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CONFIGURATION DESIGN OF TWIN RUDDER SYSTEM ON COURSE-KEEPING ABILITY OF A FERRY UNDER WIND CONDITION

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ABSTRACT

Ship course-keeping play an important role in navigation safety, particularly when ship operating under wind condition. To achieve this demand, a method of ship controlling movements through the rudder system configuration is very necessary. This paper describes the configuration design of twin rudder system on ship couse-keeping ability under wind condition. Time domain simulation program was developed for this propose. Proportional Integral Derivative (PID) controller is used to adjust the heading angle of ship according to the desired path. Several parameters such wind velocity relative and directions have been taken into account in the simulation, The results show that at wind direction of 88^0 the speed of ship course-keeping decreases with increasing wind velocity causes a large deviation of ship heading angle. Meanwhile, speed of ship course-keeping increase with increasing wind speed direction of 219^0. Ship course-keeping time with around 219^0 under wind direction of the simulation was a 11.68% lower than the sea trial.

*Keywords***:** Twin rudder; Course-keeping; Ship tracking; Simulation

1. INTRODUCTION

Course-keeping quality is most important in ship navigations due to not only save the time but also save the fuel consumption. To achieve the quality of ship course-keeping and generate accurate heading angles, one should have a controller which takes into account of ship hydrodynamics, both internal and external disturbances parameters. Ferry course keeping ability is different from that of sea-going ships due to navigation environment and ship particulars. The complexity of the navigation environment especially the influence of wind load force and moment, ferry with large superstructure are commonly more susceptible to marine accidents. Many studies relate to wind influence on ship maneuvering, the load force and moment of wind significantly affected by transversal and lateral projections of the windage area due to large superstructure of ship as well as wind velocity and wind direction relative to ship (Fujiwara and Ueno, 2006).

Molland et al. (2011) explained that effect of winds on ship maneuvering. He observed that changes of ship speed and direction caused by the wind was highly dependent on load of wind blowing, when wind direction from the bow of ship (0^0) then speed of ship tends decrease but vice versa when the wind direction from the stern (180^0). Whereas when the wind blowing from side ship tend to change its direction. The direction deviation of ship caused by wind are different for each type of ship and the steering response required. Othsu et al. (1996) reported the wind blowing from starboard bow quarters (45^0), ship steering becomes less sensitive, but more sensitive when wind from the port stern quarters (135^0). It is important to increase speed to change the direction of wind. This behavior information is very important to improve regarding ship course-keeping quality, especially ships take appropriate action in handling due to wind disturbances.

Many efforts to improve ship maneuvering have been carried out through the use of twin rudder ship controller. Yoshimura and Sakurai (1989) investigated that effect of a ship fitted twin-rudder twin-propeller on ship maneuvering. They found that hydrodynamic characteristics of a twin-rudder twin-propeller are not so much different from those of a single-propeller single-rudder ship. Khanfir et al. (2008) proposed a method for predicting mathematical model coefficient on ship maneuver fitted with a twin-propeller twin-rudder. Furthermore, They (Khanfir et al., 2011) conducted captive model tests as well as free-running tests with a single-propeller twin-rudder and a twin-propeller twin-rudder ship to evaluate the effect of drift angle on the rudder forces and some peculiar phenomena concerning rudder normal force for twin-rudder ships.

Other parameter that also affects on ship maneuver performance are from distance spacing between single rudder in twin-rudder ship (Gim, 2013, Liu, 2015 and Chen, 2018). Gim (2013) carried out a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5 - 1.0 chord length of rudder. It was found that this spacing distance between rudders in twin-rudder configurations is also affected by the interaction between the rudders and critical distance should be less than 1.0 chord length of rudder in order to decrease turbulence flow and vortices. This result is similar to the findings of Liu et al (2015) and Chen et al (2018) by using numerical simulation, confirming the excellent characteristics of twin-rudder ship compared with those of single-rudder ship. Chen et al (2018) concluded that a ship fitted with twin-rudder will operate very well at 15^0 of rudder angles. Additionally, the effectiveness of the stopping performance of the twin rudders at the lateral spacing equals to 1.3 chord length of rudder.

Based on the aforementioned studies, a design configuration of rudder system is most important features in achieving ship controlability goals. The rudder system must alter the ship control to the desired heading angle, both due to ship internal and external disturbances parameters. This paper focuses on applying the twin rudder concept to course-keeping ability of ferry under wind condition. By simulating the configuration of rudder system, course-keeping ability of the ferry expected to be improved.

2. METHODOLOGY

2.1 Mathematical Model

Ship maneuvering analysis using computer simulation utilizing modular mathematical models including hydrodynamic derivative is considered. The models was based on the equations of surge, sway and yaw motion (Equation 1), using the coordinate system shown in Figure 1.

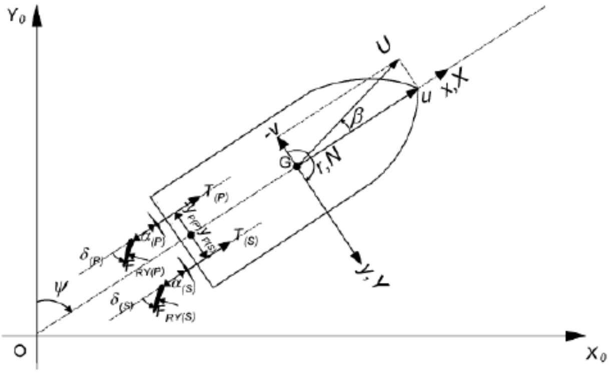

Figure 1. Coordinate system of ship

$$
\begin{aligned}
m(\dot{u}-rv) &= X_H + X_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + X_{R\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + X_W \\
m(\dot{v}-ru) &= Y_H + Y_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + Y_{R\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + Y_W \\
I_{ZZ}\ddot{\psi} &= N_H + N_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + N_{R\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + N_W
\end{aligned}
\tag{1}
$$

The notations of u, v and r are velocity components at ship's centre of gravity (G). m and I_{ZZ} represents the mass of ship and moments of inertia. X, Y, and N represent the hydrodynamic forces and moment. The subscript H, P, R and W refer to hull, propeller, rudder and wind respectively. Force and moment induced by hull (X_H, Y_H, and N_H) in principle is an approximation of polynomial function of β and r^t. The equations can be expressed by Yoshimura (2001) in Equation 3.

$$
\begin{aligned}
X_H &= \tfrac{1}{2}\rho L d U^2 (X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr} r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\
Y_H &= \tfrac{1}{2}\rho L d U^2 (Y'_\beta \beta + (Y'_r - m'_x) r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr} r'^3) \\
N_H &= \tfrac{1}{2}\rho L^2 d U^2 (N'_\beta \beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr} r'^3)
\end{aligned}
\tag{3}
$$

where: β is the drif angle at midship position by $\tan^{-1}(v/u)$ and r^t non-dimensionalized yaw rate by rL/U. X^t_0, $X^t_{\beta\beta}$, $X^t_{\beta r}$, X^t_{rr}, $X^t_{\beta\beta\beta\beta}$, Y^t_β, Y^t_r, $Y^t_{\beta\beta\beta}$, $Y^t_{\beta\beta r}$, $Y^t_{\beta rr}$, Y^t_{rrr}, N^t_β, N^t_r, $N^t_{\beta\beta\beta}$, $N^t_{\beta\beta r}$, $N^t_{\beta rr}$ and N^t_{rrr} are called the hydodynamic derivatives on ship maneuvering. Force and moment equations induced by twin propeller (X_P, Y_P, and N_P) can be expressed by Khanfir (2011) in Equation 4:

$$
\begin{aligned}
X_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} &= \rho\left((1-t_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}) n_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}^{2} D_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}^{4} K_{T\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}\left(J_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} \right)\right) \\
Y_P &= 0 \\
N_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} &= y_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} X_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}
\end{aligned}
\tag{4}
$$

where:

$$
\begin{aligned}
K_{T\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}(J_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}) &= C_1 + C_2 J_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + C_3 J_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}^{2} \\
J_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} &= (u - y_P r(1 - w_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}) / (n_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} D_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}})
\end{aligned}
$$

Where t_P is the thrust deduction coefficient in straight forward moving; K_T is the thrust coefficient of propeller force; n_P is the propeller revolution; D_P is the propeller diameter; w_P is the effective wake fraction coefficient at propeller location; J_P is the advance coefficient; C_1, C_2 and C_3 are the constants for open water propeller, respectively. The subscript S and P refer to starboard and portside

Force and moment coefficients on rudder area (X_R Y_R and N_R) can be expressed by Lee et al (1988 and 2003) model as shown in Equation 5:

$$\begin{aligned} X_{R\begin{Bmatrix}S\\P\end{Bmatrix}} &= -(1-t_{R\begin{Bmatrix}S\\P\end{Bmatrix}})F_{RY\begin{Bmatrix}S\\P\end{Bmatrix}}\sin\delta_{\begin{Bmatrix}S\\P\end{Bmatrix}} \\ Y_{R\begin{Bmatrix}S\\P\end{Bmatrix}} &= -(1+a_H)F_{RY\begin{Bmatrix}S\\P\end{Bmatrix}}\cos\delta_{\begin{Bmatrix}S\\P\end{Bmatrix}} \\ N_R &= -(x_R + a_H x_H)F_{RY\begin{Bmatrix}S\\P\end{Bmatrix}}\cos\delta_{\begin{Bmatrix}S\\P\end{Bmatrix}} + y_{P\begin{Bmatrix}S\\P\end{Bmatrix}}(1-t_{R\begin{Bmatrix}S\\P\end{Bmatrix}})F_{RY\begin{Bmatrix}S\\P\end{Bmatrix}}\sin\delta_{\begin{Bmatrix}S\\P\end{Bmatrix}} \end{aligned} \tag{5}$$

Where δ is the rudder angle; x_R and z_R are the representations of rudder location and t_R, a_H and x_H are the interactive force coefficients among hull, propeller and rudder, as the functions of the advance constant of the propeller. The rudder normal (F_{RY}) acting on the rudder stock can be expressed by Equation 6:

$$F_{RY\begin{Bmatrix}S\\P\end{Bmatrix}} = \tfrac{1}{2}\rho A_R U_{R\begin{Bmatrix}S\\P\end{Bmatrix}}^{2} f_\alpha \sin\alpha_{R\begin{Bmatrix}S\\P\end{Bmatrix}} \tag{6}$$

where A_R is the rudder area; f_α is the gradient of the lift coefficient of rudder and it can be approximated by the function of the rudder aspect ratio (f_α =6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 7,

$$\begin{aligned} U_{R\begin{Bmatrix}S\\P\end{Bmatrix}} &= \sqrt{u_{R\begin{Bmatrix}S\\P\end{Bmatrix}}^{2} + v_{R\begin{Bmatrix}S\\P\end{Bmatrix}}^{2}} \\ \alpha_{R\begin{Bmatrix}S\\P\end{Bmatrix}} &= \delta_{\begin{Bmatrix}S\\P\end{Bmatrix}} - \delta_{R\begin{Bmatrix}S\\P\end{Bmatrix}}\left(\beta_{R\begin{Bmatrix}S\\P\end{Bmatrix}}\right) \end{aligned} \tag{7}$$

The effective inflow velocity (u_R) to the rudder in surge direction can be expressed by Equation 8,

$$\begin{aligned} u_{R\begin{Bmatrix}S\\P\end{Bmatrix}} &= \varepsilon_{\begin{Bmatrix}S\\P\end{Bmatrix}} u_{P\begin{Bmatrix}S\\P\end{Bmatrix}} \\ &\times \sqrt{\eta_{P\begin{Bmatrix}S\\P\end{Bmatrix}}\left\{1+\kappa\left(\sqrt{1+\frac{8K_{T\begin{Bmatrix}S\\P\end{Bmatrix}}}{\pi J_{P\begin{Bmatrix}S\\P\end{Bmatrix}}^{2}}}-1\right)\right\}^{2} + (1-\eta_{P\begin{Bmatrix}S\\P\end{Bmatrix}})} \end{aligned} \tag{8}$$

Where:

$$\varepsilon_{\begin{Bmatrix}S\\P\end{Bmatrix}} = \frac{1-w_{R\begin{Bmatrix}S\\P\end{Bmatrix}}}{1-w_{P\begin{Bmatrix}S\\P\end{Bmatrix}}};\ \kappa = \frac{kx}{\varepsilon_{\begin{Bmatrix}S\\P\end{Bmatrix}}};\ \eta_{P\begin{Bmatrix}S\\P\end{Bmatrix}} = \frac{D_{P\begin{Bmatrix}S\\P\end{Bmatrix}}}{H_{R\begin{Bmatrix}S\\P\end{Bmatrix}}};\ u_{P\begin{Bmatrix}S\\P\end{Bmatrix}} = \left(1-w_{P\begin{Bmatrix}S\\P\end{Bmatrix}}\right)\left(u - y_{P\begin{Bmatrix}S\\P\end{Bmatrix}} r\right)$$

where ε, κ, γ_R and l_R are the parameters, describing the rudder inflow velocity angle, respectively; ($1-w$) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H) is the ratio of propeller diameter to rudder height.

The effective inflow velocity (v_R) to the rudder in sway direction can be expressed by Equation 9,

$$v_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}} = u_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}} \tan\left(\delta_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}}\right) \qquad (9)$$

Where:

$$\delta_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}} = \gamma_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}} \beta_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}} + \tan^{-1}\left(\frac{y_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}}}{x_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}}}\right)$$

$$\beta_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}} = \beta - L'_{R_{\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}} r'$$

where δ_R, κ, γ_R and l_R are the parameters, describing the rudder inflow velocity angle, respectively; ($1\text{-}w$) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H) is the ratio of propeller diameter to rudder height.

For the case of a ship operated under wind condition, force and moment (X_W, Y_W and N_W) acting on ship were expressed by Equation 10 (Fujiwara and Ueno, 2006):

$$\begin{aligned} X_W &= C_{AX}(\psi_A) q_A A_F \\ Y_W &= C_{AX}(\psi_A) q_A A_L \\ N_W &= C_{AN}(\psi_A) q_A A_L L_{OA} \end{aligned} \qquad (10)$$

Where, C_{AX}, C_{AY} and C_{AN} are the wind load forces and moments coefficients respectively as a function of the wind direction relative to ship (ψ_A). q_A is wind pressure; A_F and A_L indicate transversal and lateral projections of the windage area respectively. Wind relative direction can be expressed by Equation 11:

$$\psi_A = \tan^{-1}\left[\frac{U_T \cos\psi + U\cos\beta}{U_T \sin\psi - U\cos\beta}\right] \qquad (11)$$

Where, U_T is wind velocity and ψ is angle of wind direction with reference of coordinate system. Wind pressure (q_A) can be calculated by Equation 12 (Fujiwara et al., 2006):

$$q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi + \beta) \qquad (12)$$

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

2.2.Ship Steering Autopilot

Rudder is most important features in achieving controlability goals. The control system must alter the control surfaces to the desired heading angle. The schematic equation of a PID control system of the ship tracking can be expressed by Equation 13:

$$\delta = K_p(e) + K_d(\dot{e}) + K_i \int_0^T e(t)dt$$
$$e = (\psi_T - \psi_P) \tag{13}$$

where: δ is designed rudder angle; K_p, K_d, and K_i are proporsional gain, derivative gain and integral gain respectively; e is an error between heading target (ψ_T) and actual heading angle (ψ_P).

Figure 1 (Fossen, 2002) shows a schematic of line-of-sight (LOS) concept, a series of ship course-keeping manoeuvres, in which the conventional LOS guidance scheme can be used to calculate the required reference heading. The method calculate an imaginary line stretching between ship and target showed. To reach this track-point, the ship must adjust its heading by a reference heading angle (ψ_{ref}). In accordance, course-keeping autopilot automatically selects the next track-point coordinates (x_{k+1}, y_{k+1}) along the reference path and resets the reference of heading angle accordingly. Fossen (2002) recommended the radius of the target zone (R_0) is specified approximately two ship length. The reference of heading angle equation and target zone corection in LOS method can be expressed by Equation 14 and 15.

$$\psi_{ref}(t) = \tan^{-1}\left(\frac{y_k - y(t)}{x_k - x(t)}\right) \tag{14}$$

and

$$(x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \tag{15}$$

where, x_k and y_k are the coordinates of the track-point; $x(t)$ and $y(t)$ are the coordinates position of ship; R_0 is the radius of target zone.

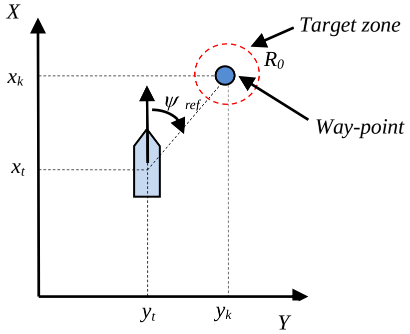

Figure 1 A schematic of the LOS concept

2.3 Simulation Program

Figure 2 shows the basic structure of ship steering autopilot, developed in this research. According to IMO (2002) criteria of ship maneuverability, the prediction of ship course-keeping should be analyzed through the swept path. The swept path of ship can be obtained by double integrating the acceleration of the ship-motion mathematical model includes hydrodynamic derivatives. The equations of motion in this time domain simulation are then solved by numerical integration Dormand–Prince Method (Maimun et al., 2011 and Muhammad et al., 2015). The control method used in the simulation is a proportional integrated derivative (PID) controller. The designed rudder angle (δ=35 *deg.*) is calculated using Equation 9 with K_p=0.1; K_i =0.0001 and K_d =10 gains for *P*, *I* and *D* respectively. The conventional line-of-sight (LOS) guidance scheme used to calculate the required reference heading (Fossen, 2002). The resistance and propulsion parameters for simulation were predicted using Holtrop Method (Holtrop and Mennen, 1982 and Holtrop, 1984). The wind component parameter were predicted by Fujiwara et al. (2006). Hydrodynamic derivatives were predicted using the derived regression equation developed by Yoshimura and Masumoto (2012).

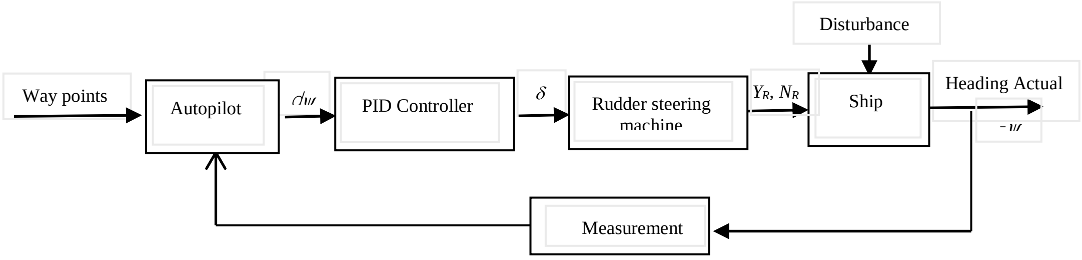

Figure 2 Basic structure of ship steering autopilot

2.4 Ship and Sea Trial Data

The object of the study is ferry ship of KMP Bontoharu (1053 Gross Tonnage), owned by PT. ASDP Indonesia Ferry with twin conventional propellers (FPP) and twin conventional rudders with the distance between rudder / propeller is 2.3 m, mounted behind the ship. Figure 3 shows the operating view of KMP Bontoharu on Bira Bulukumba harbor water way. The picture was taken on 20th, September 2015. The dimensions hull / superstructure and parameter propulsion / rudder of ship are presented in Tables 1 and Tables 2 respectively. The ship sea trial on Selayar - Bulukumba route (blue line), 15.385 nautical miles distance, 7268 second travelling time, around 6.03 m/s wind velocity and 254 deg wind direction, indicated by Figure 4.

Figure 3. The operating view of KMP Bontoharu on Bira Bulukumba harbor water way

Table 1. Dimension of ship hull and superstucture

Parameter	Value
Loa, m	54.00
Lbp,m	47.45
B, m	14
H, m	3.4
T,m	2.45
V, m/s²	6.618
Δ, Ton	1148

A_L, m^2	182.87
A_F, m^2	129.20
A_{OD}, m	218.23
C	-0.44
H_C, m	2.70
H_L, m	3.38
H_{BR}, m	10.48

Table 2 Parameter of ship propulsion and rudder.

Parameter	Value
Z	4
D, m	1.422
P, m	1.066
n	8.784
$Span, m$	1.550
$Chord, m$	0.900
A_R, m^2	1.395
BHP, HP	1000
RPM_{ME}	1850

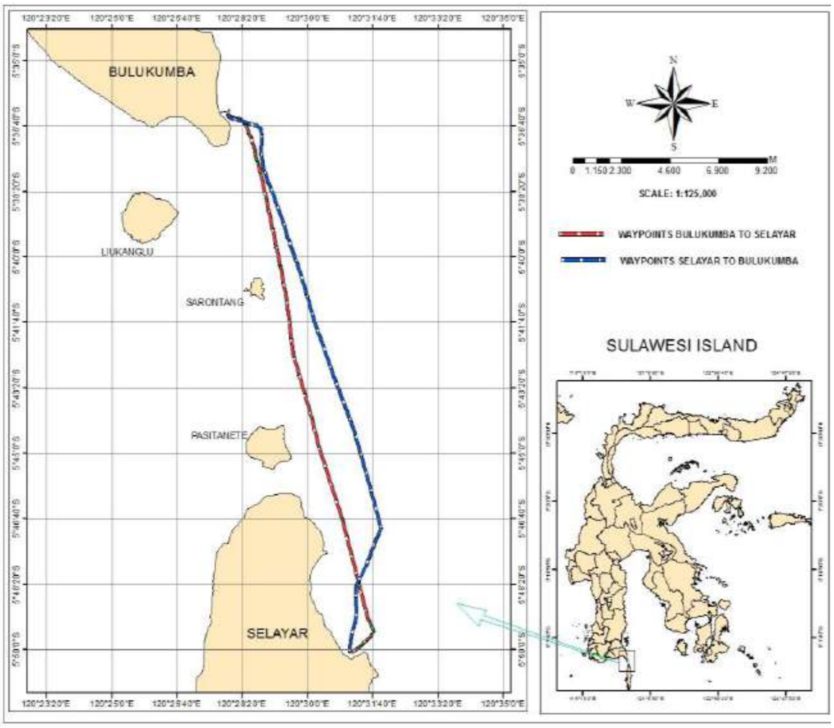

Figure 4 Selayar-Bulukumba route

3. RESULTS AND DISCUSSION

The monthly significant wind velocity and direction data were predicted by using ERA-Interim re-analysis data from European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years period from 2006-2018 at 6-hourly intervals shows in Figure 5. The data provides wind speed data with resolution of 0.25 x 0.25 degree. The peak wind speed trend show in January with maximum trend 10.06 m/s (88 deg.). Meanwhile, the trend of monthly mean wind speed in April has decreasing trends with minimum trend

6.41 m/s (219 deg.). The trends of monthly mean wind speed are varying depending on month during west monsoon or east monsoon seasons.

