xi_G + x\cos\chi)\big)\, dx \\ & + \zeta_W \omega \omega_e \sin\chi \int_{AE}^{FE} \rho\, S_y(x) e^{-kd(x)/2} \\ & \times \sin\big(k(\xi_G + x\cos\chi)\big)\, dx - \zeta_W \omega u \sin\chi \\ & \times \big[\rho S_y(x) e^{-kd(x)/2} \cos\big(k(\xi_G + x\cos\chi)\big)\big]_{AE}^{FE} \\ & + (1 + a_H)\tfrac{\rho}{2} A_R f_\alpha \varepsilon_R (1 \\ & - w_p) u \sqrt{1 + \kappa_P \frac{8K_T}{\pi J^2}}\, \upsilon_{WR} \end{aligned} \tag{4}$$

$$\begin{aligned} N_W = {} & \rho g \zeta_W \sin\chi \int_{AE}^{FE} C_1(x)\, S(x) e^{-kd(x)/2} \\ & \times x \sin\big(k(\xi_G + x\cos\chi)\big)\, dx + \zeta_W \omega \omega_e \\ & \times \sin\chi \int_{AE}^{FE} \rho\, S_y(x) e^{-kd(x)/2} x \sin\big(k(\xi_G \\ & + x\cos\chi)\big)\, dx \\ & + \zeta_W \omega u \sin\chi \int_{AE}^{FE} \rho\, S_y(x) e^{-kd(x)/2} \\ & \times \cos\big(k(\xi_G + x\cos\chi)\big)\, dx - \zeta_W \omega u \sin\chi \\ & \times \big[\rho S_y(x) e^{-kd(x)/2} x \cos\big(k(\xi_G \\ & + x\cos\chi)\big)\big]_{AE}^{FE} \\ & + (x_R + a_H x_H)\frac{\rho}{2} A_R f_\alpha \varepsilon_R (1 \\ & - w_p) u \sqrt{1 + \kappa_p \frac{8K_T}{\pi j^2}}\, \upsilon_{WR} \end{aligned} \tag{5}$$

In the above equations (3) – (5), the $C_1(x)$ is calculated using the following equation:

$$C_1(x) = \frac{\sin(k \sin\chi\, B(x)/2)}{k \sin\chi\, B(x)/2} \tag{6}$$

and the υ_{Wr} is calculate as follows:

$$\upsilon_{WR} = \zeta_W \omega \sin\chi\, exp(-kz_R) \cos(2\pi\, \xi_G/\lambda + kx_R \cos\chi) \tag{7}$$

The thrust coefficient is modeled by using polynomial regression as function of advance coefficient as follows:

$$K_T(J) = a_0 + a_1 J + a_2 J^2 \tag{8}$$

The coefficients of the equation (8) are estimated based on the thrust coefficient obtained from several advance coefficients using the following equation:

$$K_T(J) = \sum_{n=1}^{39} C_n (J)^{s_n} \left({}^{P}\!/\!_{D_P}\right)^{t_n} \left({}^{A_E}\!/\!_{A_0}\right)^{u_n} Z^{v_n} \tag{9}$$

The coefficients of equation (9) are obtained base on the statistical data of B series propeller. The advance coefficient can be calculated using the equation as follows:

$$J = \frac{(1 - w_p)u}{nD_p} \tag{10}$$

The ship speed, the drift angle and the necessary ruder angle to maintain the ship course are calculated with assumption that the ship moving in steady state condition. The steady state condition will achieve when the resultant of forces and moment induced by the wind and wave is the same as zero. Therefore the steady state condition for the three degree of freedom equation in equation (1) can be written as follows:

$$\begin{aligned} X_H + X_P + X_R + X_A + X_W &= 0 \\ Y_H + Y_P + Y_R + Y_A + Y_W &= 0 \\ N_H + N_P + N_R + N_A + N_W &= 0 \end{aligned} \tag{11}$$

When this condition achieves the ship will move with constant speed, drift angle and the heading angle. The constant heading angle means that the rudder angle becomes constant.

3. METHODOLOGY

The above mentioned mathematic models are used to analysis maneuvering performance of an Indonesian ro-ro ferry under combined action of wind and wave. In order to analyze the effect of combined wind and wave on maneuvering performance of ship, some simulation with different wind speed and wave characteristic. The fluctuation of wind is not considered in this paper. The wave is assumed to be reguler wave characterized by the wave height and its stipness. The wind direction was assumed to be the same as the wave direction. This direction ranges from 0.0 degree to 180.0 degrees with step of 5.0 degrees. The wind direction of 0.0 degree means the wind and wave come from ship forepeak (head wind and wave) and 180.0 degrees means the wind and wave come from after peak (following wind and wave). The wind and wave direction is defined to be fixed to the global coordinate system shown in Figure 1.