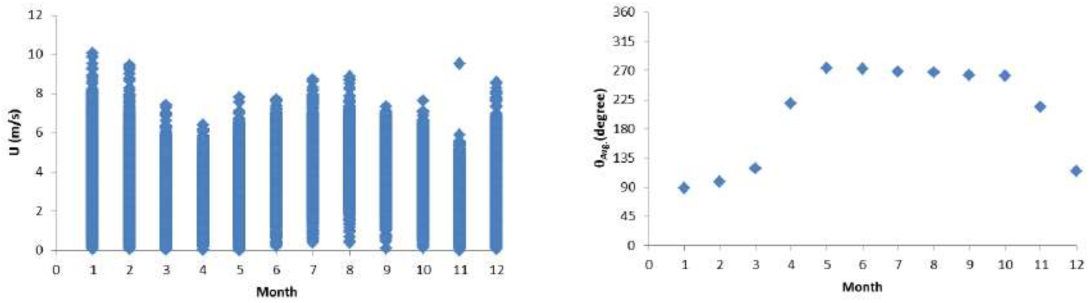

Figure 5 Significant wind velocity and direction in Selayar-Bulukumba route

Based on the wind data characteristics in figure 5, course keeping of a KMP Bontoharu have been simulated for three condition of wind direction parameter (i.e. starboard and portside athwart (88 deg. and 268 deg.) and stern (219 deg.). That information very important in ship navigation due to not only save the time but also save the fuel consumption by controlling a set twin rudder configuration design. Figure 6 shows the history result of simulation for track-keeping trajectory of a KMP Bontoharu (Selayar to Bulukumba) under wind velocities effect. The horizontal axe expresses time and vertical axe expresses heading angle (ψ), rudder angle (δ), speed ship (u) and rudder force (F_X) respectively. The winds blow from starboard athwart (ψ=88 deg) at wind velocities (U_T= 10.06 m/s) for initial ship speed (U) of 6.618 m/s. It was found that the track keeping trajectory leaving slow track deviation from initial track with low heading with big track keeping time compared without winds (U_T= 0 m/s). Meanwhile the ships track keeping trajectory with increased wind velocities caused more deviation and very low ship speed.

Figure 7 shows the history result of simulation for track-keeping trajectory of a KMP Bontoharu with winds blow from portside athwart (ψ=268 deg) at wind velocities (U_T= 6.41 m/s) for initial ship speed (U) of 6.618 m/s. Its characteristic almost similar when the winds blow from starboard athwart (ψ=88 deg). While when the wind blow from stern (ψ=219 deg) the ship speed increases with increasing wind speed as the simulation results shows in Figure 8. Corresponding time histories of rudder angles, heading angles and ship speed . It should be noted that time histories of heading angles have almost the same patterns, where as those of the rudder angles and speed ship are different in each case. This result is similar to the findings of Le at al. (2013) confirming the trend of ship track keeping trajectory under wind velocities condition.

Figure 6, 7 and 8 shows also the effects of winds speed and direction on ship speed track keeping trajectory time for initial ship speed (U) of 6.618 m/s . It was found that under wind blow from starboard athwart (ψ=88 deg) and portside athwart (ψ=268 deg) were a 7.31 % and 0.16 % ship speed reduces achived, meanwhile from stern the ship speed was relatively 2.75% increase ship speed. The latter is beneficial because track trajectory time was minimum. This trend is similar to the findings of Molland et al. (2011) and Othsu et al. (1996), supporting the beharviors of ship track keeping trajectory under winds direction.

Figure 9 shows the sea trial simulation results for track-keeping trajectory of ship with 6.03 m/s wind velocity and 254 deg wind direction at initial ship speed of 3.94 m/s. It was found that 6.418 second travelling time. The simulation travelling time is a 11.68% higher compared with the sea trial results. The possible reason is the simulation did not include wave. Table 3 indicates the summary of simulation and sea trial results of ship track-keeping trajectories.

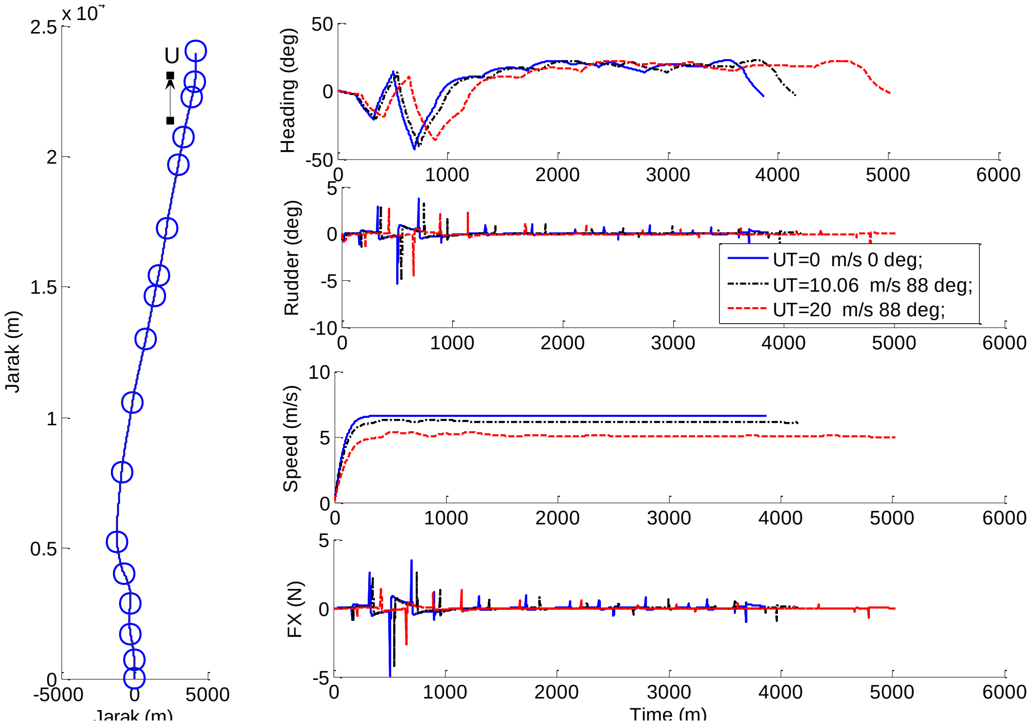

Figure 6 Ship trajectory with difference wind speed (U_T) at 88deg

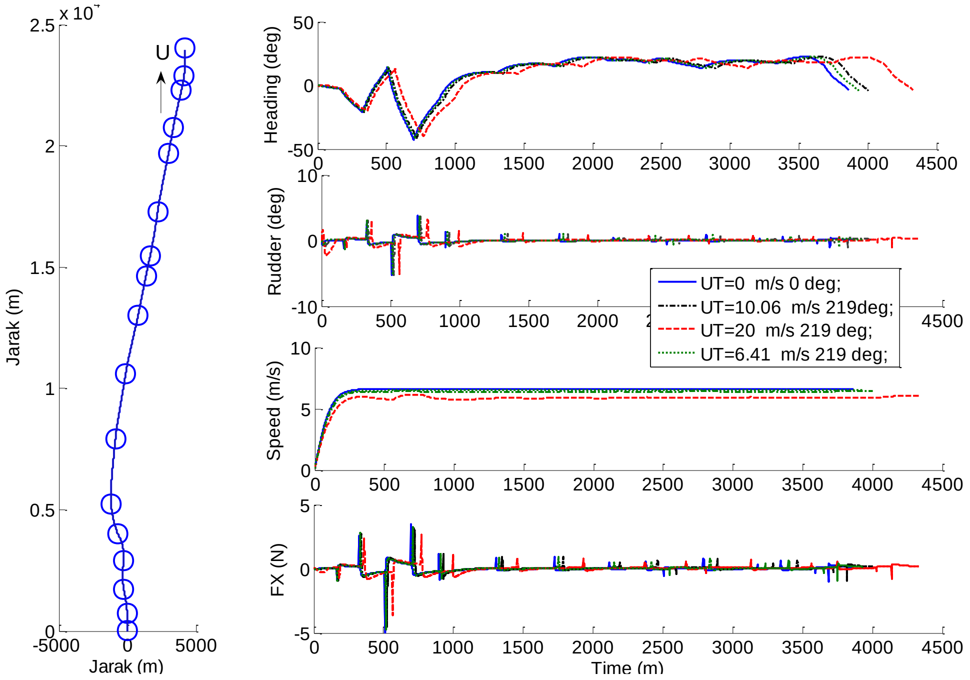

Figure 7 Ship trajectory with difference wind speed (U_T) at 219 deg

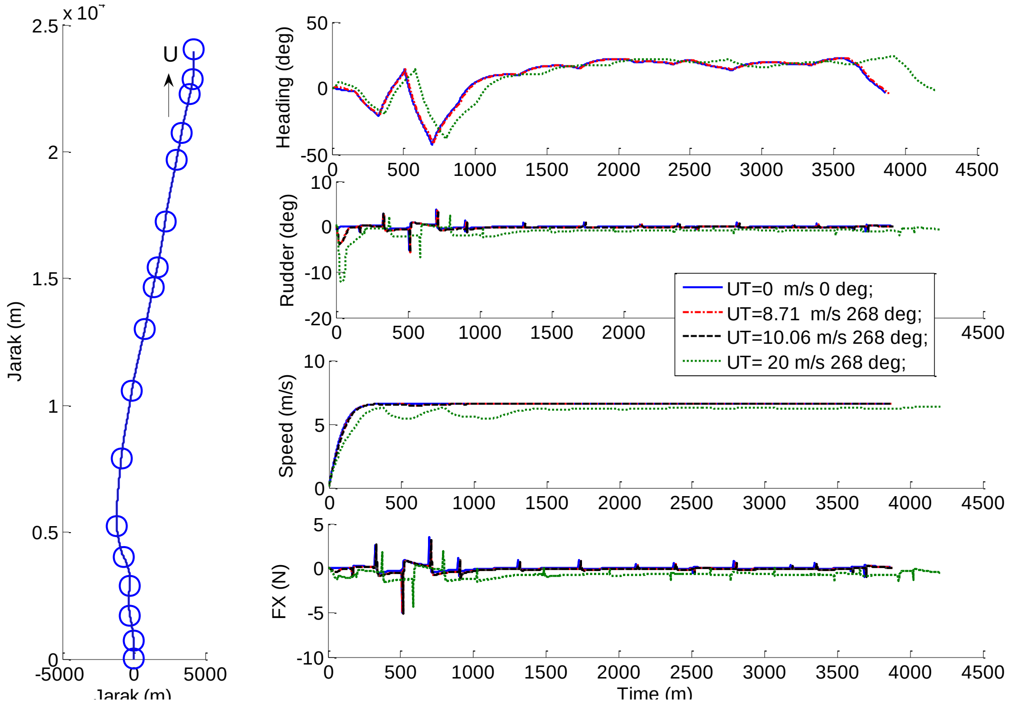

Figure 8 Ship trajectory with difference wind speed (U_T) at 268 deg

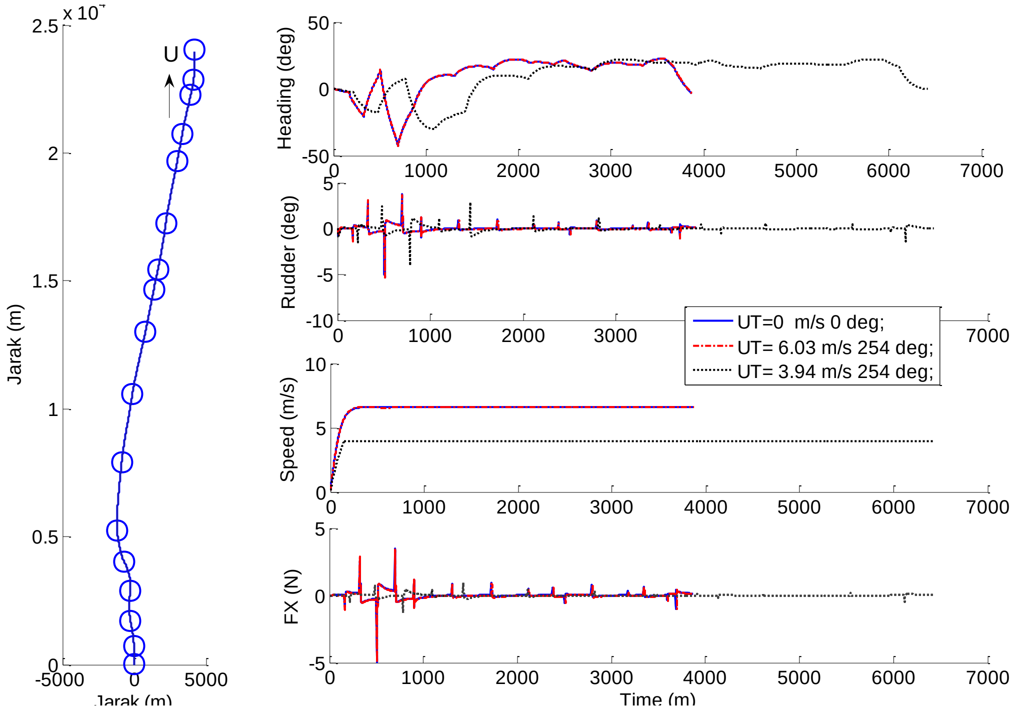

Figure 9 Simulation of ship trajectory at (U_T=6.03 m/s) at 254deg

Table 4. Simulation and sea trial result of ship- tracking trajectories

Routes	$\psi_{(deg)}$	U_T (m/s)	U (m/s)	δ (deg/s.)	Deg	Fx (N)	Track time (s)	
Selayar- Bulukumba	0	0	6.618	-42.76	-5.312	-4.939	3866	Fig. 6
Selayar- Bulukumba	88	10.06	6.134	-40.90	-5.270	-4.209	4158	Fig. 6
Selayar- Bulukumba	88	20	4.991	-35.37	-4.488	-2.655	5024	Fig. 6
Selayar- Bulukumba	219	6.41	6.526	-42.31	-5.299	-4.644	3932	Fig. 7
Selayar- Bulukumba	219	10.06	6.436	-41.96	-5.437	-4.723	4002	Fig. 7
Selayar- Bulukumba	219	20	6.031	-40.22	-5.157	-3.630	4332	Fig. 7
Selayar- Bulukumba	268	8,71	6.629	-42.14	-5.312	-5.085	3881	Fig. 8
Selayar- Bulukumba	268	10.06	6.629	-42.14	-5.312	-5.085	3881	Fig. 8
Selayar- Bulukumba	268	20	6.355	-38.61	-12.32	-4.208	4208	Fig. 8
Selayar- Bulukumba	254	6.03	6.636	-42.52	-4.335	-4.946	3872	Fig. 9
Selayar- Bulukumba	254	6.03	3.94	-28.94	-3.489	-1.319	6418	Fig. 9

4. CONCLUSION

A configuration design of twin rudder system on ship couse-keeping ability under winds speed and directions was analyzed through computer simulation of MATLAB-Simulink program. The object the reseach was ferry ship of KMP Bontoharu (1053 gross tonnage) by *PT. ASDP Indonesia Ferry*. The results indicated that the ship track keeping trajectory under increased wind velocities at 0 deg direction caused more deviation and very low ship speeds. When wind direction from starboard bow around 88 deg. high deviation and reduced ship speed obtained, while from port stern around 210 deg. results in small deviation and relatively constant ship speed. By simulating fluctuated wind velocity and direction, the quality of the ship course-keeping with accurate heading angles, increase in safety may be achieved.

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Configuration Design of Twin Rudder System on Course-Keeping Ability of A Ferry Ship Under Wind Condition

Abstract. Ship course-keeping plays an important role in navigation safety, particularly when ship operating under wind condition. To stabilize the ship's course, a method for controlling ship movements through the rudder system configuration is necessary. This paper describes the configuration design of twin rudder system on the ship course-keeping ability under wind condition. Time domain simulation program was developed for this purpose. Proportional Integral Derivative (PID) controller is used to adjust the heading angle of ship according to the desired path. Several parameters such as relative wind velocity and directions have been taken into account in the simulation, The result shows that at wind direction of 88 deg., the speed of the ship course-keeping decreases. However, the increasing wind velocity causes a large deviation of the ship heading angle. Meanwhile, speed of the ship course-keeping increase with the increasing wind speed direction of 219 deg. Ship course-keeping time with around 219 deg. under wind direction of the simulation was a 11.68% lower than the sea trial.

Keywords: Proportional integral derivative controller; Course-keeping; Ship tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigations due to not only save the time but also save the fuel consumption. To achieve the quality of ship course-keeping and generate accurate heading angles, a controller which takes into account of ship hydrodynamics, both internal and external disturbances parameters should be installed. Ferry ship course keeping ability is different from that of sea-going ships due to navigation environment and ship particulars. The complexity of the navigation environment especially the influence of wind load force and moment makes ferry ship with large superstructure are more susceptible to marine accidents. Many studies relate to wind influence on ship maneuvering, the load force and moment of wind have significantly affected by transversal and lateral projections of the windage area due to large superstructure of ship as well as wind velocity and wind direction relative to ship (Fujiwara and Ueno, 2006).

Molland et al. (2011) have explained the effect of winds on ship maneuvering. He observed that changes of the ship speed and direction caused by the wind was highly dependent on the load of wind blowing. When wind direction is coming from the bow of ship (0 deg.), then speed of ship tends to decrease but vice versa when the wind direction from the stern (180 deg.). Whereas when the wind blowing from the side of the ship, it tends to change its direction. The direction deviation of ship caused by wind are different for each type of ship and the steering response required. Ohtsu et al. (1996) reported that the wind blowing from starboard bow quarters (45 deg.) made the ship steering becomes less sensitive but more sensitive when the wind was coming from the port stern quarters (135 deg.). It is important to increase the ship speed to change due to different direction of the wind. This behaviour information is very important to improve ship course-keeping quality, especially when the ships need to take appropriate action in handling the wind disturbances.

Many efforts to improve ship maneuvering have been carried out through the use of twin rudder ship controller. Yoshimura and Sakurai (1989) investigated the effect of a ship fitted twin-rudder twin-propeller on ship maneuvering. They found that hydrodynamic characteristics of a twin-rudder twin-propeller are not so much different from those of a single-propeller single-rudder ship. Khanfir et al. (2008) proposed a method for predicting mathematical model coefficient on ship maneuver fitted with a twin-propeller twin-rudder. Furthermore, they (Khanfir et al., 2011) conducted captive model tests as well as free-running tests with a single-propeller twin-rudder and a twin-propeller twin-rudder ship to evaluate the effect of drift angle on the rudder forces and some peculiar phenomena concerning rudder normal force for twin-rudder ships.

Other parameter that also effects on ship maneuver performance are from distance spacing between single rudder in twin-rudder ship (Gim, 2013, Liu, 2015 and Chen, 2018). Gim (2013) carried out a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5 - 1.0 chord length of rudder. It was found that this spacing distance between rudders in twin-rudder configurations is also affected by the interaction between the rudders and the critical distance should be less than 1.0 chord length of rudder in order to decrease turbulence flow and vortices. This result is similar to the findings of Liu et al (2015) and Chen et al (2018) by using numerical simulation, confirming the excellent characteristics of twin-rudder ship compared with those of single-rudder ship. Chen et al (2018) concluded that a ship fitted with twin-rudder will operate very well at 15 deg. of rudder angles. Additionally, the effectiveness of the stopping performance of the twin rudders at the lateral spacing equals to 1.3 chord length of rudder.

Based on the aforementioned studies, a design configuration of rudder system is the most important features in achieving ship controllability goals. The rudder system must alter the ship control to the desired heading angle, both due to ship internal and external disturbances parameters. This paper focuses on applying the twin rudder concept to course-keeping ability of ferry ship under wind condition. By simulating the configuration of rudder system, course-keeping ability of the ferry ship is expected to be improved.

2. Methods

2.1. Mathematical Model

Ship maneuvering analysis using computer simulation utilizing modular mathematical models including considering hydrodynamic derivative. The models was based on the equations of surge, sway and yaw motion (Equation 1), using the coordinate system shown in Figure 1.

$$
\begin{aligned}
m(\dot{u}-rv) &= X_H + X_{P\begin{Bmatrix}S\\P\end{Bmatrix}} + X_{R\begin{Bmatrix}S\\P\end{Bmatrix}} + X_W \\
m(\dot{v}-ru) &= Y_H + Y_{P\begin{Bmatrix}S\\P\end{Bmatrix}} + Y_{R\begin{Bmatrix}S\\P\end{Bmatrix}} + Y_W \qquad (1) \\
I_{ZZ}\ddot{\psi} &= N_H + N_{P\begin{Bmatrix}S\\P\end{Bmatrix}} + N_{R\begin{Bmatrix}S\\P\end{Bmatrix}} + N_W
\end{aligned}
$$

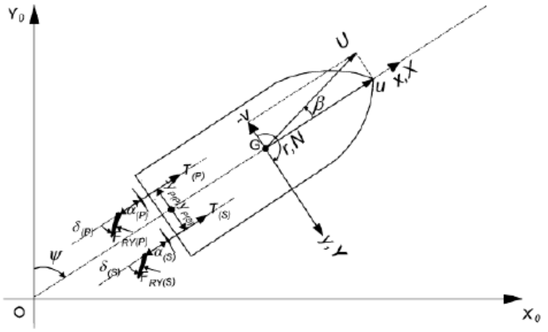

Figure 1 Coordinate system of ship

The notations of *u, v* and *r* are velocity components at ship's centre of gravity (*G*). *m* and I_{ZZ} represents the mass of ship and moments of inertia. *X, Y,* and *N* represent the hydrodynamic forces and moment. The subscript *H, P, R* and *W* refer to hull, propeller, rudder and wind respectively. Force and moment induced by hull (X_H, Y_H, and N_H) in principle is an approximation of polynomial function of β and r'. The equations be expressed by Yoshimura (2001) in Equation 2.

$$\begin{aligned}
X_H &= \tfrac{1}{2}\rho LdU^2(X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr}r'^2 + X'_{\beta\beta\beta\beta}\beta^4)\\
Y_H &= \tfrac{1}{2}\rho LdU^2(Y'_\beta\beta + (Y'_r - m'_x)r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr}r'^3)\\
N_H &= \tfrac{1}{2}\rho L^2dU^2(N'_\beta\beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr}r'^3)
\end{aligned} \qquad (2)$$

where: β is the drif angle at midship position by $\tan^{-1}(v/u)$ and r^t non-dimensionalized yaw rate by rL/U. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} are called the hydodynamic derivatives on ship maneuvering. Force and moment equations induced by twin propeller (X_P, Y_P, and N_P) can be expressed (Khanfir, 2011 and Dash, 2015) in Equation 3:

$$\begin{aligned}
X_{P\left\{\substack{S\\P}\right\}} &= \rho\left((1 - t_{P\left\{\substack{S\\P}\right\}})n_{P\left\{\substack{S\\P}\right\}}^{\;2} D_{P\left\{\substack{S\\P}\right\}}^{\;4} K_{T\left\{\substack{S\\P}\right\}}\left(J_{P\left\{\substack{S\\P}\right\}}\right)\right);\ Y_P = 0\\
N_{P\left\{\substack{S\\P}\right\}} &= y_{P\left\{\substack{S\\P}\right\}} X_{P\left\{\substack{S\\P}\right\}}
\end{aligned} \qquad (3)$$

where $K_{T\left\{\substack{S\\P}\right\}}(J_{P\left\{\substack{S\\P}\right\}}) = C_1 + C_2 J_{P\left\{\substack{S\\P}\right\}} + C_3 J_{P\left\{\substack{S\\P}\right\}}^{\;2}$ and $J_{P\left\{\substack{S\\P}\right\}} = (u - y_P r(1 - w_{P\left\{\substack{S\\P}\right\}}))/(n_{P\left\{\substack{S\\P}\right\}} D_{P\left\{\substack{S\\P}\right\}})$

Where t_P is the thrust deduction coefficient in straight forward moving; K_T is the thrust coefficient of propeller force; n_P is the propeller revolution; D_P is the propeller diameter; w_P is the effective wake fraction coefficient at propeller location; J_P is the advance coefficient; C_1, C_2 and C_3 are the constants for open water propeller, respectively. The subscript *S* and *P* refer to starboard and portside

Force and moment coefficients on rudder area (X_R Y_R and N_R) can be expressed in model as shown in Equation 4:

$$\begin{aligned}
X_{R\left\{\substack{S\\P}\right\}} &= -(1 - t_{R\left\{\substack{S\\P}\right\}})F_{RY\left\{\substack{S\\P}\right\}}\sin\delta_{\left\{\substack{S\\P}\right\}}\\
Y_{R\left\{\substack{S\\P}\right\}} &= -(1 + a_H)F_{RY\left\{\substack{S\\P}\right\}}\cos\delta_{\left\{\substack{S\\P}\right\}}\\
N_R &= -(x_R + a_H x_H)F_{RY\left\{\substack{S\\P}\right\}}\cos\delta_{\left\{\substack{S\\P}\right\}} + y_{P\left\{\substack{S\\P}\right\}}(1 - t_{R\left\{\substack{S\\P}\right\}})F_{RY\left\{\substack{S\\P}\right\}}\sin\delta_{\left\{\substack{S\\P}\right\}}
\end{aligned} \qquad (4)$$

Where δ is the rudder angle; x_R and z_R are the representations of rudder location and t_R, a_H and x_H are the interactive force coefficients among hull, propeller and rudder, as the functions of the advance constant of the propeller. The rudder normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

$$F_{RY\left\{\substack{S\\P}\right\}} = \tfrac{1}{2}\rho A_R U_{R\left\{\substack{S\\P}\right\}}^{\;2} f_\alpha \sin\alpha_{R\left\{\substack{S\\P}\right\}} \qquad (5)$$

where A_R is the rudder area; f_α is the gradient of the lift coefficient of rudder and it can be approximated by the function of the rudder aspect ratio (f_α =6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6,

$$U_{R\left\{\substack{S\\P}\right\}} = \sqrt{u_{R\left\{\substack{S\\P}\right\}}^{\;2} + v_{R\left\{\substack{S\\P}\right\}}^{\;2}} \quad \text{and} \quad \alpha_{R\left\{\substack{S\\P}\right\}} = \delta_{\left\{\substack{S\\P}\right\}} - \delta_{R\left\{\substack{S\\P}\right\}}\left(\beta_{R\left\{\substack{S\\P}\right\}}\right) \qquad (6)$$

The effective inflow velocity (u_R) to the rudder in surge direction can be expressed by Equation 7,

$$u_{R\left\{{S \atop P}\right\}} = \varepsilon_{\left\{{S \atop P}\right\}} u_{P\left\{{S \atop P}\right\}} \times \sqrt{\eta_{P\left\{{S \atop P}\right\}} \left\{1+\kappa\left(\sqrt{1+\frac{8K_{T\left\{{S \atop P}\right\}}}{\pi J_{P\left\{{S \atop P}\right\}}{}^{2}}}-1\right)\right\}^{2} + (1-\eta_{P\left\{{S \atop P}\right\}})} \tag{7}$$

Where: $\varepsilon_{\left\{{S \atop P}\right\}} = \dfrac{1-w_{R\left\{{S \atop P}\right\}}}{1-w_{P\left\{{S \atop P}\right\}}}$; $\kappa = \dfrac{kx}{\varepsilon_{\left\{{S \atop P}\right\}}}$; $\eta_{P\left\{{S \atop P}\right\}} = \dfrac{D_{P\left\{{S \atop P}\right\}}}{H_{R\left\{{S \atop P}\right\}}}$; $u_{P\left\{{S \atop P}\right\}} = \left(1-w_{P\left\{{S \atop P}\right\}}\right)\left(u-y_{P\left\{{S \atop P}\right\}} r\right)$

where ε, κ, γ_R and l_R are the parameters, describing the rudder inflow velocity angle, respectively; (1-w) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H) is the ratio of propeller diameter to rudder height.

The effective inflow velocity (v_R) to the rudder in sway direction can be expressed by Equation 8,

$$v_{R_{\left\{{S \atop P}\right\}}} = u_{R_{\left\{{S \atop P}\right\}}} \tan\left(\delta_{R_{\left\{{S \atop P}\right\}}}\right) \tag{8}$$

Where: $\delta_{R_{\left\{{S \atop P}\right\}}} = \gamma_{R_{\left\{{S \atop P}\right\}}} \beta_{R_{\left\{{S \atop P}\right\}}} + \tan^{-1}\left(y_{R_{\left\{{S \atop P}\right\}}} \big/ x_{R_{\left\{{S \atop P}\right\}}}\right)$ and $\beta_{R_{\left\{{S \atop P}\right\}}} = \beta - L'_{R_{\left\{{S \atop P}\right\}}} r$

where δ_R, κ, γ_R and l_R are the parameters, describing the rudder inflow velocity angle, respectively; (1-w) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H) is the ratio of propeller diameter to rudder height. For the case of a ship operated under wind condition, force and moment (X_W, Y_W and N_W) acting on ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A) q_A A_F; \quad Y_W = C_{AX}(\psi_A) q_A A_L; \quad N_W = C_{AN}(\psi_A) q_A A_L L_{OA} \tag{9}$$

Where, C_{AX}, C_{AY} and C_{AN} are the wind load forces and moments coefficients respectively as a function of the wind direction relative to ship (ψ_A). q_A is wind pressure; A_F and A_L indicate transversal and lateral projections of the windage area respectively. Wind relative direction can be expressed by Equation 10:

$$\psi_A = \tan^{-1}\left[\frac{U_T \cos\psi + U \cos\beta}{U_T \sin\psi - U \cos\beta}\right] \tag{10}$$

Where, U_T is wind velocity and ψ is angle of wind direction with reference of coordinate system. Wind pressure (q_A) can be calculated by Equation 11 (Fujiwara et al., 2006):

$$q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi + \beta) \tag{11}$$

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

2.2. Ship Steering Autopilot

Rudder is most important features in achieving controlability goals. The control system must alter the control surfaces to the desired heading angle. The schematic equation of a PID control system of the ship tracking can be expressed by Equation 12:

$$\delta = K_p(e) + K_d(\dot{e}) + K_i \int_0^T e(t)dt \text{ and } \quad e = (\psi_T - \psi_P) \qquad (12)$$

where: δ is designed rudder angle; K_p, K_d, and K_i are proporsional gain, derivative gain and integral gain respectively; e is an error between heading target (ψ_T) and actual heading angle (ψ_P).

2.3 Simulation Program

According to IMO (2002) criteria of ship maneuverability, the prediction of ship course-keeping should be analyzed through the swept path. The swept path of ship can be obtained by double integrating the acceleration of the ship-motion mathematical model includes hydrodynamic derivatives. The equations of motion in this time domain simulation are then solved by numerical integration Dormand–Prince Method (Maimun et al., 2011 and Muhammad et al., 2015). The control method used in the simulation is a proportional integrated derivative (PID) controller. The designed rudder angle (δ=*35 deg.*) is calculated using Equation 9 with K_p=0.1; K_i =0.0001 and K_d =10 gains for *P*, *I* and *D* respectively. The conventional line-of-sight (LOS) guidance scheme is used to calculate the required reference heading (Fossen, 2002). The resistance and propulsion parameters for simulation are predicted using Holtrop Method (Holtrop and Mennen, 1982 and Holtrop, 1984). The wind component parameter is predicted by Fujiwara et al. (2006). Hydrodynamic derivatives are predicted using the derived regression equation developed by Yoshimura and Masumoto (2012).

2.4 Ship and Sea Trial Data

The object of the study is ferry ship of KMP Bontoharu (1053 Gross Tonnage), owned by PT. ASDP Indonesia Ferry with twin conventional propellers (FPP) and twin conventional rudders with the distance between rudder / propeller is 2.3 m, mounted behind the ship. The dimensions hull / superstructure and parameter propulsion / rudder of ship are presented in Tables 1 and Tables 2 respectively. The ship sea trial on Selayar - Bulukumba route (blue line) is 15.385 nautical miles distance, 7268 second travelling time, around 6.03 m/s wind velocity and 254 deg wind direction. The data was taken on 20th, September 2015

Table 1 Dimension of ship hull and superstucture

Parameter	Value
Loa, m	54.00
Lbp,m	47.45
B, m	14
H, m	3.4
T,m	2.45
V, m/s^2	6.618
Δ, *Ton*	1148
A_L, m^2	182.87
A_F, m^2	129.20
A_{OD}, *m*	218.23
C	-0.44
H_C, *m*	2.70
H_L, *m*	3.38
H_{BR}, *m*	10.48

Table 2 Parameter of ship propulsion and rudder.

Parameter	Value
Z	4
D, m	1.422
P, m	1.066
n	8.784
Span, m	1.550
Chord, m	0.900
A_R, m^2	1.395
BHP, HP	1000
RPMME	1850

3. Results and Discussion

The monthly significant wind velocity and direction data were predicted by using ERA-Interim re-analysis data from European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years period from 2006-2018 at 6-hourly intervals shows in Figure 2. The data provides wind speed data with resolution of 0.25 x 0.25 degree. The peak wind speed trend show in January with maximum trend of 10.06 m/s (88 deg.). Meanwhile, the trend of monthly mean wind speed in April has decreasing trends with minimum trend of 6.41 m/s (219 deg.). The trends of monthly mean wind speed are varying depending on month during west monsoon or east monsoon seasons.

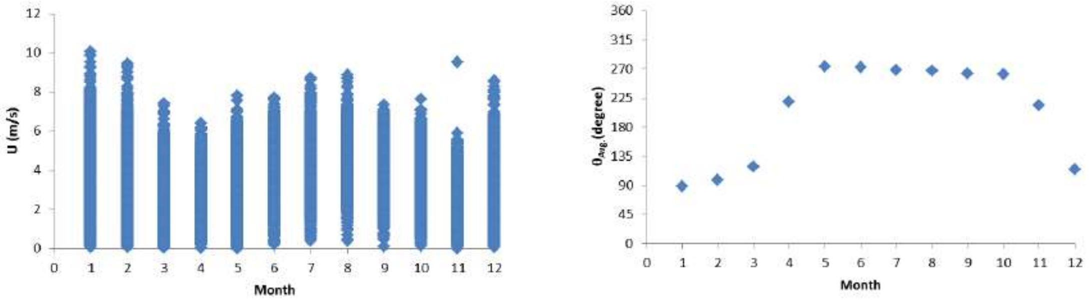

Figure 2 Significant wind velocity and direction in Selayar-Bulukumba route

Based on the wind data characteristics in figure 5, course keeping of a KMP Bontoharu have been simulated for three conditions of wind direction parameter (i.e. starboard and portside athwart (88 deg. and 268 deg.) and stern (219 deg.). The information is very important in ship navigation due to not only save the time but also save the fuel consumption by controlling a set twin rudder configuration design. Figure 3 shows the history result of simulation for track-keeping trajectory of a KMP Bontoharu (Selayar to Bulukumba) under wind velocities effect. The horizontal axis expresses time while vertical axis expresses heading angle (ψ), rudder angle (δ), speed ship (u) and rudder force (F_X) respectively. The wind blows from starboard athwart (ψ=88 deg) at wind velocities (U_T= 10.06 m/s) for initial ship speed (U) of 6.618 m/s. It was found that the track keeping trajectory leaving slow track deviation from initial track with low heading with big track keeping time compared without winds (U_T= 0 m/s). Meanwhile the ships track keeping trajectory with increased wind velocities caused more deviation and very low ship speed.

Figure 4 shows the history result of simulation for track-keeping trajectory of a KMP Bontoharu with wind blows from portside athwart (ψ=268 deg) at wind velocities (U_T= 6.41 m/s) for initial ship speed (U) of 6.618 m/s. Its characteristic almost similar when the wind blows from starboard athwart (ψ=88 deg). While when the wind blows from stern (ψ=219 deg), the ship speed increases with the increasing wind speed as the simulation results shows in Figure 5. It should be noted that time histories of heading angles have almost the same patterns correspondingly, where as those of the rudder angles and speed ship are different in each case. This result is similar to the findings of Le at al. (2013) which confirming the trend of ship track keeping trajectory under wind velocities condition.

Figure 3, 4 and 5 shows also the effects of winds speed and direction on ship speed track keeping trajectory time for initial ship speed (U) of 6.618 m/s . It was found that under the wind blows from starboard athwart (ψ=88 deg) and portside athwart (ψ=268 deg), a 7.31 % and 0.16 % ship speed reduces were achived, meanwhile if the wind blows from the stern, the ship speed was relatively increase 2.75%. The latter is beneficial because track trajectory time was minimum. This trend is similar to the findings of Molland et al. (2011) and Ohtsu et al. (1996), supporting the behaviour of ship track keeping trajectory under winds direction.

Figure 6 shows the sea trial simulation results for track-keeping trajectory of ship with 6.03 m/s wind velocity and 254 deg. wind direction at initial ship speed of 3.94 m/s. It was found that the travelling time is 6.418 second. The simulation travelling time is a 11.68% higher compared with the sea trial results. The possible reason is because the simulation did not include wave. Table 3 indicates the summary of simulation and sea trial results of ship track-keeping trajectories.