The principle dimension, rudder dimension and propulsion characteristics of the subject ship are shown in Table 1 and Table 2 respectively.

Table 1. Principle 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
Prismatic coefficient (C_P)	0.804
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. Propulsion and rudder dimensions

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
Rudder coefficient (f_Λ)	2.10
Transverse rudder position (y_R)	±2.55 m
Long. Rudder position (x_R)	15.75 m

The wind direction relative to the ship will change when ship direction or the heading is change. The wind and wave direction relative to the ship due to alteration of the ship heading angle is defined as shown in Figure 2.

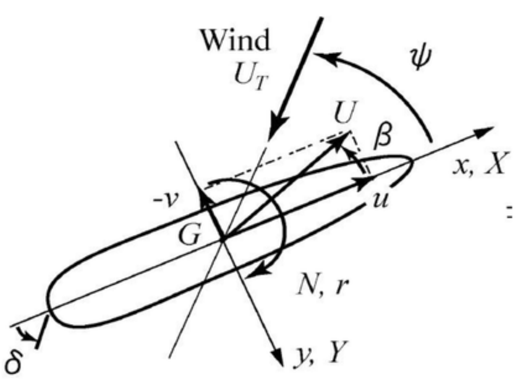

Figure 2. Definition of the wind direction relative to the ship due to alteration of heading angle

The wave characteristic using in simulation is determined based on the wave steepness of 0.005, 0.01, 0.02 and 0.03 with the wave height of 0.50 meters, 1.0 meters, 2.0 meters and 3.0 meters. These mean that the wave length was keep to be constant of 100.0 meters. The wind velocity ranges from 1 m/s up to 20 m/s with increasing of 5 m/s. In order to investigate the effect of wind independently, the numerical simulation is performed for different wind velocity with constant wave steepness. The same procedure is conducted in order to analysis the effect of wave independently. Here, the numerical simulation is performed for constant wind velocity with different wave steepness. The wave frequency in each numerical simulation follows the relationship between the wave number and the wave frequency for linear wave.

The added mass in sway direction is assumed to be dependent of the sectional area for each section. It was determined to be 10 percents of the sectional area of the considered section. The ship length between perpendiculars was divided into 20 sections. Increasing the number of section, the accuracy of estimated added mass in sway direction and forces and moment induced by the wave increases. However, it will be time consuming. Dividing to be 20 sections may be enough in analysis effect of wind and wave point of view.

The solution of the steady state condition shown in the equation (11) consists of the ship speed, the drift angle and the rudder angle is obtained by using numerical iteration of Newton-Rhapson method. The maximum rudder angle is set to be 35.0 degrees as the maximum possible rudder angle for real ships. When the rudder angle is larger than 35.0 degrees the solution is defined that the ship cannot be controlled by the rudder.

4. NUMERICAL RESULTS AND DISCUSION

The first numerical simulation has been conducted is for constant wave height with five different wind velocity. Here the effect of wind velocity on the maneuvering performance with certain wave height is investigated. The results of numerical simulation are shown in Figure 3 for the drift angle, Figure 4 for the rudder angle and Figure 5 for the ship speed.

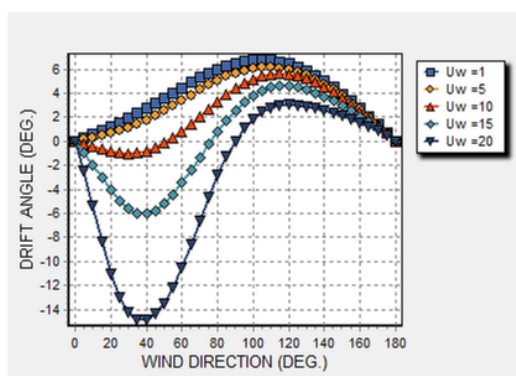

Figure 2. Drift angle for different wind velocity with wave height of 1.0 meter

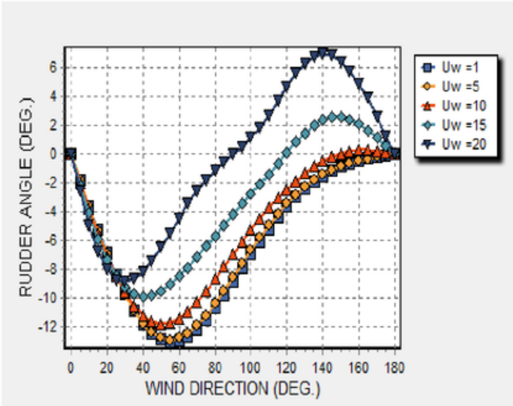

Figure 4. The rudder angle for several wind velocities with wave height of 1.0 meter