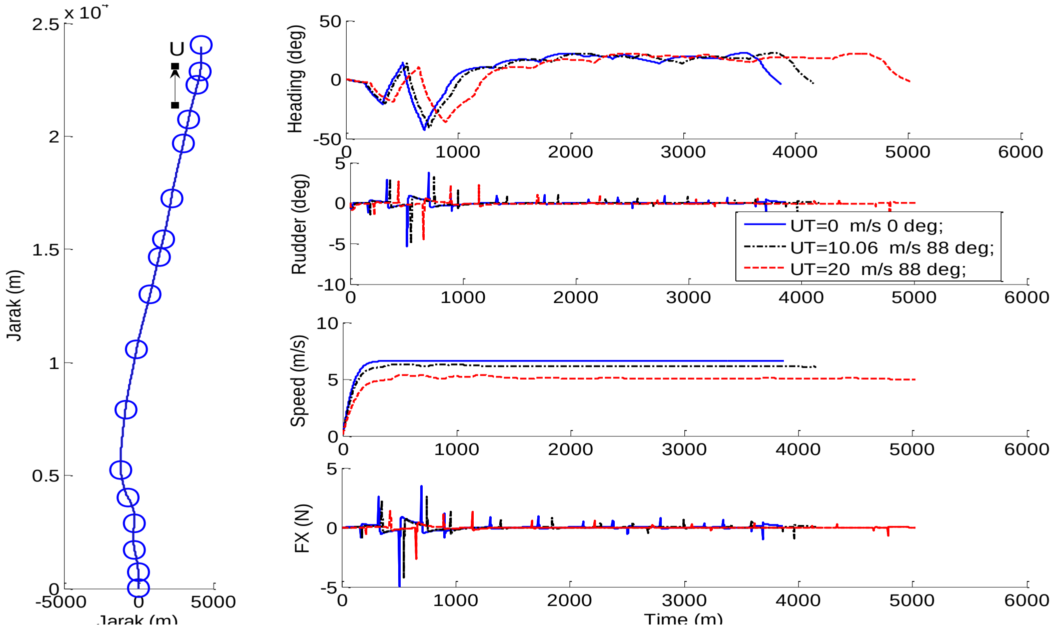

Figure 3 Ship trajectory with difference wind speed (U_T) at 88deg

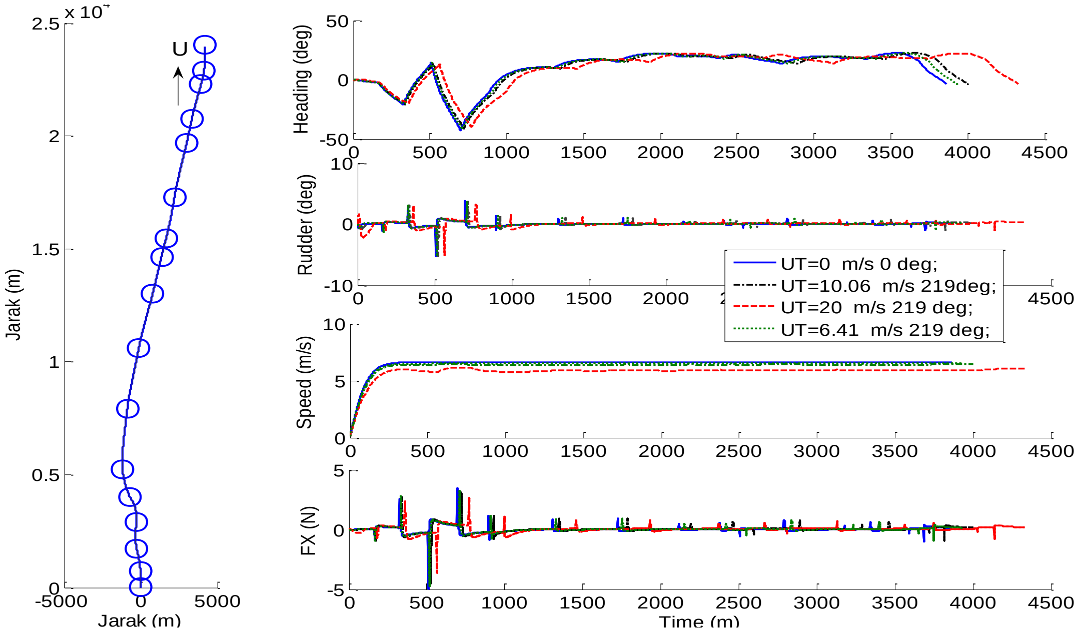

Figure 4 Ship trajectory with difference wind speed (U_T) at 219 deg

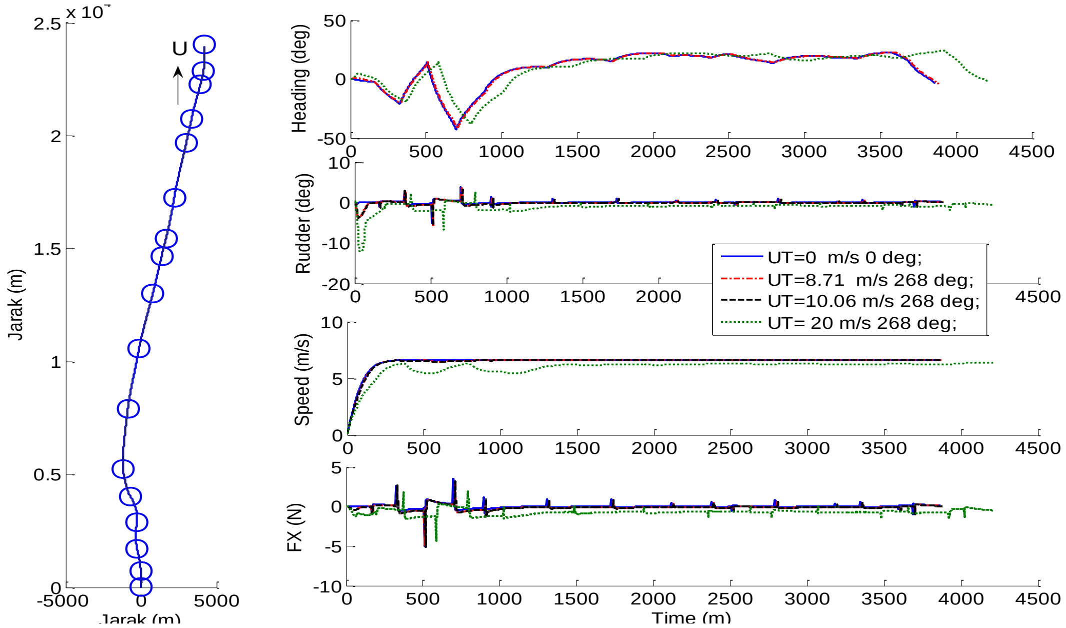

Figure 5 Ship trajectory with difference wind speed (U_T) at 268 deg

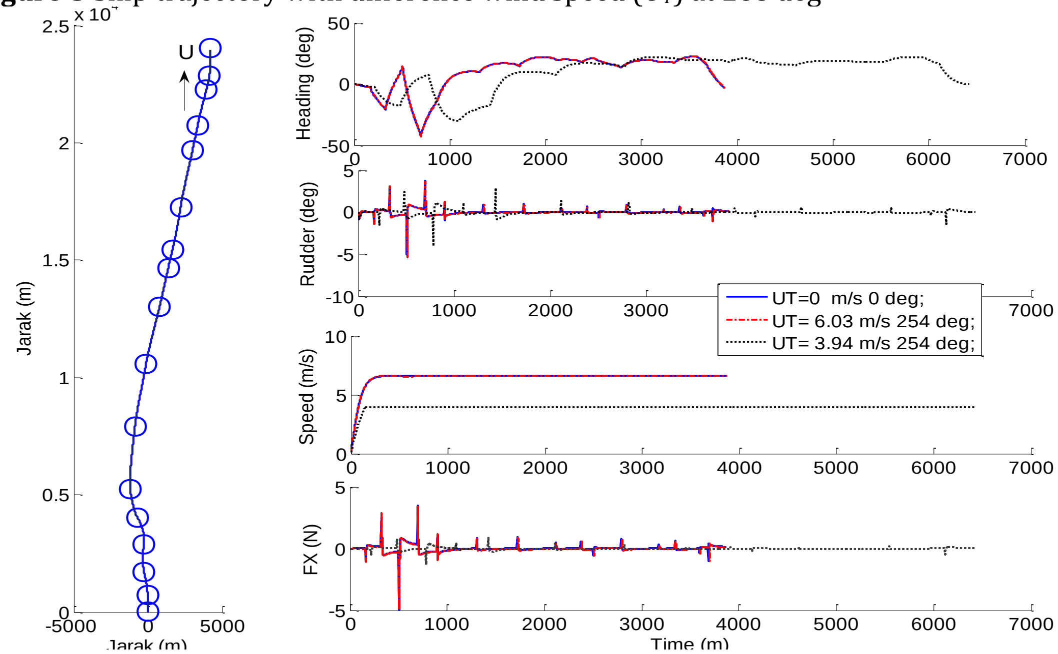

Figure 6 Simulation of ship trajectory at (U_T =6.03 m/s) at 254deg

Table 3 Simulation and sea trial result of ship- tracking trajectories

Routes	ψ (deg)	U_T (m/s)	U (m/s)	δ (deg/s.)	δ_R (deg)	Fx (N)	Track time (s)
Selayar- Bulukumba	0	0	6.618	-42.76	-5.312	-4.939	3866
Selayar- Bulukumba	88	10.06	6.134	-40.90	-5.270	-4.209	4158
Selayar- Bulukumba	88	20	4.991	-35.37	-4.488	-2.655	5024
Selayar- Bulukumba	219	6.41	6.526	-42.31	-5.299	-4.644	3932
Selayar- Bulukumba	219	10.06	6.436	-41.96	-5.437	-4.723	4002
Selayar- Bulukumba	219	20	6.031	-40.22	-5.157	-3.630	4332
Selayar- Bulukumba	268	8,71	6.629	-42.14	-5.312	-5.085	3881
Selayar- Bulukumba	268	10.06	6.629	-42.14	-5.312	-5.085	3881
Selayar- Bulukumba	268	20	6.355	-38.61	-12.32	-4.208	4208
Selayar- Bulukumba	254	6.03	6.636	-42.52	-4.335	-4.946	3872
Selayar- Bulukumba	254	6.03	3.94	-28.94	-3.489	-1.319	6418

4. Conclusions

A configuration design of twin rudder system on the ship course-keeping ability under winds speed and directions was analysed through computer simulation of MATLAB-Simulink program. The object of the research was ferry ship of KMP Bontoharu (1053 gross tonnage) by PT. ASDP Indonesia Ferry. The results indicated that the ship track keeping trajectory under increased wind velocities at 0 deg. direction have cause more deviation and very low ship speeds. When wind direction from starboard bow around 88 deg., high deviation and reduced ship speed were obtained, while from port stern around 219 deg., the result shows small deviation of the ship course and relatively constant ship speed. By simulating the fluctuated wind velocity and direction, the quality of the ship course-keeping with accurate heading angles may be achieved as well as increase the ship safety.

Acknowledgements

The authors would like to thank Lembaga Penelitian dan Pengabdian (LPPM) Universitas Hasanuddin. This work was supported by Hibah Penelitian Dasar Unhas under grand No. 2006/UN4.1/KEP/2019. The authors would also like to thanks PT. Angkutan Sungai, Danau dan Perairan (ASDP) Indonesia Ferry and PT. Biro Klasifikasi Indonesia for the sea trial and ship data collection.

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Lampiran 4

Universitas Hasanuddin

Andi Haris <andi_haris@ft.unhas.ac.id>

[IJTech] Editor Decision

1 message

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Reply-To: "noreply@ijtech.eng.ui.ac.id" <noreply@ijtech.eng.ui.ac.id>
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Decision Result : Revise

Dear **Dr. Andi Haris Muhammad**

We have finished the review and made decision on your manuscript entitled **[CONFIGURATION DESIGN OF TWIN RUDDER SYSTEM ON COURSE-KEEPING ABILITY OF A FERRY SHIP UNDER WIND CONDITION]** which was submitted to International Journal of Technology.

We have decided that your manuscript **Need to be Revised**

We also send you the review result from the reviewers. Here is the detail review result:

Notes from Editor:
1. Please revise according to the reviewer's comment, highlights for all in different color that changed

Waiting review from suggested reviewer.

Please login into application https://ijtech.eng.ui.ac.id/login for more detail.

You must respond to this revise and resubmit request before **03 Feb 2021**, after which point we will presume that you have withdrawn your submission from International Journal of Technology (IJTech) Online System.

Yours sincerely,

Dr. Nyoman Suwartha
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Reviewer 1

Date Review : 14 Sep 2020 - 10:29

Introduction : - There are lots of related literature that have been published in conjunction with the twin rudder system on course-keeping. The author should review more the relevant references to highlight what is new as the novelty of the work, the innovation, and the frontiers of this paper.

Methodology : - The coefficients of open water propeller (C1, C2, C3) which significant to thrust computation are not presented, and if the data are not available there is no explanation on how the coefficients are estimated.
- The subscript {S, P} which denotes the thrust/rudder normal force at the starboard and portside is not described in detailed computation whether S+P or there is an interaction coefficient between them.
- The governing terms of wind-loads (CAX, CAY, CAN) in Eq. (9) as a function of the wind direction relative to the ship are not clear on how those coefficients are determined
- The control method, the foremost important on course-keeping is only applying the standard PID, furthermore, there is no clear parameter to set the values of proportional gain. For instance, the authors might be better to incorporate and discuss the specific controller of course-keeping under wind load i.e. the disturbance observer, model-based controller, or other specific methods.

Results and Discussion : - The results and discussion are mainly of the simulation results. The discussion of the results is very shallow. Although the authors have cited several references as parts of the method in the simulation program (in Section 2.3), however, there is no validation of the simulation program with the experiment data. The authors should provide a relevant discussion of the proposed simulation program with reliable data of the experiment. The discussion should emphasize the know-how, findings, limitation of the simulation programs, boundary conditions and the underlying physics need to be strengthened. Otherwise, it would not convince the reliability of the simulation program to the reader.

- There is no academic citation of the significant wind velocity and direction data which predicted by using the ERA-Interim re-analysis data from ECMWF as shown in Fig.2 and explanation for the way of data collection.

- There are some fatal errors in the discussion which cause ambiguity in understanding, starting from “Figure 4 shows… from portside athwart (wind direction= 268 deg.)”, in fact, Fig.4 shows the results of wind direction = 219 deg. Furthermore, when discussing the wind blows from the stern (wind direction= 219 deg.), it is said that “the ship speed increases with the increasing wind speed as shown in Fig.5”, however, if we see the results of ship speed in Fig.5, in fact, the ship speeds do not increase even when the wind velocity (UT = 20 m/s).

- The conclusion of the paper is weak. The author should give the applicable scope of the conclusions of this paper.

References : There are lots of related literature that have been published in conjunction with the twin rudder system on course-keeping. The author should review more the relevant references to highlight what is new as the novelty of the work, the innovation, and the frontiers of this paper.

Other :

Originality	2 *(fair)*
Technical	2 *(fair)*
Methodology	2 *(fair)*
Readability	3 *(average)*
Practicability	3 *(average)*
Organization	3 *(average)*
Importance	3 *(average)*

Result **Done, Revisions Required**

Additional Comment

Attachment File:

Review Attachment

Reviewer 2

Date Review : 19 Sep 2020 - 21:12

Introduction : The introduction together with the background of the paper is described obviously. There is a clear research statement at the end of this part. Some mistakes appear: Para 2: "He observed that changes of the ship's speed ..." 'He' must be changed with 'They' Para 2: "... but more sensitive when the wind was coming from ..." The words 'was coming'to change with the word 'came' Para 3: "Furthermore, they (Khanfir et al., 2011) conducted .." to change with Kanfir et al. (2011) conducted ..." Para 4: Correction on citations, it should be Liu et al. (2015) and Chen et al. (2018).

Methodology : The description of Methods is sufficient, but there are some corrections. Para 1: The first sentence is incorrect grammatically. The word 'utilizing' to change with 'utilizes' Further, more explanations are required together with the use of suitable references. Para 2: "The equations be expressed ..." to change with "....were expressed ..." The references should be types as (Kanfir et al., 2011 and Dash et al., 2015). Further, explanations of Equations 4 to 8 require an appropriate reference. (Fujiwara et al., 2006) should be (Fujiwara and Ueno, 2006). Tables 1 and Tables 2 respectively should be 'Tables 1 and 2, respectively'

Deskripsi Metode sudah cukup, tetapi ada beberapa koreksi. Paragraf 1: Kalimat pertama salah secara tata bahasa. Kata 'memanfaatkan' untuk berubah dengan 'memanfaatkan'. Lebih lanjut, diperlukan lebih banyak penjelasan bersama dengan penggunaan referensi yang sesuai. Paragraf 2: "Persamaan diekspresikan ..." berubah dengan ".... diekspresikan ..." Referensi harus memiliki tipe seperti (Kanfir et al., 2011 dan Dash et al., 2015). Lebih lanjut, penjelasan Persamaan 4 sampai 8 membutuhkan referensi yang sesuai. (Fujiwara et al., 2006) harus (Fujiwara dan Ueno, 2006). Tabel 1 dan Tabel 2 masing-masing harus 'Tabel 1 dan 2, masing-masing'

Results and Discussion : Results and Discussion are OK, but lack of comparative analysis with other papers to support the findings. Authors mentioned Molland et al (2011) - this is a textbook and not a journal paper and Ohshu et al. (1996). Authors should elaborate what it means by 'similar.' There are some grammatical errors as well: Para 1: "... interval shows in Figure 2." should be "... interval shown in Figure 2." Para 2: "..in figure 5, ..." should be "... in Figure 5,..." "have been simulated" should be "has been simulated" Para 3: "Its characteristic almost similar ...." should be "... is almost similar ..." Para 4: "Figure 3, 4 and 5 shows ..." should be "Figures 3, 4, and 5 show ...." "winds speed" should be "wind speeds" "..the ship speed was relatively increase 2.75%." should be "...the ship speed relatively increased about 2.75%" Para 5: "..time is 6.418 second" should be "... is 6.418 seconds." "... travelling time is a 11.68% higher compared with the ..." should be "... travelling time is 11.68% higher than the ..." Table 3 needs further explanation in order to conclude Figures 3 to 6.

References : This part is OK and correct.

Other : Within the Conclusion, the statement of computer simulation of MATLAB-Simulation program appears; this term is not mentioned in the abstract, method, and discussion. I suggest authors to mention it in Abstract, Method, and Discussion, accordingly. Further, authors said "... as well as increase the ship safety" in which the term safety is not discussed at all but mentioned in abstract. I suggest authors to elaborate the safety context in the Discussion. The word 'grand' in Acknowledgments to change with 'Grant'

Originality	3 *(average)*
Technical	3 *(average)*
Methodology	3 *(average)*
Readability	4 *(above average)*
Practicability	3 *(average)*

Organization	3 *(average)*
Importance	4 *(above average)*

Result	**Done, Revisions Required**
Additional Comment	

Attachment File:
-

Dear Dr. Agus Sunjarianto Pamitran, Prof. Nandy Putra & Dr. Nyoman Suwartha,

Thank you for inviting me as a reviewer for the manuscript **#ME-3829** entitled **"CONFIGURATION DESIGN OF TWIN RUDDER SYSTEM ON COURSE-KEEPING ABILITY OF A FERRY SHIP UNDER WIND CONDITION"** that was submitted to the International Journal of Technology.

My review results for the manuscript **#ME-3829** are as follows,

In this paper, a method was presented to control the ship movement by using the twin rudder system on course-keeping under wind conditions. To do this, a PID controller was used to adjust the heading angle of the ship according to the desired path. Some parametrical studies i.e. relative wind velocity and directions were taken into account in the simulation. The simulation results were then discussed based on the full-scale trial data i.e. ship particulars, ship speed & trajectory of a Ferry ship.

Overall, the work is valuable. However, **in its current form, the paper cannot be accepted unless the following comments have been addressed**.

Major problems:

1. The results and discussion are mainly of the simulation results. The discussion of the results is very shallow. Although the authors have cited several references as parts of the method in the simulation program (in Section 2.3), however, there is no validation of the simulation program with the experiment data. The authors should provide a relevant discussion of the proposed simulation program with reliable data of the experiment. The discussion should emphasize the know-how, findings, limitation of the simulation programs, boundary conditions and the underlying physics need to be strengthened. Otherwise, it would not convince the reliability of the simulation program to the reader.
2. There are lots of related literature that have been published in conjunction with the twin rudder system on course-keeping. The author should review more the relevant references to highlight what is new as the novelty of the work, the innovation, and the frontiers of this paper.
3. The coefficients of open water propeller (C_1, C_2, C_3) which significant to thrust computation are not presented, and if the data are not available there is no explanation on how the coefficients are estimated.
4. The subscript $\{S, P\}$ which denotes the thrust/rudder normal force at the starboard and portside is not described in detailed computation whether $S+P$ or there is an interaction coefficient between them.
5. The governing terms of wind-loads (C_{AX}, C_{AY}, C_{AN}) in Eq. (9) as a function of the wind direction relative to the ship are not clear on how those coefficients are determined.
6. The control method, the foremost important on course-keeping is only applying the standard PID, furthermore, there is no clear parameter to set the values of proportional gain. For instance, the authors might be better to incorporate and discuss the specific controller of course-keeping under wind load i.e. the disturbance observer, model-based controller, or other specific methods.
7. There is no academic citation of the significant wind velocity and direction data which predicted by using the ERA-Interim re-analysis data from ECMWF as shown in Fig.2 and explanation for the way of data collection.

8. There are some fatal errors in the discussion which cause ambiguity in understanding, starting from “Figure 4 shows… from portside athwart (ψ=268 deg.)”, in fact, Fig.4 shows the results of ψ = 219 deg. Furthermore, when discussing the wind blows from the stern (ψ = 219 deg.), it is said that “the ship speed increases with the increasing wind speed as shown in Fig.5”, however, if we see the results of ship speed in Fig.5, in fact, the ship speeds do not increase even when the wind velocity (U_T = 20 m/s).
9. The conclusion of the paper is weak. The author should give the applicable scope of the conclusions of this paper.

Minor problems:

1. The quality of Fig.1 is poor. The fonts are small size and the drawing is not clear.
2. There are some grammatical mistakes and typing errors in the text, for instances, after Eq.(2) “drif angle”, “hydodynamic”. In Section Results and Discussion, “speed ship”. The English can be improved.
3. The description of the variables after Eq.(7) are overlapping and rewritten after Eq.(8)
4. In Subsection 2.3, the authors wrote “… is calculated using Equation 9”, Do the authors mean “… is calculated using Equation 12”?
5. In Section Results and Discussion, the authors wrote “… wind data characteristic in Figure 5”, Do the authors mean “… wind data characteristic in Figure 2”?
6. In Fig.3-6, on the left-hand side figure of the ship trajectory, the titles of the axis are not English, the *x*-axis title and the power of the *y*-axis are half-cut. On the right-hand side figure, the unit of the *x*-axis “Time” is mistaken.

Sincerely yours,

Kurniawan Teguh Waskito

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Andi Haris <andi_haris@ft.unhas.ac.id>

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Author(s) : Andi Haris Muhammad, Daeng Paroka, Sabaruddin Rahman, Mohammad Rizal Firmansyah

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Configuration Design of Twin Rudder System on Course-Keeping Ability of A Ferry Ship Under Wind Condition

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[1]*Put author's affiliation here, complete with address, postal code, and country*
[2]*Put author's affiliation here, complete with address, postal code, and country*
[2]*Put author's affiliation here, complete with address, postal code, and country*

Abstract. Ship course-keeping plays a vital role in navigation safety, mainly when ship operating under wind condition. A method for controlling ship movements through the rudder system configuration is necessary to stabilise the ship's course. This paper describes the twin rudder system's configuration design on the ship course-keeping ability under wind condition. Time-domain simulation of MATLAB-Simulink program was developed for this purpose. The Proportional Integral Derivative (PID) controller is used to adjust the ship's heading angle according to the desired path. Several parameters, such as relative wind velocity and directions, have been taken into account in the simulation. The result shows that at wind direction of 88 deg., the ship course-keeping speed decreases. However, the increasing wind velocity causes a large deviation of the ship heading angle. Meanwhile, the speed of the ship course-keeping increase with the rising wind speed direction of 219 deg. Ship course-keeping time with around 219 deg. under wind direction of the simulation was 11.68% lower than the sea trial.

Keywords: Proportional integral derivative controller; Course-keeping; Ship tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigations due to saving time and saving fuel consumption. To achieve the quality of ship course-keeping and generate accurate heading angles, a controller that consider ship hydrodynamics, both internal and external disturbances parameters should be installed. Keeping the Ferry ship course is different from that of sea-going ships due to navigation environment and ship particulars. The navigation environment's complexity especially the influence of wind load force and moment makes ferry ship with the large superstructure are more susceptible to marine accidents. Many studies relate to wind effect on ship maneuvering, the load force and moment of wind have significantly affected by transversal and lateral projections of the windage area due to large superstructure of the ship and wind velocity and direction relative to ship (Fujiwara and Ueno, 2006). Paroka et al. (2016) have simulated the effect of wind on ferry ship maneuvering. They explained that changes in ship speed caused by wind are highly dependent on wind velocity and direction. When the wind direction came from the bow to the ship's starboard (0 to 100 deg.), its speed tends to decrease. While the decrease in ship speed is not significant in the direction of the wind comes from the starboard to the ship's stern (100 to 180 deg.). Whereas when the wind blowing from the

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side of the ship (20 to 140 deg.), it tends to change its direction. The direction deviations of the ship caused by wind vary for each type of ship and the steering response required. Ohtsu et al. (1996) reported that the wind blowing from starboard bow quarters (45 deg.) made the ship steering becomes less sensitive but more sensitive when the wind was coming from the port stern quarters (135 deg.). It is crucial to increase the ship speed to change due to the different direction of the wind. This behaviour information is essential to improve ship course-keeping quality, especially when the ships need to take appropriate action in handling the wind disturbances. The improving quality of the ship's course-keeping ability in wind condition is strongly influenced by the steering response to the load of the wind blowing through the use of the appropriate configuration design of rudder system (Hasegawa et al., 2006).

Many efforts to improve ship maneuvering have been carried out through the use of twin rudder ship controller. Yoshimura and Sakurai (1989) investigated the effect of a ship fitted twin-rudder twin-propeller on ship maneuvering. They found that a twin-rudder twin-propeller's hydrodynamic characteristics are not so much different from those of a single-propeller single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ship maneuver fitted with a twin-propeller twin-rudder. Furthermore, Khanfir et al. (2011) have conducted captive model tests and free-running tests with a single-propeller twin-rudder and a twin-propeller twin-rudder ship. The tests' purpose is to evaluate the effect of drift angle on the rudder forces and some peculiar phenomena concerning normal rudder force for twin-rudder ships.

Other parameters that affect ship maneuver performance are from distance spacing between single rudder in the twin-rudder ship. Gim (2013) carried out a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5 - 1.0 chord length of the rudder. It was found that this spacing distance between rudders in twin-rudder configurations is also affected by the interaction between the rudders and the critical distance should be less than 1.0 chord length of rudder to decrease turbulence flow and vortices. This result is similar to the findings of Chen et al. (2018) by using numerical simulation, confirming the excellent characteristics of the twin-rudder ship compared with those of single-rudder ship. Chen et al. (2018) concluded that a ship fitted with twin-rudder would operate very well at 15 deg. of rudder angles. Additionally, the effectiveness of the twin rudders' stopping performance at the lateral spacing equals 1.3 chord length of the rudder.

Based on the studies mentioned earlier, the rudder system's configuration is the most crucial feature in achieving ship controllability goals. The rudder system must alter the ship control to the desired heading angle, both due to ship internal and external disturbances parameters. This paper focuses on applying the twin-rudder system to improve ferries' course-keeping quality under wind conditions. By simulating the fluctuated wind velocity and direction according to the ship's operating route, the quality of the ship course-keeping with accurate heading angles may be achieved and increase the ship safety.

2. Methods

2.1. *Mathematical Model*

Ship maneuvering analysis using computer simulation utilizes modular mathematical models including considering hydrodynamic derivative. The models were based on the surge, sway and yaw motion (Equation 1), using the coordinate system shown in Figure 1. The notations of u, v and r, are velocity components at ship's centre of gravity (G). m and I_{ZZ} represent the mass of the ship and moments of inertia. X, Y, and N represent the hydrodynamic forces and moment. The subscript H, P, R and W refer to hull, propeller, rudder and wind. In principle, force and moment induced by hull (X_H, Y_H, and N_H) is an approximation of polynomial function of β and r'. The equations were expressed by Yoshimura et al. (2001) in Equation 2.

$$\begin{aligned} m(\dot{u}-rv) &= X_H + X_P + X_R + X_W \\ m(\dot{v}-ru) &= Y_H + Y_P + Y_R + Y_W \\ I_{ZZ}\dot{\psi} &= N_H + N_P + N_R + N_W \end{aligned} \qquad (1)$$

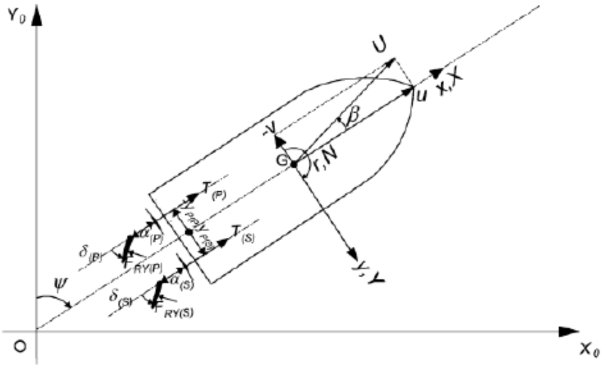

Figure 1 Coordinate system of ship

$$\begin{aligned} X_H &= \tfrac{1}{2}\rho L d U^2 (X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr}r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\ Y_H &= \tfrac{1}{2}\rho L d U^2 (Y'_\beta\beta + (Y'_r - m'_x)r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr}r'^3) \\ N_H &= \tfrac{1}{2}\rho L^2 d U^2 (N'_\beta\beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr}r'^3) \end{aligned} \qquad (2)$$

where: β is the drift angle at the midship position by $\tan^{-1}(v/u)$ and r' non-dimensionalized yaw rate by rL/U. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} are called the hydrodynamic derivatives on ship maneuvering. Force and moment induced by twin-propeller (X_P Y_P and N_P) can be expressed by Khanfir et al. (2011) in Equation 3:

$$\begin{aligned} X_P &= \rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}(J_{P(S)}) + (1-t_{P(P)})y_{P(P)}n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}(J_{P(P)})\Big) \\ N_P &= \rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}\Big) + \rho\Big((1-t_{P(P)})n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}\Big) \end{aligned} \qquad (3)$$

where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}}) = k_0 + k_1 J_{P\substack{(S)\\(P)}} + k_2 J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\left\{\substack{S\\P}\right\}} = (u - y_P r(1 - w_{P\left\{\substack{S\\P}\right\}})/(n_{P\left\{\substack{S\\P}\right\}} D_{P\left\{\substack{S\\P}\right\}})$

where: t_P is the thrust deduction coefficient in straight forward moving; K_T is the thrust coefficient of propeller force; n_P is the propeller revolution. D_P is the propeller diameter; w_P is the effective wake fraction coefficient at propeller location; J_P is the advance coefficient; while k_0, k_1 and k_2 are the constants for open water propeller, respectively. The sub-subscript *(S)* and *(P)* refer to starboard and portside.

Force and moment due to twin-rudder (X_R Y_R and N_R) can be expressed by Equation 4 to 8 (Khanfir et al., 2011):

$$\begin{aligned} X_R &= -(1-t_{R(S)}F_{RY(S)}\sin\delta_{(S)} - (1-t_{R(P)}F_{RY(P)}\sin\delta_{(P)} \\ Y_R &= -(1+a_H)\big(F_{RY(S)}\cos\delta_{(S)} + F_{R(YS)}\cos\delta_{(P)}\big) \\ N_R &= -(x_R + a_H x_H)\big(F_{RY(S)}\cos\delta_{(S)} + F_{RY(P)}\cos\delta_{(P)}\big) + f(x_R) \\ f(x_R) &= y_{P(S)}(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)} \end{aligned} \qquad (4)$$

where: δ is the rudder angle; x_R and z_R are the representations of rudder location and t_R, a_H and x_H are the interactive force coefficients among hull, propeller and rudder, as the functions of the advance constant of the propeller. The rudder normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

$$F_{RY\substack{(S)\\(P)}} = \tfrac{1}{2}\rho A_R U_{R\substack{(S)\\(P)}}{}^2 f_\alpha \sin\alpha_{R\substack{(S)\\(P)}} \qquad (5)$$

where: A_R is the rudder area; f_α is the gradient of the lift coefficient of the rudder, and it can be approximated by the function of the rudder aspect ratio (f_α =6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6,

$$U_{R^{(S)}_{(P)}} = \sqrt{u_{R^{(S)}_{(P)}}{}^2 + v_{R^{(S)}_{(P)}}{}^2} \qquad \text{and} \qquad \alpha_{R^{(S)}_{(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R^{(S)}_{(P)}}\left(\beta_{R^{(S)}_{(P)}}\right) \tag{6}$$

The effective inflow velocity (u_R) to the rudder in surge direction can be expressed by Equation 7.

$$u_{R^{(S)}_{(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P^{(S)}_{(P)}} \times \sqrt{\eta_{P^{(S)}_{(P)}}\left\{1+\kappa\left(\sqrt{1+8K_{T^{(S)}_{(P)}}\Big/\pi J_{P^{(S)}_{(P)}}{}^2} - 1\right)\right\}^2 + (1-\eta_{P^{(S)}_{(P)}})} \tag{7}$$

Where: $\varepsilon_{\substack{(S)\\(P)}} = 1 - w_{R^{(S)}_{(P)}}\Big/1 - w_{P^{(S)}_{(P)}}$; $\kappa = kx\Big/\varepsilon_{\substack{(S)\\(P)}}$; $\eta_{P^{(S)}_{(P)}} = D_{P^{(S)}_{(P)}}\Big/H_{R^{(S)}_{(P)}}$; $u_{P^{(S)}_{(P)}} = \left(1 - w_{P^{(S)}_{(P)}}\right)\left(u - y_{P^{(S)}_{(P)}} r\right)$

where ε, κ, γ_R and l_R are the parameters, describing the rudder inflow velocity angle, while (1-w) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H) is the ratio of propeller diameter to rudder height.

The effective inflow velocity (v_R) to the rudder in sway direction can be expressed by Equation 8.

$$v_{R^{(S)}_{(P)}} = u_{R^{(S)}_{(P)}} \tan\left(\delta_{R^{(S)}_{(P)}}\right) \tag{8}$$

where: $\delta_{R^{(S)}_{(P)}} = \gamma_{R^{(S)}_{(P)}} \beta_{R^{(S)}_{(P)}} + \tan^{-1}\left(y_{R^{(S)}_{(P)}}\Big/x_{R^{(S)}_{(P)}}\right)$ and $\beta_{R^{(S)}_{(P)}} = \beta - L_{R^{(S)}_{(P)}} r$

where δ_R is the angle of rudder; β_R is the effective drift angle at rudder; L_R is the flow-straightening coefficient of yaw rate. For the case of a ship operated under wind condition, force and moment (X_W, Y_W and N_W) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A) q_A A_F; \quad Y_W = C_{AY}(\psi_A) q_A A_L; \quad N_W = C_{AN}(\psi_A) q_A A_L L_{OA} \tag{9}$$

where $\psi_A = \tan^{-1}\left[U_T \cos\psi + U\cos\beta / U_T \sin\psi - U\cos\beta\right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi+\beta)$

C_{AX}, C_{AY} and C_{AN} are the wind load forces and moments coefficients respectively as a function of the wind direction relative to ship (ψ_A). U_T and ψ are wind velocity and direction angle with reference of coordinate system; q_A is wind pressure, q_T is wind pressure due to elevation of center of windage area and q_S is wind pressure induced by wind velocity without elevation effect. A_F and A_L indicate transversal and lateral projections of the windage area respectively.

2.2. Ship Steering Autopilot

The rudder is the most critical features in achieving controllability goals. The control system must alter the control surfaces to the desired heading angle. The schematic equation of a PID control system of the ship tracks can be expressed by Equation 10:

$$\delta = K_p(e) + K_d(\dot{e}) + K_i \int_0^T e(t)\,dt \quad \text{and} \quad e = (\psi_T - \psi_P) \tag{10}$$

where: δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain and integral gain respectively; *e* is an error between heading target (ψ_T) and actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference headings angle. The reference heading angle equation and target zone correction can be expressed by Equations 11.

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t)/x_k - x(t)) \text{ and } (x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \qquad (11)$$

where, x_k and y_k are the track-point coordinates; $x(t)$ and $y(t)$ are the coordinates position of the ship; R_0 is the radius of the target zone.

2.3 Simulation Program

According to IMO (2002) criteria of ship maneuvering, the swept path should be used to analyse the ship course-keeping prediction. The ship's swept path can be obtained by double integrating the ship motion mathematical model's acceleration includes hydrodynamic derivatives. Numerical integration of Dormand–Prince Method (Maimun et al., 2011 and Muhammad et al., 2015) then solves the equations of motion in this time-domain simulation of MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for acting hull force and moment in Equation 2 and interaction force coefficient among hull, propeller and rudder are predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). That regression equation is one of the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circle and zigzag maneuvering on ships with twin-rudder and twin-propeller systems and validation through model testing or free-running tests. The ship's resistance coefficients for simulation are predicted using Holtrop Method (Holtrop and Mennen, 1982 and Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\, J_P - 0.1178\, J_P{}^2$) is predicted using polynomial regression based on the open water test's statistical data for B-series propeller (Carlton, 2007). The coefficient of wind load force and moment in equation 9 is predicted using the methodology proposed by Fujiwara et al. (2006). The control method used in the simulation is a proportional integrated derivative (PID) controller. The designed rudder angle (δ=35 deg.) is calculated using Equation 10 with PID gain (K_p = 0.1; K_i = 0.0001 and K_d = 10) obtained by trial and error calculations.

2.4 Ship and Sea Trial Data

The study's object is ferry ship of KMP Bontoharu (1053 Gross Tonnage), owned by PT. ASDP Indonesia Ferry with twin-propellers and twin-rudders with the distance between rudder / propeller is 2.3 m. The particulars of the ship are presented in Table 1. The ship sea trial on Selayar to Bulukumba route is 15.385 nautical miles distance, 7268 second travelling time, around 6.03 m/s wind velocity and 254 deg wind direction. The data was taken on 20th, September 2015.

Table 1 Particulars of ship

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m^2	182.87	*Z*	2 x 4
Lbp,m	47.45	A_F, m^2	129.20	*D, m*	1.450
B, m	14	A_{OD}, *m*	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_G, *m*	2.70	*n*	8.784
V, m/s²	6.618	H_L, *m*	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, *m*	10.48	*Chord, m*	0.900
				A_R, m^2	2 x 1.395

BHP, HP	2 x 1000
RPMME	1850

2.5 Wind Data

The monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years from 2006-2018 at 6-hourly intervals. The model provides wind speed data with a resolution of 0.25 x 0.25 degree. This model has been validated by Dee et al. (2011). Furthermore, it has been validated locally by Lina et al. (2015) using eight buoys data deployed in the Yellow and the East China Seas. In this study, coordinate for the observation data is on -5,75^{o}S and 120.5^{o}E.

3. Results and Discussion

The wind speed show's peak trend in January with maximum trend of 10.06 m/s (88 deg.) as shown in Figure 2. Meanwhile, April's monthly wind speed trend has decreasing trends with the minimum trend of 6.41 m/s (219 deg.). The movements of monthly wind speed are varying depending on the month during West or East monsoon seasons.

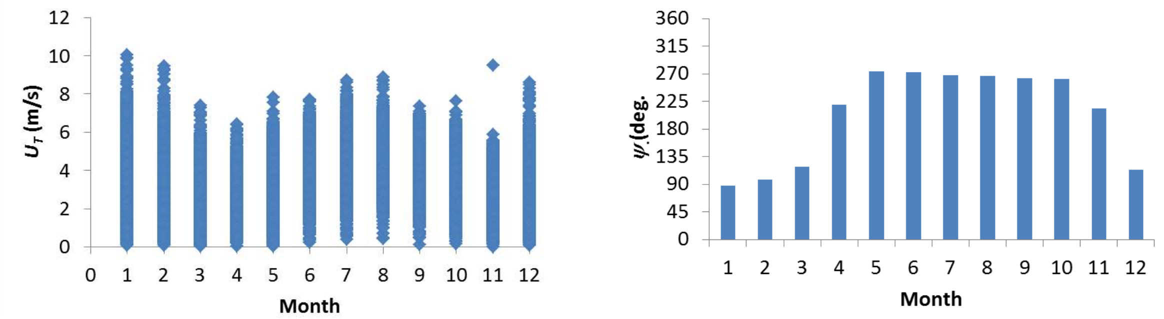

Figure 2 Significant wind velocity and direction in Selayar-Bulukumba route

Based on the wind data characteristics in Figure 2, course-keeping of a KMP Bontoharu has been simulated for three conditions of wind direction parameters, namely, starboard bow (88 deg.) and port stern of the ship (219 and 268 deg.) by using the time domain simulation program of MATLAB-Simulink. The information is essential in ship navigation due to saving the time and saving the fuel consumption by controlling a twin rudder configuration design. Figure 3 shows the history result of simulation for the track-keeping trajectory of a KMP Bontoharu (Selayar to Bulukumba) under wind velocities effect. The horizontal axis expresses time while the vertical axis expresses heading angle (ψ), rudder angle (δ), and speed ship (u) respectively. The wind blows from starboard bow (88 deg) at wind velocities (10.06 m/s) for initial ship speed (U) of 6.618 m/s. It was found that the track keeping trajectory, leaving slow track deviation from the initial track with low heading with big track keeping time compared without winds (U_T= 0 m/s). Meanwhile, the ships track keeping trajectory with increased wind velocities caused more deviation and very low ship speed.

Figure 4 shows the simulation results of the KMP Bontoharu track-keeping with wind blows from the port stern (219 degrees) at wind velocity range (0 to 20 m/s) for the initial ship speed (U) of 6.618 m/s. It was found that the track keeping trajectory, leaving fast track deviation from the initial track with high heading with short track-keeping time at each blown wind velocity compared without winds (U_T = 0 m/s). These characteristics are different when the wind blows from the starboard side (88 deg.). The angle of the wind direction causes this differences as found by Ohtsu et al. (1996) related to changes in ship heading and rudder angle caused by wind velocity and direction on a track-keeping of ship. Figure 5 shows the history result of simulation for the track-keeping trajectory of a KMP Bontoharu with wind blows from the port stern (268 deg.) at wind velocity range (0 to 20 m/s) for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed is 0.27% reduce compared without winds (U_T=0 m/s), while the speed of the ship 6.06 % increases at a wind speed of 20 m/s. The changes in the speed of the ship is caused by the direction of movement of the ship.

Figure 6 shows the sea trial simulation results for ship track-keeping trajectory with 6.03 m/s wind velocity and 254 deg. wind direction at initial ship speed of 3.98 m/s. It was found that travelling time is 6.419 second. The simulation travelling time is 11.68% higher compared with the sea trial result. The possible reason is that the simulation did not include wave.

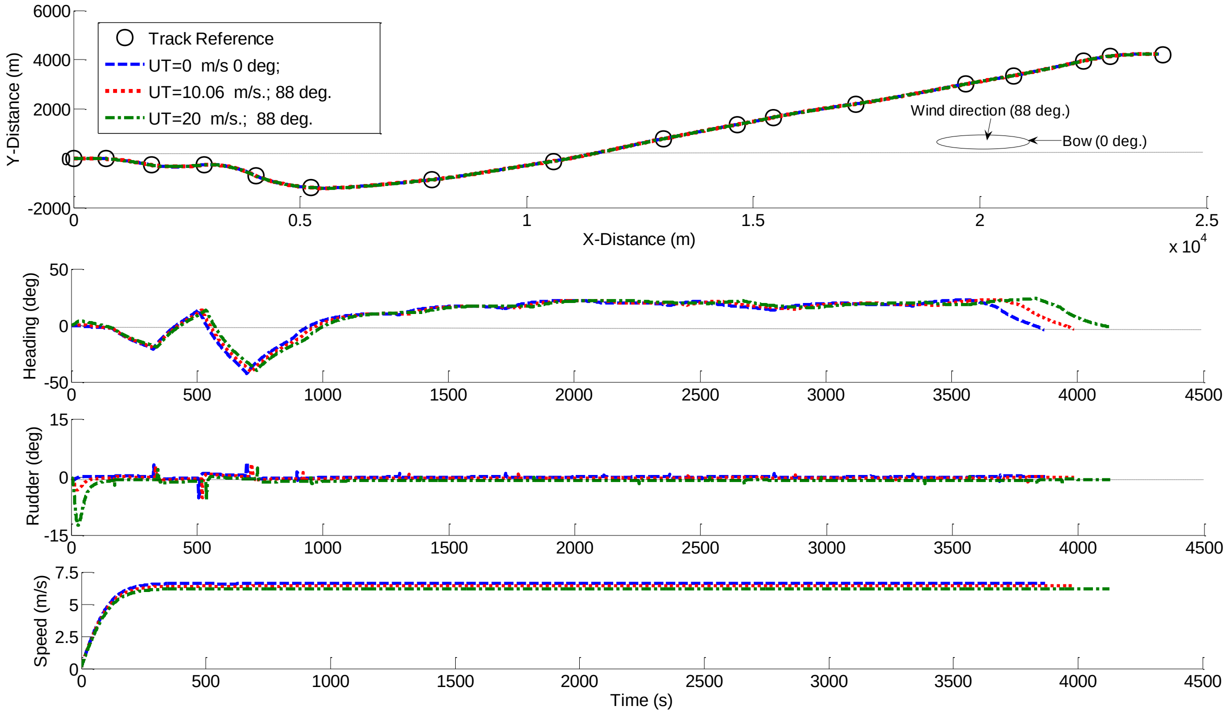

Figure 3 Ship trajectory with different wind speed (U_T) at 88 deg.

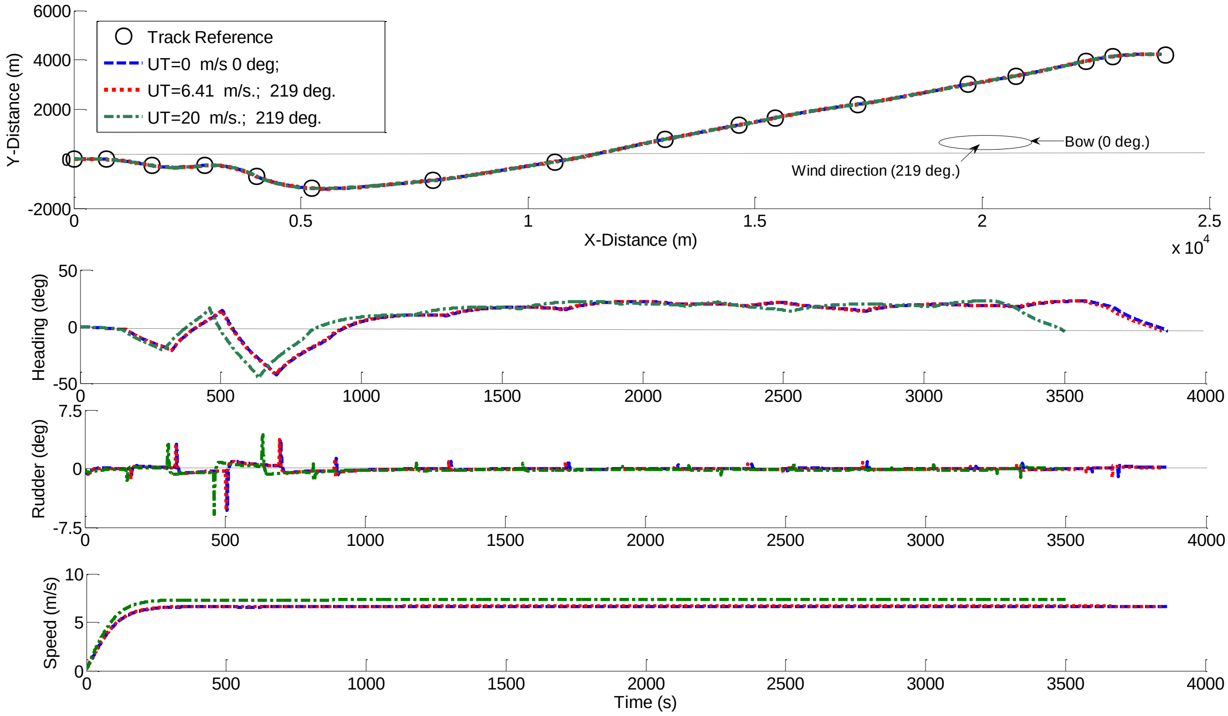

Figure 4 Ship trajectory with different wind speed (U_T) at 219 deg.