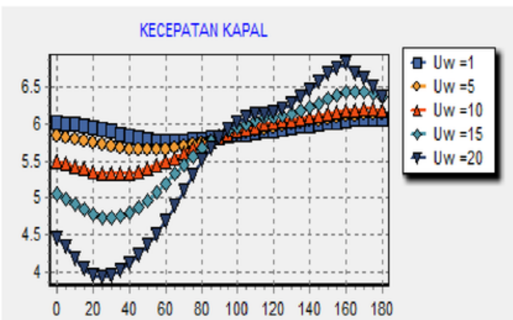

Figure 5. Ship speed for several wind velocities with wave height of 1.0 meter

In cases of wind velocity is smaller than 10.0 m/s, the ship drift to starboard for all wind and wave direction. The wind and wave come from the portside. When the wind velocity is larger than 10.0 m/s direction of ship drift changes from portside to starboard in the wind and wave direction of 50.0 degrees for wind velocity of 10.0 m/s, 70.0 degrees for the wind velocity of 15.0 m/s and 90.0 degrees if the wind velocity of 20.0 m/s. Paroka, et. al [7] investigated effect of wind without wave for the same ship subject. They show that the ship drift to the starboard for all wind direction with maximum drift angle occurs in the wind direction of 60.0 degrees. This facts show that in case of low wind velocity, the drift motion dominantly affected by the wave. Therefore the ship drift to the starboard in all wind direction. When the wind velocity increases, the effect of wind gradually increases especially for the wind direction smaller than 10.0 m/s. However, the wind effect can be neglected in cases of following wind. It can be concluded that the wind effect on drift motion become significant in head wind condition but in case of following wind, the drift motion is dominantly affected by the wave.

The necessary rudder angle in order to maintain the ship course increases due to increase of the wind velocity except in cases of wind and wave direction smaller than 20.0 degrees. In this range of wind direction, the wind velocity has no significant effect on the rudder angle. The necessary rudder angle increases due to increase the wind velocity for the wind direction larger than 20.0 degrees. However, the increasing of rudder angle becomes small for high wind velocity especially when the wing velocity is higher than 15.0 m/s. As the same as the drift motion, the rudder angle to portside when the wind direction is smaller than 80.0 degrees for wind velocity of 1.0 m/s and the wind direction of 120.0 for wind velocity of 5 m/s. If the wind direction is larger than 80.0 degrees for wind velocity of 1.0 m/s, the rudder angle should be to the starboard side in order to maintain the ship course. For the wind velocity of 5.0 m/s, it will occur when the wind direction is larger than 120.0 degrees. In cases of higher wind velocity, the rudder angle will be to the portside in all wind direction. It has been notified in the previous research [7] that the necessary rudder angle to maintain the ship course under action of wind without wave tends to the portside for all wind direction. This means that the combined wind and wave has significant effect on the necessary rudder angle when the wind and wave direction is 120.0 degrees on mostly in cases of head wind and wave. This fact coincides with the effect of combined wind and wave to the drift motion of the ship.

The ship speed tends to decreases due to increase of the wind velocity when the wind direction is smaller than 80.0 degrees. The ship speed is larger than the normal speed when the wind direction is larger than 80.0 degrees. The minimum ship speed occurs in the wind direction of 25.0 degrees for the wind velocity of 20.0 m/s. The significant decreasing of the ship speed occurs due to wind and wave forces acting on ship hull. As results, the drift motion increase and the ship speed becomes slower. For the following wind and wave, the alteration of ship speed is smaller compared with the head wind and wave cases. The thrust coefficient of propeller decreases due to increasing the ship speed. The wind and wave forces induced thrust force to increases the ship speed. At the same time the coefficient of propeller thrust decreases so that the ship speed does not significantly increases. This means that there is loss of engine power when the ship sails in the following wind and wave. Oppositely, the propeller torque increases due to decrease of the ship speed. As a result, the fuel consumption tends to be increases in case of head wind and wave.

Figure 6 shows the drift angle for five different wind velocities with wave height of 2.0 meters. The ship drift to the portside when the wind direction smaller than 80.0 degrees does not significantly change due to increases of the wave height from 1.0 meter to be 2.0 meters. However the drift angle increases due to increase of the wave height if wind direction is larger than 80.0 degrees. The maximum drift angle for wave height of 2.0 meters is larger than that of the wave height of 1.0 meter when the wind direction is larger than 80.0 degrees. This fact shows the drift angle significantly affected by the wave when the wind and wave direction is larger than 80.0 degrees.