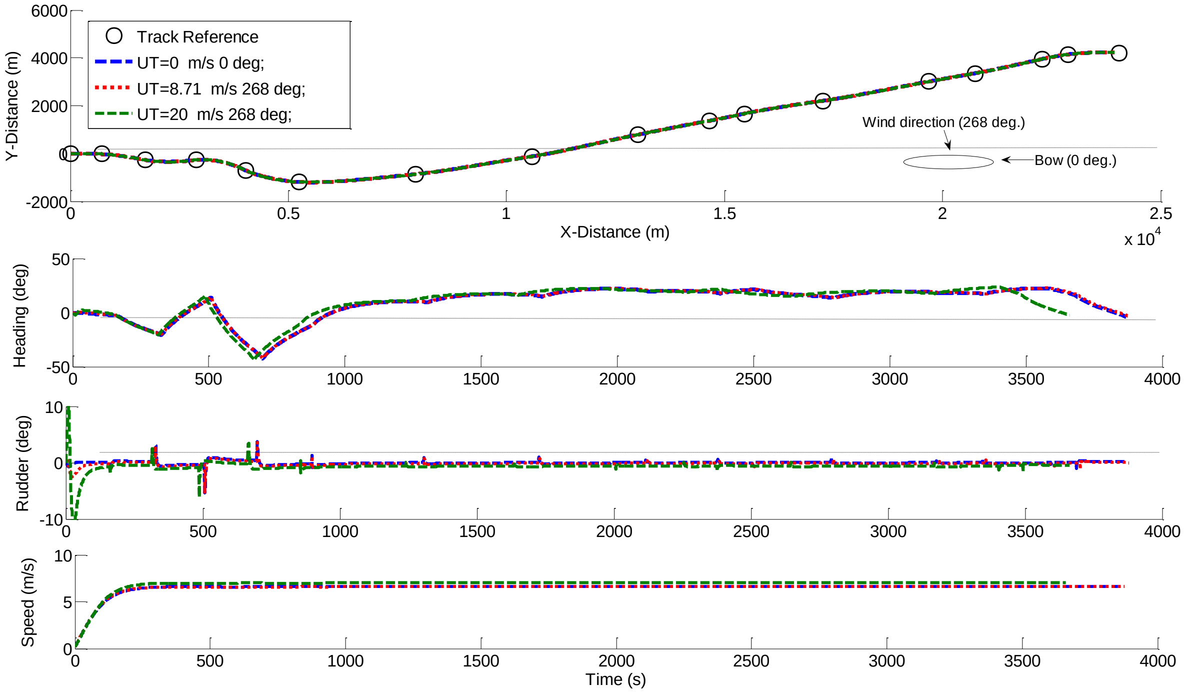

Figure 5 Ship trajectory with different wind speed (U_T) at 268 deg.

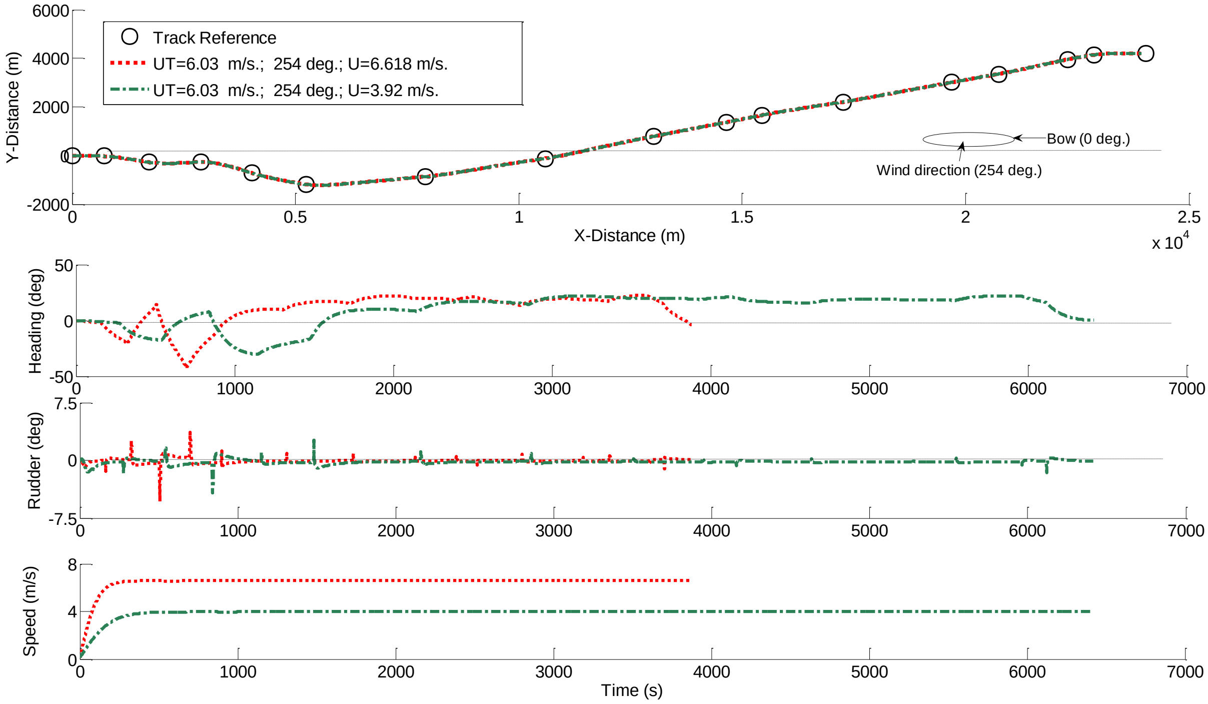

Figure 6 Sea trial simulation result of ship trajectory with different initial ship speed (*U*).

Figures 3, 4 and 5 also shows the effects of winds velocity and direction on ship speed track keeping trajectory for initial ship speed (*U*) of 6.618 m/s. It was found that under the wind blows from starboard bow (88 deg.) with a wind velocity of 20 m/s, the ship speed was 6.24 %, which was reduced without wind (U_T=0 m/s). While if the wind blows from the port stern (219 and 268 deg.), the ship speed was relatively increased 10.74 and 6.06 % respectively. The two latter are beneficial because the track trajectory time was minimum. In general, when the wind blows from the starboard and port to the stern of the ship (98 to 268 deg.), the track trajectory time of the ship tend to benefit compared with wind blows from the bow to the starboard and port of the ship as shown the simulation results in Figure 6. The ship's reduced speed when the wind blows from the bow to the starboard side (less than 100 degrees) similar to the findings of Paroka et al. (2016) related to changes in ship speed caused by wind speed and direction on a ferry ship maneuvering.

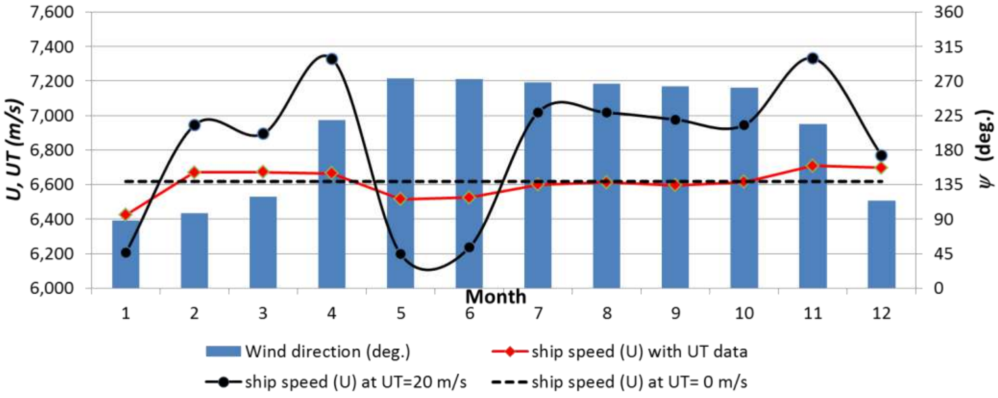

Figure 6 Tracking trajectories of ship speed with different wind velocity and direction.

4. Conclusions

A twin rudder system configuration on the ship course-keeping ability under wind speed and directions was analysed through computer simulation of the MATLAB-Simulink program. The results indicated that the applying twin rudder system to the course-keeping ability of ferry ships in wind conditions is very well used the PID controller to reduce ship deviation and increase ship speed by adjusting the ship's heading angle according to the desired path. The track trajectory time of ferry ship course keeping caused by wind is highly dependent on wind velocity and direction. When the wind blows from the starboard and port side to stern (98 to 268 deg.), the ship's travel time tends to benefit compared with wind blows from the bow to the side of the ship.

Acknowledgements

The authors would like to thank the Institute for Research and Community Service (LPPM) Hasanuddin University. Unhas Basic Research has supported this work under Grant No. 2006/UN4.1/KEP/2019. The authors would also like to thanks PT. (Persero) ASDP Indonesia Ferry Brach of Selayar and PT. (Persero) Biro Klasifikasi Indonesia (BKI) for the sea trial and ship data collection.

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List of Changes

Manuscript:

Configuration Design of Twin Rudder System on Course-Keeping Ability of A Ferry Ship Under Wind Condition

Response and Revision made by Author(s)

Reviewer #1:

No	Comments	Revision/Changes
1	There are lots of related literature that have been published in conjunction with the twin rudder system on course-keeping. The author should review more the relevant references to highlight what is new as the novelty of the work, the innovation, and the frontiers of this paper	Some literature reviews related to twin-rudder systems on ship course-keeping as recommended by reviewer have been added/revised in section 1 (paragraph 1; page 1). The innovation in this study, namely the application of a twin-rudder system to improve the quality of the course-keeping of ferry ship in wind conditions has been revised in Section 1 (paragraph 4; page 2).
2	The coefficients of open water propeller (C1, C2, C3) which significant to thrust computation are not presented, and if the data are not available there is no explanation on how the coefficients are estimated	The prediction method of open water propeller coefficient (C1, C2 and C3) has been added in Section 2.3 (page 5)
3	The subscript {S, P} which denotes the thrust/rudder normal force at the starboard and portside is not described in detailed computation whether S+P or there is an interaction coefficient between them	The prediction method of interaction force coefficient between the hull, propeller and rudder has been added in Section 2.3 (page 5).
4	The governing terms of wind-loads (CAX, CAY, CAN) in Eq. (9) as a function of the wind direction relative to the ship are not clear on how those coefficients are determined	The prediction method of wind load coefficient (CAX, CAY and CAN) has been added in Section 2.3 (page 5).
5	The control method, the foremost important on course-keeping is only applying the standard PID, furthermore, there is no clear parameter to set the values of proportional gain. For instance, the authors might be better to incorporate and discuss the specific controller of course-keeping under wind load i.e. the disturbance observer, model-based controller, or other specific methods.	The prediction method of PID gain parameters has been added in Section 2.3 (page 5).
6	The results and discussion are mainly of the simulation results. The discussion of the results is very shallow. Although the authors have cited several references as parts of the method in the simulation	The discussion of the research as recommended by reviewer has been revised by cited several references in section 3 (paragraph 3; page 6 and paragraph 5; page 8-9). The validation of simulation program proposed

	program (in Section 2.3), however, there is no validation of the simulation program with the experiment data. The authors should provide a relevant discussion of the proposed simulation program with reliable data of the experiment. The discussion should emphasize the know-how, findings, limitation of the simulation programs, boundary conditions and the underlying physics need to be strengthened. Otherwise, it would not convince the reliability of the simulation program to the reader.	has been explained in the section 2.3 (page 5).
7	There is no academic citation of the significant wind velocity and direction data which predicted by using the ERA-Interim re-analysis data from ECMWF as shown in Fig.2 and explanation for the way of data collection.	The academic citation related to the significant wind velocity and direction predicted by using the ERA-Interim re-analysis data from ECMWF as recommended by reviewer has been added by cited several references in section 2.5 (page 6).
8	There are some fatal errors in the discussion which cause ambiguity in understanding, starting from “Figure 4 shows… from portside athwart (wind direction= 268 deg.)”, in fact, Fig.4 shows the results of wind direction = 219 deg. Furthermore, when discussing the wind blows from the stern (wind direction= 219 deg.), it is said that “the ship speed increases with the increasing wind speed as shown in Fig.5”, however, if we see the results of ship speed in Fig.5, in fact, the ship speeds do not increase even when the wind velocity (UT = 20 m/s).	Some fatal errors in discussion have been revised in section 3 (paragraph 3; page 6-7).
9	The conclusion of the paper is weak. The author should give the applicable scope of the conclusions of this paper	The conclusions in this paper have been revised in section 4 (page 9).
10	There are lots of related literature that have been published in conjunction with the twin rudder system on course-keeping. The author should review more the relevant references to highlight what is new as the novelty of the work, the innovation, and the frontiers of this paper.	The references correspond to twin-rudder systems on ship course-keeping as recommended by reviewer have been added in references list.

Reviewer #2:

No	Comments	Revision/Changes
1	The introduction together with the background of the paper is described obviously. There is a clear research statement at the end of this part. Some	Some typing errors in introduction as recommended by reviewer have been revised in section 1 (paragraphs 2 and 3; pages 1 and 2).

	mistakes appear: Para 2: "He observed that changes of the ship's speed ..." 'He' must be changed with 'They' Para 2: "... but more sensitive when the wind was coming from ..." The words 'was coming'to change with the word 'came' Para 3: "Furthermore, they (Khanfir et al., 2011) conducted .." to change with Kanfir et al. (2011) conducted ..." Para 4: Correction on citations, it should be Liu et al. (2015) and Chen et al. (2018).	
2	The description of Methods is sufficient, but there are some corrections. Para 1: The first sentence is incorrect grammatically. The word 'utilizing' to change with 'utilizes' Further, more explanations are required together with the use of suitable references. Para 2: "The equations be expressed ..." to change with "....were expressed ..." The references should be types as (Kanfir et al., 2011 and Dash et al., 2015). Further, explanations of Equations 4 to 8 require an appropriate reference. (Fujiwara et al., 2006) should be (Fujiwara and Ueno, 2006). Tables 1 and Tables 2 respectively should be 'Tables 1 and 2, respectively'	Some typing errors have been revised in section 2 (paragraphs 1 – 3; pages 2 - 4). .
3	Results and Discussion are OK, but lack of comparative analysis with other papers to support the findings. Authors mentioned Molland et al (2011) - this is a textbook and not a journal paper and Ohshu et al. (1996). Authors should elaborate what it means by 'similar.' There are some grammatical errors as well: Para 1: "... interval shows in Figure 2." should be "... interval shown in Figure 2." Para 2: "..in figure 5, ..." should be "... in Figure 5,..." "have been simulated" should be "has been simulated" Para 3: "Its characteristic almost similar ...." should be "... is almost similar ..." Para 4: "Figure 3, 4 and 5 shows ..." should be "Figures 3, 4, and 5 show ...." "winds speed" should be "wind speeds" "..the ship speed was relatively increase 2.75%." should be "...the ship speed relatively increased about 2.75%" Para 5: "..time is 6.418 second" should be "... is 6.418 seconds." "... travelling time is a 11.68% higher compared with the ..." should be "... travelling time is 11.68%	The discussion of the research has been revised by cited several references in section 3 (paragraph 3; page 6 and paragraph 5; page 8-9). Some typing errors have been revised in section 3 (paragraphs 1 – 5; pages 6 - 9).

	higher than the ..." Table 3 needs further explanation in order to conclude Figures 3 to 6.	
4	This part is OK and correct.	-
5	Within the Conclusion, the statement of computer simulation of MATLAB-Simulation program appears; this term is not mentioned in the abstract, method, and discussion. I suggest authors to mention it in Abstract, Method, and Discussion, accordingly. Further, authors said "... as well as increase the ship safety" in which the term safety is not discussed at all but mentioned in abstract. I suggest authors to elaborate the safety context in the Discussion. The word 'grand' in Acknowledgments to change with 'Grant'	The statement of computer simulation of MATLAB-Simulation program used in the research as recommended by reviewer has been mentioned in the abstract, methods (section 2.3) and discussion (section 3 paragraph 2). Based on the research focus in part 1 (page 2), the discussion is limited to adjusting the heading angle of the ship according to the desired trajectory, while the increase of the ship safety has a positive impact on the accuracy of the heading angle obtained. The word typing error has been revised in acknowledgements (pages 9).

Lampiran 7

Universitas Hasanuddin

Andi Haris <andi_haris@ft.unhas.ac.id>

[IJTech] Editor Decision

2 messages

IJTech <noreply@ijtech.eng.ui.ac.id> Mon, Feb 22, 2021 at 12:13 PM
Reply-To: "noreply@ijtech.eng.ui.ac.id" <noreply@ijtech.eng.ui.ac.id>
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Decision Result : Revise

Dear **Dr. Andi Haris Muhammad**

We have finished the review and made decision on your manuscript entitled **[CONFIGURATION DESIGN OF TWIN RUDDER SYSTEM ON COURSE-KEEPING ABILITY OF A FERRY SHIP UNDER WIND CONDITION]** which was submitted to International Journal of Technology.

We have decided that your manuscript **Need to be Revised**

We also send you the review result from the reviewers. Here is the detail review result:

Notes from Editor:
1. Please revise according to the reviewer's comment, and highlights in different color that changed 2. It is suggested to include at least 3 relevant IJTech articles as references

Reviewer (1)

Introduction:
-

Methodology:
The quality of Fig. 1 is poor and not appropriate as a standard figure in a Journal paper. The fonts are small size, the image resolution is too low, and the drawing is not clear. In responding the previous comment regarding the control method which is the most important on course-keeping, the authors described the method by using the trial and error method as written in Subsection 2.3. Why do the authors use the trial and error calculation? However, in the case of course-keeping of a Ferry ship which susceptible to wind condition, the authors had better to discuss more specific controller of course-keeping under wind load i.e. the disturbance observer, model-based controller, or other specific methods and figure out more clearly the specific control being used.

Results and Discussion:
In Section 3, Fig. 3 – 5, the authors described the wind direction of 88, 219, and 268 deg. as the wind blows from the starboard bow, port stern, and port stern, respectively. The following descriptions in the paragraph are also not consistent. It is obviously mistaken descriptions which should be described from the port bow, starboard stern, and port stern, respectively. In addition, the author had better to revise the oval shape as illustration of the two-dimension view of a Ferry ship to be more clearly describe the bow and stern parts. The conclusion of the paper is still weak. The applicable scope, the conclusion of the method being used, the benefit and the drawback had better to be concluded as well as the future improvement.

References:
Overall English used in the paper is somewhat less readability. There are still many grammatical error and sentence structures need to be improved for a better readability.

Other:

Originality	2 *(fair)*
Technical	2 *(fair)*
Methodology	3 *(average)*

Readability	1 *(poor)*
Practicability	3 *(average)*
Organization	2 *(fair)*
Importance	3 *(average)*

Additional Comment:

Attachment File:
Review Attachment

Reviewer (2)

Introduction:
Well improved and supported the research statement at the end Introduction.

Methodology:
Clear and well presented. However, there is a small mistake in mentioning the coordinate of the observation data which is said "-5.75 S". This is wrong, I think it should be "+5.75 S".

Results and Discussion:
Well done and nicely presented and laid out, but some minor mistakes still appear. It is written "The wind speed show's peak trend ....". The word "show's" is not correct and it should be either "show" or "showed" because it is a verb. Figures 3, 4, and 5 also shows ......The word "shows" is incorrect and it should be "show".

References:
The numbers and various references seem to be adequate. However, the authors are better if add some newer references from years 2019 and 2020 to strengthen their findings.

Other:
At the end of the abstract, the authors said the difference between their work and the sea trial. The authors are suggested to explain the reason behind this.

Originality	3 *(average)*
Technical	3 *(average)*
Methodology	3 *(average)*
Readability	3 *(average)*
Practicability	4 *(above average)*
Organization	3 *(average)*
Importance	4 *(above average)*

Additional Comment:

Attachment File:
-

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You must respond to this revise and resubmit request before **01 Mar 2021**, after which point we will presume that you have withdrawn your submission from International Journal of Technology (IJTech) Online System.

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Manuscript Submission Confirmation

Dear Dr. Andi Haris Muhammad,

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Configuration Design of Twin Rudder System on Course-Keeping Ability of A Ferry Ship Under Wind Condition

Put authors name here[1*], Put author name here[1], Put author name here[1], Put author name here[2], Put authors name here[2]

[1]*Put author’s affiliation here, complete with address, postal code, and country*
[2]*Put author’s affiliation here, complete with address, postal code, and country*
[2]*Put author’s affiliation here, complete with address, postal code, and country*

Abstract. Ship course-keeping plays a vital role in navigation safety, mainly when a ship operating under wind conditions. A method for controlling ship movements through the rudder system configuration is necessary to stabilise its ship's course. This paper describes the twin rudder system's configuration design on the ship course-keeping ability under wind conditions. Time-domain simulation of MATLAB-Simulink program was developed for this purpose. The Proportional Integral Derivative (PID) controller is used to adjust the ship‘s heading angle according to the desired path. Several parameters, such as relative wind velocity and directions, have been taken into account in the simulation. The result shows that at a wind direction of 88 deg., the ship course-keeping speed decreases. However, the increasing wind velocity causes a large deviation of the ship heading angle. Meanwhile, the ship‘s course-keeping speed increase with the rising wind speed direction of 219 deg. Ship course-keeping time with around 219 deg under wind direction of the simulation was 11.84% lower than the sea trial. The possible reason is that the simulation did not include wave and current.

Keywords: Proportional integral derivative controller; Course-keeping; Ship tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigations due to saving time and saving fuel consumption. To achieve the quality of ship course-keeping and generate accurate heading angles, a controller that considers ship hydrodynamics, both internal and external disturbances parameters, should be installed. Keeping the Ferry ship course is different from that of sea-going ships due to the navigation environment and ship particulars. The navigation environment’s complexity, especially wind load force and moment, makes ferry ship with the large superstructure, is more susceptible to marine accidents. Many studies relate to wind effect on ship maneuvering; the load force and moment of wind have significantly affected transversal and lateral projections of the windage area due to the large superstructure of the ship and wind velocity and direction relative to ship (Fujiwara and Ueno, 2006). Paroka et al. (2016) have simulated the effect of wind on ferry ship maneuvering. They explained that changes in ship speed caused by wind are highly dependent on wind velocity and direction. When the wind direction came from the bow to the ship's starboard (0 to 100 deg.), its speed tends to decrease. While the decrease in ship speed is not significant in the wind’s direction comes from the starboard to the ships stern

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(100 to 180 deg.). Whereas when the wind blowing from the side of the ship (20 to 140 deg.), it tends to change its direction. The direction deviations of the ship caused by wind vary for each type of ship, and the steering response is required. Ohtsu et al. (1996) reported that the wind blowing from starboard bow quarters (45 deg.) made the ship's steering becomes less sensitive but more sensitive when the wind was coming from the port stern quarters (135 deg.). It is crucial to increase the ship speed to change due to the different direction of the wind. This behaviour information is essential to improve ship course-keeping quality, especially when the ships need to take appropriate action in handling the wind disturbances. The improving quality of the ship's course-keeping ability in wind conditions is strongly influenced by the steering response to the wind blowing load through the appropriate configuration design of the rudder system (Hasegawa et al., 2006). The steering control has an essential role in responding to external forces to the ship's yaw motion stability and course-keeping ability during manoeuvers (Paroka, 2020).

Many efforts to improve ship maneuvering have been carried out by using a twin rudder ship controller. Yoshimura and Sakurai (1989) investigated the effect of a ship-fitted twin-rudder twin-propeller on ship maneuvering. They found that a twin-rudder twin-propeller's hydrodynamic characteristics are not so different from those of a single-propeller single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ship maneuver fitted with a twin-propeller twin-rudder. Furthermore, Khanfir et al. (2011) have conducted captive model tests and free-running tests with a single-propeller twin-rudder and a twin-propeller twin-rudder ship. The tests' purpose is to evaluate the drift angle's effect on the rudder forces and some peculiar phenomena concerning normal rudder force for twin-rudder ships.

Other parameters that affect ship maneuver performance are from distance spacing between single rudders in the twin-rudder ship. Gim (2013) carried out a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5 - 1.0 chord length of the rudder. It was found that this spacing distance between rudders in twin-rudder configurations is also affected by the interaction between the rudders, and the critical distance should be less than 1.0 chord length of rudder to decrease turbulence flow and vortices. This result is similar to the findings of Chen et al. (2018) by using numerical simulation, confirming the excellent characteristics of the twin-rudder ship compared with those of a single-rudder ship. Chen et al. (2018) concluded that a ship fitted with a twin-rudder would operate very well at 15 deg. of rudder angles. Additionally, the effectiveness of the twin rudders' stopping performance at the lateral spacing equals 1.3 chord length of the rudder.

Based on the studies mentioned earlier, the rudder system's configuration is the most crucial feature in achieving ship controllability goals. The rudder system must alter the ship control to the desired heading angle, both due to ship internal and external disturbances parameters. This paper focuses on applying the twin-rudder system to improve ferries' course-keeping quality under wind conditions. Simulating the fluctuated wind velocity and direction according to the ship's operating route, the ship's course-keeping quality with accurate heading angles may be achieved and increase the ship's safety.

2. Methods

2.1. Mathematical Model

Ship maneuvering analysis using computer simulation utilizes modular mathematical models, including considering hydrodynamic derivative. The models were based on the surge, sway, and yaw motion (Equation 1), using the coordinate system shown in Figure 1.

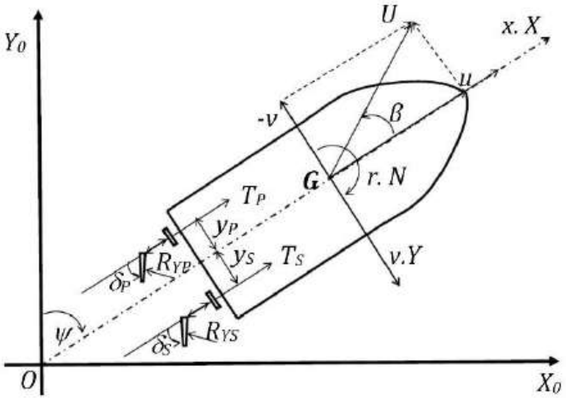

Figure 1 Coordinate system of ship

$$
\begin{aligned}
m(\dot{u}-rv) &= X_H + X_P + X_R + X_W \\
m(\dot{v}-ru) &= Y_H + Y_P + Y_R + Y_W \\
I_{ZZ}\ddot{\psi} &= N_H + N_P + N_R + N_W
\end{aligned}
\tag{1}
$$

The notations of u, v and r, are velocity components at the ship's centre of gravity (G). m and I_{ZZ} represent the mass of the ship and moments of inertia. X, Y, and N represent the hydrodynamic forces and moment. The subscript H, P, R, and W refer to hull, propeller, rudder, and wind. In principle, force and moment induced by hull (X_H, Y_H, and N_H) approximate β and r' polynomial function. The equations were expressed by Yoshimura et al. (2001) in Equation 2.

$$
\begin{aligned}
X_H &= \tfrac{1}{2}\rho LdU^2(X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr}r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\
Y_H &= \tfrac{1}{2}\rho LdU^2(Y'_\beta\beta + (Y'_r - m'_x)r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr}r'^3) \\
N_H &= \tfrac{1}{2}\rho L^2 dU^2(N'_\beta\beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr}r'^3)
\end{aligned}
\tag{2}
$$

where: β is the drift angle at the midship position by $\tan^{-1}(v/u)$ and r' non-dimensionalized yaw rate by rL/U. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} are called the hydrodynamic derivatives on ship maneuvering. Force and moment induced by twin-propeller (X_P Y_P and N_P) can be expressed by Khanfir et al. (2011) in Equation 3.

$$
\begin{aligned}
X_P &= \rho\Big((1-t_{P(S)})y_{P(S)}{n_{P(S)}}^2{D_{P(S)}}^4K_{T(S)}(J_{P(S)}) + (1-t_{P(P)})y_{P(P)}{n_{P(P)}}^2{D_{P(P)}}^4K_{T(P)}(J_{P(P)})\Big) \\
N_P &= \rho\Big((1-t_{P(S)})y_{P(S)}{n_{P(S)}}^2{D_{P(S)}}^4K_{T(S)}\Big) + \rho\Big((1-t_{P(P)})n_{P(P)}{}^2{D_{P(P)}}^4K_{T(P)}\Big)
\end{aligned}
\tag{3}
$$

where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}}) = k_0 + k_1 J_{P\substack{(S)\\(P)}} + k_2 J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\substack{(S)\\(P)}} = (u - y_P r(1-w_{P\substack{(S)\\(P)}})/(n_{P\substack{(S)\\(P)}}D_{P\substack{(S)\\(P)}})$

where: t_P is the thrust deduction coefficient in straightforward moving; K_T is the thrust coefficient of propeller force; n_P is the propeller revolution. D_P is the propeller diameter; w_P is the effective wake fraction coefficient at propeller location; J_P is the advance coefficient; while k_0, k_1, and k_2 are the constants for open water propeller, respectively. The sub-subscript (S) and (P) refer to starboard and portside.

Force and moment due to twin-rudder (X_R Y_R and N_R) can be expressed by Equation 4 to 8 (Khanfir et al., 2011).

$$
\begin{aligned}
X_R &= -(1-t_{R(S)}F_{RY(S)}\sin\delta_{(S)} - (1-t_{R(P)}F_{RY(P)}\sin\delta_{(P)} \\
Y_R &= -(1+a_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{R(YS)}\cos\delta_{(P)}\right) \\
N_R &= -(x_R + a_H x_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{RY(P)}\cos\delta_{(P)}\right) + f(x_R) \\
f(x_R) &= y_{P(S)}(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)}
\end{aligned}
\tag{4}
$$

where: δ is the rudder angle; x_R and z_R are the representations of rudder location, and t_R, a_H, and x_H are the interactive force coefficients among hull, propeller, and rudder, as the functions of the advance constant of the propeller. The rudder normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5.

$$
F_{RY^{(S)}_{(P)}} = \tfrac{1}{2}\rho A_R U_{R^{(S)}_{(P)}}^{\;2} f_\alpha \sin\alpha_{R^{(S)}_{(P)}} \tag{5}
$$

where: A_R is the rudder area; f_α is the gradient of the lift coefficient of the rudder, and it can be approximated by the function of the rudder aspect ratio (f_α =6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6.

$$
U_{R^{(S)}_{(P)}} = \sqrt{u_{R^{(S)}_{(P)}}^{\;2} + v_{R^{(S)}_{(P)}}^{\;2}} \qquad \text{and} \qquad \alpha_{R^{(S)}_{(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R^{(S)}_{(P)}}\left(\beta_{R^{(S)}_{(P)}}\right) \tag{6}
$$

The effective inflow velocity (u_R) to the rudder in surge direction can be expressed by Equation 7.

$$
u_{R^{(S)}_{(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P^{(S)}_{(P)}} \times \sqrt{\eta_{P^{(S)}_{(P)}}\left\{1+\kappa\left(\sqrt{1+8K_{T^{(S)}_{(P)}}\Big/\pi J_{P^{(S)}_{(P)}}^{\;2}}-1\right)\right\}^2 + (1-\eta_{P^{(S)}_{(P)}})} \tag{7}
$$

where: $\varepsilon_{\substack{(S)\\(P)}} = 1 - w_{R^{(S)}_{(P)}}\Big/1 - w_{P^{(S)}_{(P)}}$; $\kappa = kx\Big/\varepsilon_{\substack{(S)\\(P)}}$; $\eta_{P^{(S)}_{(P)}} = D_{P^{(S)}_{(P)}}\Big/H_{R^{(S)}_{(P)}}$; $u_{P^{(S)}_{(P)}} = \left(1 - w_{P^{(S)}_{(P)}}\right)\left(u - y_{P^{(S)}_{(P)}}r\right)$

Here, ε, κ, γ_R, and l_R are the parameters describing the rudder inflow velocity angle, while (1-w) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H) is the ratio of propeller diameter to rudder height.

The effective inflow velocity (v_R) to the rudder in sway direction can be expressed by Equation 8.

$$
v_{R^{(S)}_{(P)}} = u_{R^{(S)}_{(P)}} \tan\left(\delta_{R^{(S)}_{(P)}}\right) \tag{8}
$$

where: $\delta_{R^{(S)}_{(P)}} = \gamma_{R^{(S)}_{(P)}}\beta_{R^{(S)}_{(P)}} + \tan^{-1}\left(y_{R^{(S)}_{(P)}}\Big/x_{R^{(S)}_{(P)}}\right)$ and $\beta_{R^{(S)}_{(P)}} = \beta - L_{R^{(S)}_{(P)}}r$

Here, δ_R is the rudder angle; β_R is the effective drift angle at rudder; L_R is the flow-straightening coefficient of yaw rate. For the case of a ship operated under wind condition, force and moment (X_W, Y_W, and N_W) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006).

$$
X_W = C_{AX}(\psi_A)q_A A_F; \quad Y_W = C_{AY}(\psi_A)q_A A_L; \quad N_W = C_{AN}(\psi_A)q_A A_L L_{OA} \tag{9}
$$

where $\psi_A = \tan^{-1}\left[U_T\cos\psi + U\cos\beta / U_T\sin\psi - U\cos\beta\right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi+\beta)$

C_{AX}, C_{AY}, and C_{AN} are the wind load forces and moments coefficients, respectively, as a function of the wind direction relative to ship (ψ_A). U_T and ψ are wind velocity and direction angles with reference to the coordinate system; q_A is wind pressure, q_T is wind pressure due to elevation of the center of windage area, and q_S is wind pressure induced by wind velocity without elevation effect. A_F and A_L indicate transversal and lateral projections of the windage area, respectively.

2.2. Ship Steering Autopilot

The rudder is the most critical feature in achieving controllability goals. The control system must alter the control surfaces to the desired heading angle. The schematic equation of a PID control system of the ship tracks can be expressed by Equation 10 (Lee et al.,2009).

$$\delta = K_p(e) + K_d(\dot{e}) + K_i\int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \tag{10}$$

where: δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain, and integral gain respectively; e is an error between heading target (ψ_T) and actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference headings angle. The reference heading angle equation and target zone correction can be expressed by Equations 11.

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t)/x_k - x(t)) \text{ and } (x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \tag{11}$$

Where: x_k and y_k are the track-point coordinates; $x(t)$ and $y(t)$ are the ship's coordinates position; R_0 is the target zone's radius.

2.3 Simulation Program

According to IMO (2002) criteria of ship maneuvering, the swept path should be used to analyse the ship's course-keeping prediction. The ship's swept path can be obtained by double integrating the ship motion mathematical model's acceleration includes hydrodynamic derivatives. Numerical integration of Dormand–Prince Method (Maimun et al., 2011 and Muhammad et al., 2015) then solves the equations of motion in this time-domain simulation MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for acting hull force and moment in Equation 2 and interaction force coefficient among hull, propeller, and rudder are predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). That regression equation is one of the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circle and zigzag maneuvering on ships with twin-rudder and twin-propeller systems and validation through model testing or free-running tests. In many cases, the regression equation has been used to predict ferry ship maneuvering under action wind and wave conditions (Paroka et al., 2015, 2016, and 2017b). The ship's resistance coefficients for simulation are predicted using Holtrop Method (Holtrop and Mennen, 1982; and Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\, J_P - 0.1178\, J_P{}^2$) is predicted using polynomial regression based on the open water test's statistical data for the B-series propeller (Carlton, 2007). The coefficient of wind load force and moment in equation 9 is predicted using the methodology proposed by Fujiwara et al. (2006). The control method used in the simulation is a proportional integrated derivative (PID) controller. The designed rudder angle (δ=±35 deg.) is calculated using Equation 10 with PID gain (K_p = 2.208; K_i = 0.027 and K_d = 45.372) and was selected using the pole placement method with the second-order linear Nomoto model of the ship (Nomoto et al., 1957). The methods used by Paroka et al. (2017a) in developing the automatic control system to predict avoiding ferry ship collision and compared by free-running experiment.

2.4 Ship and Sea Trial Data

The study's object is the ferry ship of KMP Bontoharu (1053 Gross Tonnage), owned by PT. ASDP Indonesia Ferry with twin-propellers and twin-rudders with the distance between rudder/propeller is 2.3 m. The particulars of the ship are presented in Table 1. The ship sea trial on Selayar to Bulukumba route is 15.385 nautical miles distance, 7268 second travelling time, around 6.03 m/s wind velocity, and 254 deg wind direction. The data was taken on 20th September 2015.

Table 1 Particulars of ship

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m²	182.87	*Z*	2 x 4
Lbp,m	47.45	A_F, m²	129.20	*D, m*	1.450
B, m	14	A_{OD}, m	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_C, m	2.70	*n*	8.784
V, m/s²	6.618	H_L, m	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, m	10.48	*Chord, m*	0.900
				A_R, m²	2 x 1.395
				BHP, HP	2 x 1000
				RPMME	1850

2.5 Wind Data

The monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years from 2006-2018 at 6-hourly intervals. The model provides wind speed data with a resolution of 0.25 x 0.25 degrees. This model has been validated by Dee et al. (2011). Furthermore, it has been validated locally by Lina et al. (2015) using eight buoys data deployed in the Yellow and the East China Seas. In this study, the coordinate for the observation data is on 5,75°S and 120.5°E.

3. Results and Discussion

The wind speed show peak trend in January with a maximum 10.06 m/s (88 deg.) trend as shown in Figure 2. Meanwhile, April's monthly wind speed trend has decreasing trends with the minimum trend of 6.41 m/s (219 deg.). The movements of monthly wind speed are varying depending on the month during West or East monsoon seasons.

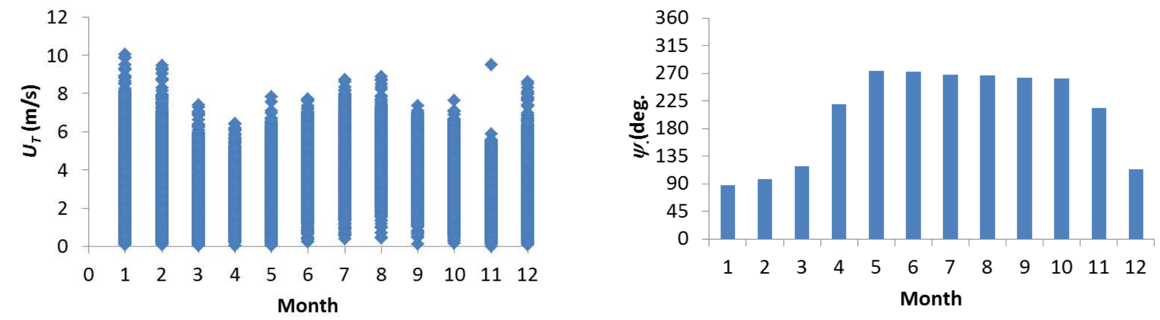

Figure 2 Significant wind velocity and direction in Selayar-Bulukumba route

Based on the wind data characteristics in Figure 2, course-keeping of a KMP Bontoharu has been simulated for three conditions of wind direction parameters, namely, starboard bow (88 deg.) and portside stern of the ship (219 and 268 deg.) by using the time domain simulation program of MATLAB-Simulink. The information is essential in ship navigation due to saving time and saving fuel consumption by controlling a twin rudder configuration design. Figure 3 show the history result of simulation for the track-keeping trajectory of a KMP Bontoharu (Selayar to Bulukumba) under wind velocities effect. The horizontal axis expresses time while the vertical axis expresses heading angle (ψ), rudder angle (δ), and speed ship (u), respectively. The wind blows from the starboard bow (88 deg) at wind velocities (10.06 m/s) for an initial ship speed (U) of 6.618 m/s. It was found that the track keeping trajectory, leaving slow track deviation from the initial track with low heading with big track keeping time compared without winds (U_T= 0 m/s). Meanwhile, the ships track keeping trajectory with increased wind velocities caused more deviation and low ship speed.

Figure 4 show the simulation results of the KMP Bontoharu track-keeping with wind blows from the portside stern (219 degrees) at a wind velocity range (0 to 20 m/s) for the initial ship speed (U) of 6.618 m/s. It was found that the track keeping trajectory, leaving fast track deviation from the initial track with high heading with short track-keeping time at each blown wind velocity compared without winds (U_T = 0 m/s). These characteristics are different when the wind blows from the starboard side (88 deg.). The wind direction angle causes these differences as found by Ohtsu et al. (1996) related to changes in a ship heading and rudder angle caused by wind velocity and direction on a ship's track-keeping. Figure 5 show the history result of simulation for the track-keeping trajectory of a KMP Bontoharu with wind blows from the portside stern (268 deg.) at wind velocity range (0 to 20 m/s) for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed is 0.27% reduce compared without winds (U_T=0 m/s), while the speed of the ship 5.96 % increases at a wind speed of 20 m/s. The changes in the speed of the ship are caused by the direction of movement of the ship.

Figure 6 show the sea trial simulation results for ship track-keeping trajectory with 6.03 m/s wind velocity and 254 deg. wind direction at an initial ship speed of 3.98 m/s. It was found that travelling time is 6.407second. The simulation travelling time is 11.84% higher compared with the sea trial result. The possible reason is that the simulation did not include wave and current.

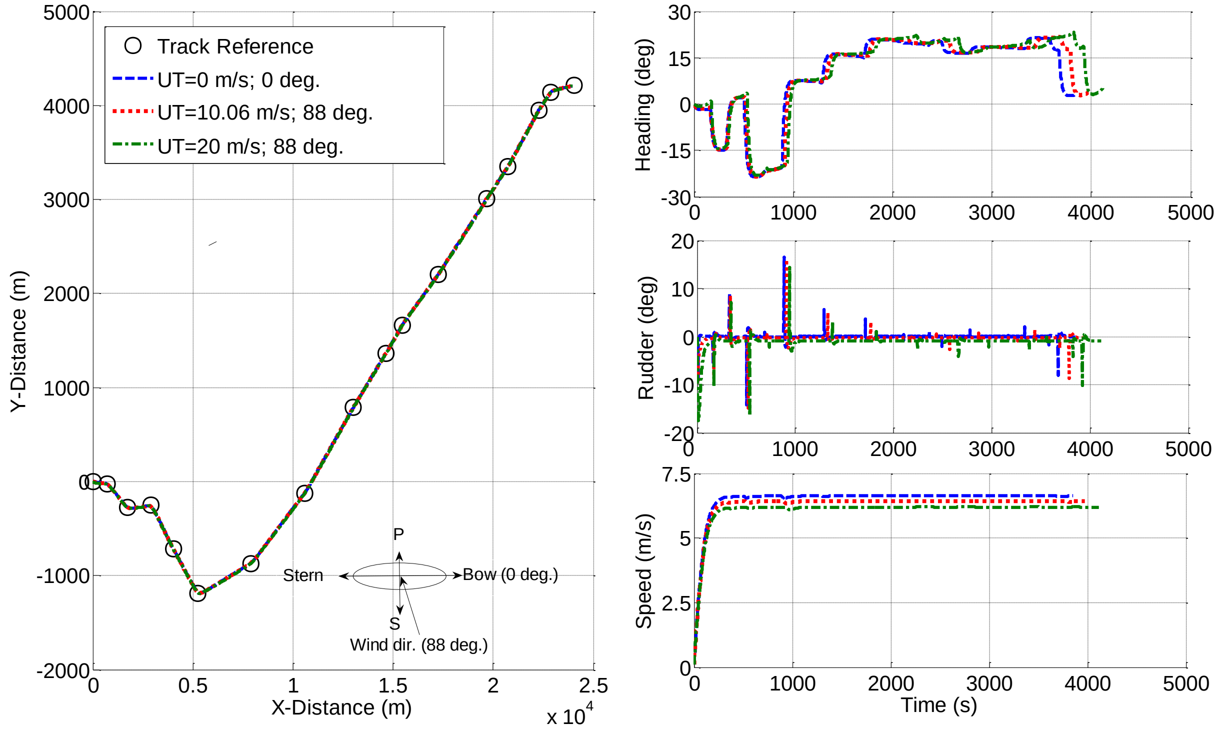

Figure 3 Ship trajectory with different wind speeds (U_T) at 88 deg.