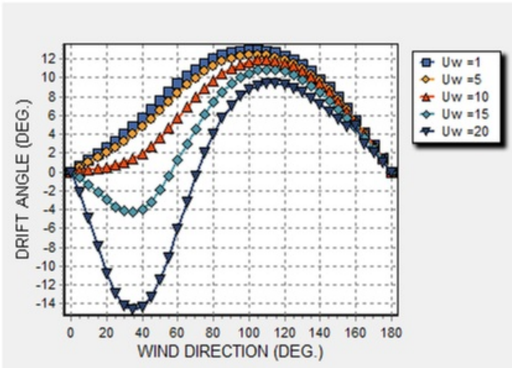

Figure 6. Drift angle for five different wind velocities for the wave height of 2.0 meters.

The necessary rudder angle in order to maintain the ship course is not affected by the wind velocity when the wind direction is smaller than 20.0 degrees as shown in Figure 7. However, the necessary rudder angle increases due to increase the wave height in this range of wind direction. This means that the wave height dominantly affect the rudder angle compared with the wind velocity. The necessary rudder angle for wave height of 2.0 meters is smaller than that of the wave height of 1.0 meter in the wind direction larger than 90.0 degrees. This is because the drift motion increases due to increase of the wave height. As results the necessary rudder angle decreases. Even the necessary rudder angle decreases if the wave height increase, the ship may be in dangerous condition in cases of following wind and waves. The ship speed may significantly increase and the same as the wave celerity or surf-riding condition.

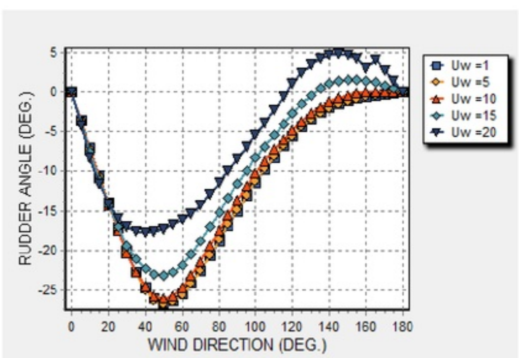

Figure 7. The necessary rudder angle for several wind velocity, here the wave height is 2.0 meters

The ship speed for several wind velocity for wave height of 2.0 meters are shown in Figure 8. The ship speed does not significantly change due to increase of the wave height from 1.0 meter to 2.0 meters in all wind and wave directions. This results show that effect of wind velocity on the ship speed is more significant compared with wave effect. The wave may increase the ship speed especially in following seas but at the same time the propeller thrust decreases due to increase the ship speed. When the ship operating in the head sea, the ship speed reduces due to wave force and resistance induced by the wave. Therefore there is little difference of ship speed between the wave height of 1.0 meter and 2.0 meters when the wind and wave direction is smaller than 70.0 degrees.

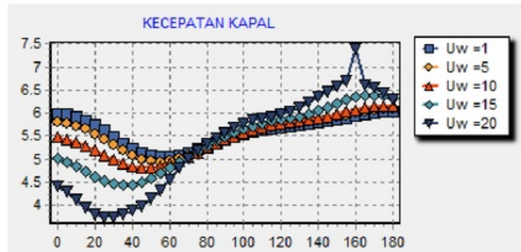

Figure 8. Ship speed for several wind velocity with wave height of 2.0 meters.

For more detail analysis of combined wind and wave effect on ship maneuverability, numerical simulations for wind velocity of 15.0 m/s and the wave height of 0.50 meters, 1.0 meter, 2.0 meters and 3.0 meters are conducted with results shown in Figure 9 for the drift angle, Figure 10 for the necessary rudder angle and Figure 11 for the ship speed.

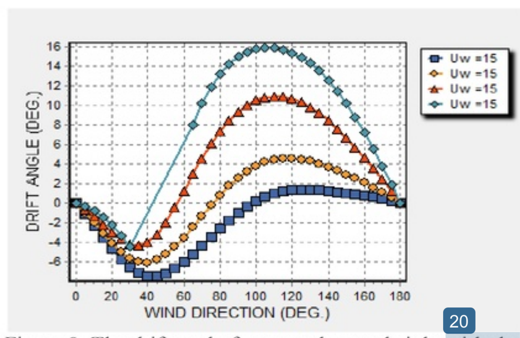

Figure 9. The drift angle for several wave height with the wind velocity of 15.0 m/s

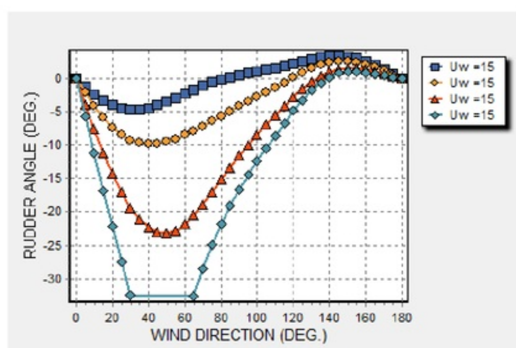

Figure 10. The rudder angle for several wave height with wind velocity of 15.0 m/s

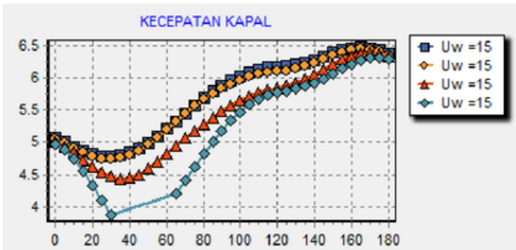

Figure 11. The ship speed for several wave height with wind velocity of 15.0 m/s

The effect of wave height on the drift motion is significant for the wind and wave direction of 40.0 degrees or larger. For the wind direction smaller than 40.0 degrees, the drift angle does not significantly change due to increase of the wave height. This result coincides with the result obtained from the simulation with constant wave height for several wind velocity. The drift angle does not change significantly due to increase of the wind velocity when the wind direction is larger than 40.0 degrees. A significant increasing of the drift angle due to increase of the wind velocity occurs when the wind direction is smaller than 40.0 degrees. Both results of the drift angle for variation of wind velocity with constant wave height and variation of wave height with constant wind velocity shows that the wind velocity has significant effect on the drift motion when the wind direction is smaller than 40.0 degrees. The significant effect of wave occurs if the wind direction is larger than 40.0 degrees.

The necessary rudder angle to maintain the ship course significantly increases when the wave height increases if the wind and wave direction is smaller than 140.0 degrees. When the wind and wave direction is larger than 140.0 degrees, the necesary rudder angle tends to be constant due to increase of the wave height for the same wind and wave direction. This means that the the wave hegiht has no significant effect on the necessary rudder angle in cases of wave direction is larger than 140.0 degrees.

Figure 11 shows that the effect of wave height on ship speed becomes significant onle when the wind and wave direction ranges from 20.0 degrees up to 100.0 degrees. For small wave height the ship speed tends to be constan due to increase the wave height for the same wind and wave direction in all possible wind and wave direction. Significant reduction of the ship speed due to increase of the wave height occur in the range of wave height from 1.0 meter up to 3.0 meters. Comparison between the ship speed for different wind velocity with the same wave height shown in Figure 5 and Figure 8 with the ship speed for different wave height with the same wind velocity shown in Figure 11 shows that the wind velocity has more significant effect on the alteration of the ship speed than the wave height. Figure 11 also show that the significant effect of the wave height on the ship speed occurs only for wind direction smaller than 140.0 degrees or in cases of head and beam wind and waves.

5. CONCLUSIONS

Effect of combined wind and wave on maneuvering performance of an Indonesian Ro-ro ferry has been investigated for several different wind velocity and wave height with the direction of wind and wave from 0.0 degrees (head wind and wave) up to 180.0 degrees (following wind and wave). Based on the results of numerical simulation and discussion, some conclusion can be remarked as follows:

1. Effect of wind velocity on the drift motion becomes significant when the wind and wave direction is smaller than 80.0 degrees. In cases of wind and wave direction is larger than 80.0 degrees, the wind velocity effect tends to be decrease and the wave effect increase to be become dominant in the wind direction of 100 degrees or larger.
2. The necessary rudder angle in order to maintain the ship course is significantly affected by the wind velocity when the wind and wave direction is larger than 20.0 degrees. The wave effect on the necessary rudder angle occurs in the wind direction smaller than 100.0 degrees.
3. The yaw motion or ship cource may become unstable in case of high wind velocity and large wave height. The ship cannot be controlled by the rudder because the necessary rudder angle become larger than the maximum possible rudder angle for real ship. Therefore, the course stability is important to analyze in case of heavy weather.
4. The wind velocity has more significant effect on the alteration of ship speed compared with the wave height. The effect of wave arises when the wave height is larger than 1.0 meter. The maximum effect of wave height occurs in the wind and wave direction ranges from 20.0 degrees up to 100.0 degrees, mostly in beam wind and wave condition.

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