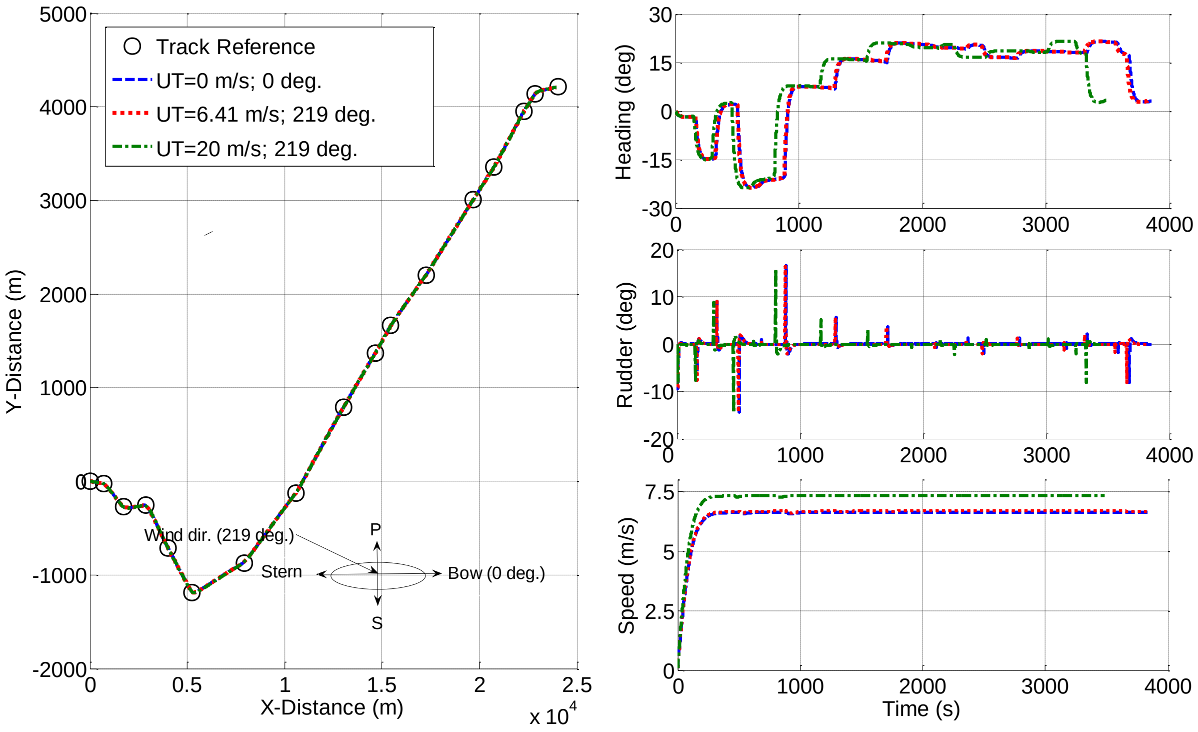

Figure 4 Ship trajectory with different wind speeds (U_T) at 219 deg.

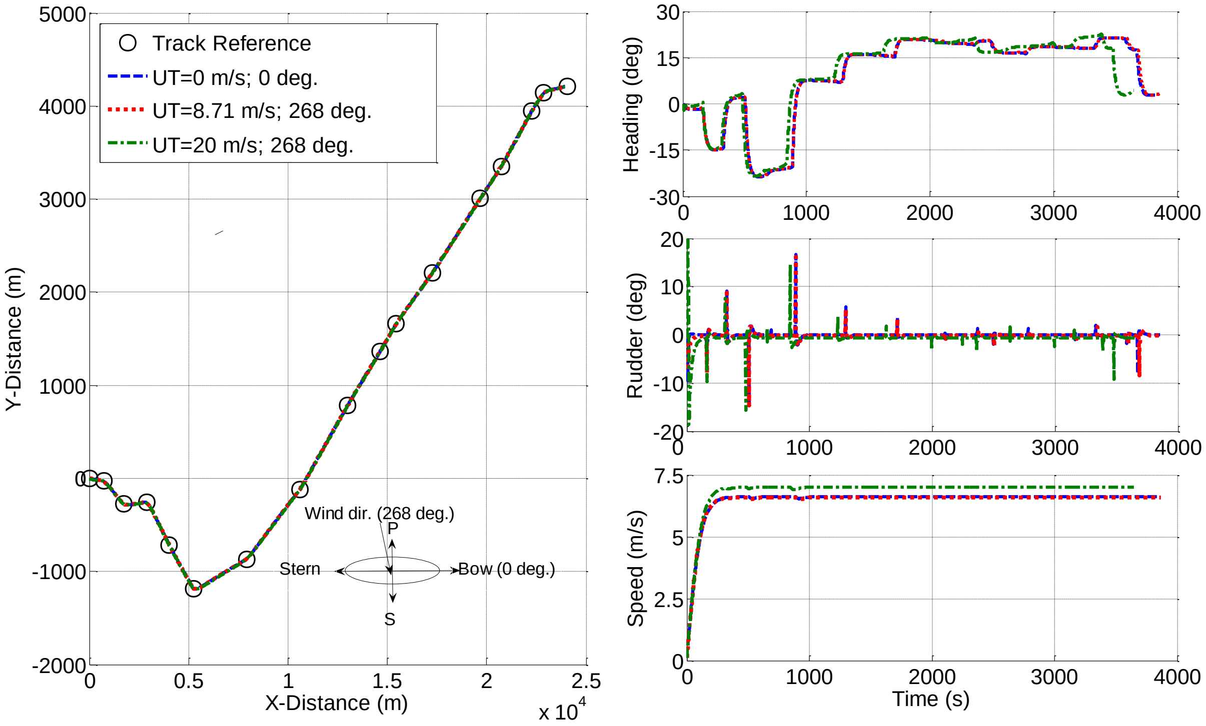

Figure 5 Ship trajectory with different wind speeds (U_T) at 268 deg.

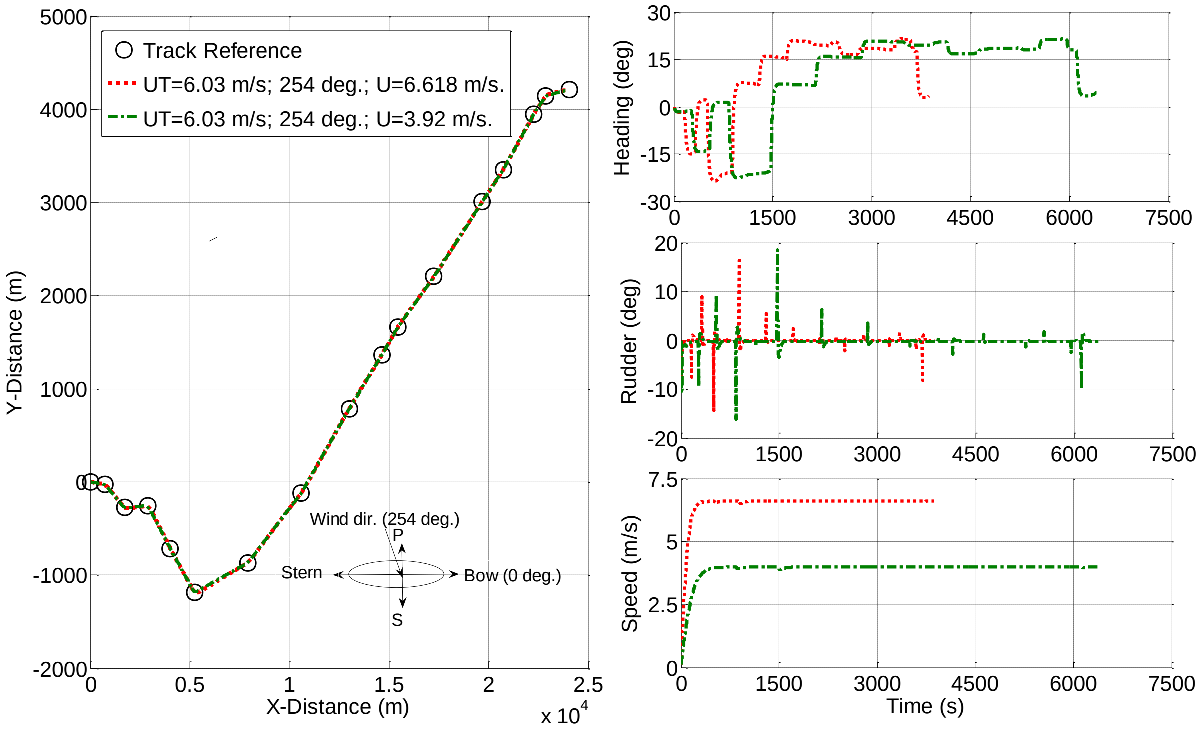

Figure 6 Sea trial simulation result of ship trajectory with different initial ship speeds (*U*).

Figures 3, 4, and 5 also show the effects of winds velocity and direction on ship speed track keeping trajectory for initial ship speed (*U*) of 6.618 m/s. It was found that under the wind blows from the starboard bow (88 deg.) with a wind velocity of 20 m/s, the ship speed was 6.36 %, which was reduced without wind (U_T=0 m/s). While if the wind blows from the portside stern (219 and 268 deg.), the ship speed was relatively increased by 10.74 and 5.96 %, respectively. The two latter are beneficial because the track trajectory time was minimum. In general, when the wind blows from the starboard and portside to the stern of the ship (98 to 268 deg.), the track trajectory time of the ship tend to benefit compared with wind blows from the bow to the starboard and portside of the ship as shown the simulation results in Figure 7. The ship's reduced speed when the wind blows from the bow to the starboard (less than 100 degrees) similar to the findings of Paroka et al. (2016) related to changes in ship speed caused by wind speed and direction on a ferry ship maneuvering.

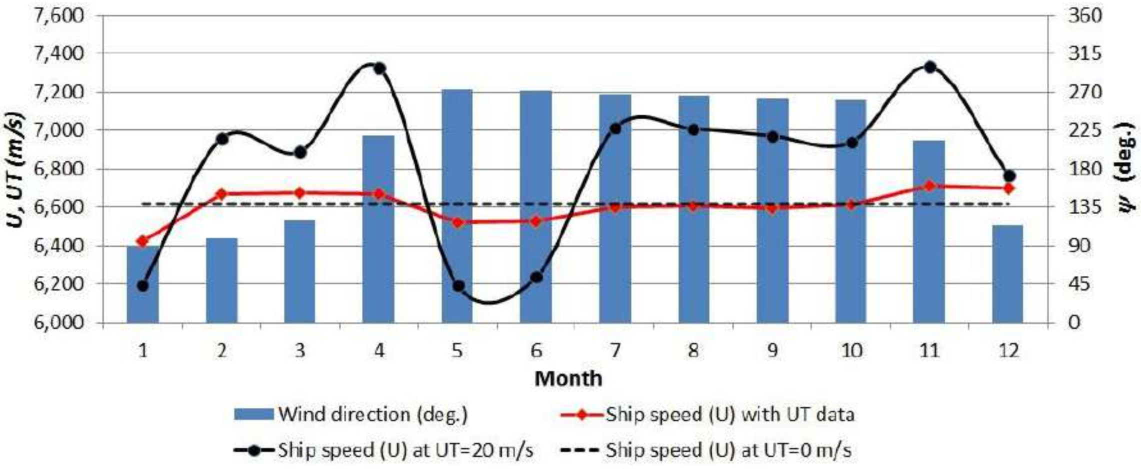

Figure 7 Tracking trajectories of ship speed with different wind velocities and direction.

4. Conclusions

A twin rudder system configuration on the ship course-keeping ability under wind speed and directions was analysed through the MATLAB-Simulink program's computer simulation. The results indicated that applying the twin rudder system to ferry ships' course-keeping ability in wind conditions is very well used by the PID controller to reduce ship deviation and increase ship speed by adjusting the ship's heading angle to the desired path. The track trajectory time of ferry ship course keeping caused by wind is highly dependent on wind velocity and direction. When the wind blows from the starboard and portside to stern (98 to 268 deg.), the ship's travel time tends to benefit compared with wind blows from the bow to the side of the ship. Through this research, the PID controller method can be applied to assist the movement of ships against other environmental influences such as waves and currents. However, the course-keeping quality of the ship is highly depend on the selected PID parameters.

Acknowledgements

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List of Changes

Manuscript:

Configuration Design of Twin Rudder System on Course-Keeping Ability of A Ferry Ship Under Wind Condition

Response and Revision made by Author(s)

Reviewer #1:

No	Comments	Revision/Changes
1	The quality of Fig. 1 is poor and not appropriate as a standard figure in a Journal paper. The fonts are small size, the image resolution is too low, and the drawing is not clear.	The quality of Fig. 1 (font size and resolution) have been revised in section 2 (page 2).
2	In responding the previous comment regarding the control method which is the most important on course-keeping, the authors described the method by using the trial and error method as written in Subsection 2.3. Why do the authors use the trial and error calculation? However, in the case of course-keeping of a Ferry ship which susceptible to wind condition, the authors had better to discuss more specific controller of course-keeping under wind load i.e. the disturbance observer, model-based controller, or other specific methods and figure out more clearly the specific control being used	The control method used in simulation as recommended by reviewer have been revised/added in subsection 2.3 (page 6). The specific controller designed in simulation has been described in abstract (sentence 6); section 1 (paragraph 4); sub section 2.2 and 2.3. Generally, the control method post revised has been improved to fast and more accurate the rudder angle and heading responds of the ship as shown in Figure 3-6.
3	In Section 3, Fig. 3 – 5, the authors described the wind direction of 88, 219, and 268 deg. as the wind blows from the starboard bow, port stern, and port stern, respectively. The following descriptions in the paragraph are also not consistent. It is obviously mistaken descriptions which should be described from the port bow, starboard stern, and port stern, respectively. In addition, the author had better to revise the oval shapes as illustration of the two-dimension view of a Ferry ship with a proper illustration to be more clearly describe the bow and stern parts.	The oval shapes as illustration describe the wind from the starboard bow (88 deg.) and Port stern (219 and 268 deg.) as recommended by reviewer has been revised in section 3 (Figure 3 -5).
4	The conclusion of the paper is still weak. The applicable scopes, the conclusion of the methods being used, the advantages and the drawbacks had better to be concluded as well for the future improvements.	The conclusions in this paper have been added in section 4 (sentence 6), regarding the advantages and drawback of PID controller method to applied in ship movement.
5	Overall English used in the paper is	Some grammatical errors and sentence

	somewhat less readability. There are still many grammatical error and sentence structures need to be improved for the better readability	structures as corrected by reviewer have been revised. (in blue color)

Reviewer #2:

No	Comments	Revision/Changes
1	Introduction: Well improved and supported the research statement at the end Introduction.	-
2	Methodology: Clear and well presented. However, there is a small mistake in mentioning the coordinate of the observation data which is said "-5.75 S". This is wrong, I think it should be "+5.75 S".	The symbol typing error as corrected by reviewer have been revised in methodology section (sub section 2.3.)
3	Results and Discussion: Well done and nicely presented and laid out, but some minor mistakes still appear. It is written "The wind speed show's peak trend ....". The word "show's" is not correct and it should be either "show" or "showed" because it is a verb. Figures 3, 4, and 5 also shows ......The word "shows" is incorrect and it should be "show".	The word typing errors as corrected by reviewer have been revised in result and discussion section (section 3).
4	References: The numbers and various references seem to be adequate. However, the authors are better if add some newer references from years 2019 and 2020 to strengthen their findings.	- The new references (2020) used related to this research as recommended by reviewer have been added in introduction (section 1, paragraph 1) and references list.
5	Other: At the end of the abstract, the authors said the difference between their work and the sea trial. The authors are suggested to explain the reason behind this.	The author suggestion related to differences between simulation and sea trial as recommended by reviewer has been added in abstract (page 1).

Editor:

No	Notes	Revision/Changes
1	Please revise according to the reviewer's comment, and highlights in different color that changed 2. It is suggested to include at least 3 relevant IJTech articles as references	Some Ijtech articles relate to this research have been cited in introduction (Paroka, 2020), methodology (Muhammad et al., 2015 and Paroka et al., 2017). Over all, the manuscript has been revised as requested by reviewers shown in blue color

Lampiran 9

Universitas Hasanuddin

Andi Haris <andi_haris@ft.unhas.ac.id>

[IJTech] Editor Decision

2 messages

IJTech <noreply@ijtech.eng.ui.ac.id> Mon, Mar 8, 2021 at 2:13 PM
Reply-To: "noreply@ijtech.eng.ui.ac.id" <noreply@ijtech.eng.ui.ac.id>
To: andi_haris@ft.unhas.ac.id
Cc: d_paroka@yahoo.com, sabarahman5@gmail.com, mr.firmansyah@gmail.com

International Journal of Technology
www.ijtech.eng.ui.ac.id

Editor Decision on #R3-ME-3829 : Accepted

Ms ID **#R3-ME-3829**
Title : CONFIGURATION DESIGN OF TWIN RUDDER SYSTEM ON COURSE-KEEPING ABILITY OF A FERRY SHIP UNDER WIND CONDITION
Author(s) : Andi Haris Muhammad, Daeng Paroka, Sabaruddin Rahman, Mohammad Rizal Firmansyah

Dear **Dr. Andi Haris Muhammad** ,

Greetings from Depok,

The editorial board is delighted to inform you that your paper entitled "CONFIGURATION DESIGN OF TWIN RUDDER SYSTEM ON COURSE-KEEPING ABILITY OF A FERRY SHIP UNDER WIND CONDITION" has been accepted to be published on IJTech. **Congratulation!**

In order to ensure the readability and the quality of the journal, Starting from 1st of January 2020, all accepted articles to publish will be subjected to article processing charge (APC) of US$ 550 for Regular Publication or US$ 650 for Special Edition Publication, as announced in IJTech's website. This fee covers the review process, line editing, layouting, DOI deposit, printing, and shipping cost.

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Warmest regards,

Dr. Mohammed Ali Berawi
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Editor in Chief
International Journal of Technology (IJTech)
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IJTech is currently indexed in SCOPUS and Emerging Sources Citation Index (ESCI) Thomson Reuters

Andi Haris <andi_haris@ft.unhas.ac.id> Mon, Mar 8, 2021 at 7:23 PM
To: andiharis.m@gmail.com

[Quoted text hidden]

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Andi Haris <andi_haris@ft.unhas.ac.id>

Confirmation of IJTech payment

1 message

Andi Haris <andi_haris@ft.unhas.ac.id> Tue, Mar 9, 2021 at 5:58 PM
To: ijtech@eng.ui.ac.id

Dear Editor in Chief IJTech,

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Nama : ANDI HARIS MUHAMMAD
Nomor Rekening : 0573272381
Nama Cabang : BNI TAMALANREA

Jumlah : 8.085.000

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IJTech <ijtech@eng.ui.ac.id> Mon, Mar 15, 2021 at 12:59 PM
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Cc: andiharis.m@gmail.com

Dear Dr. Andi Haris Muhammad,

Thank you for your confirmation and for sending the payment slip,

Please find the attachment to see the receipt,

We greatly appreciate your efforts to follow the new system at IJTech.

We will notify you about the next publication process

If there are any inquiries, do not hesitate to contact us,

Thank you for your cooperation,

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On 2021-03-11 10:56, Andi Haris wrote:

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>
> Best regards,
>
> Andi Haris Muhammad
> Hasanuddin University
> Email: andi_haris@ft.unhas.ac.id; andiharis.m@gmail.com
> Telp: 081241793233

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Lampiran 11

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Andi Haris <andi_haris@ft.unhas.ac.id>

[IJTech-ME-3829] Result of Line-editing of the Paper

3 messages

IJTech <ijtech@eng.ui.ac.id> Thu, Apr 1, 2021 at 12:14 PM
To: andi_haris@ft.unhas.ac.id
Cc: d_paroka@yahoo.com, sabarahman5@gmail.com, mr.firmansyah@gmail.com

Dear Dr. Andi Haris Muhammad,

We have conducted line editing for your paper as part of the publication process in IJTech. Enclosed, please find the comments from the line editor indicated by the character in color besides black.
We would like to ask you to complete the following:

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After the revision complete, please send it back to ijtech@eng.ui.ac.id or reply to this email, no later than **April 03, 2021**
We will proceed to the next step (Layouting, Final proof & Copyright) of the revised paper before printing.

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Andi Haris <andi_haris@ft.unhas.ac.id> Sat, Apr 3, 2021 at 6:58 PM
To: IJTech <ijtech@eng.ui.ac.id>

Dear Editor in Chief IJTech,

Thank you very much for editing our paper entitled "Configuration Design of Twin Rudder System on Course-Keeping Ability of A Ferry Ship Under Wind Condition" (ME-3829). We would like to inform you that we have already revised / added the paper accordingly to the line editor comments with green font color. The evidence of the paper is attached in this email.

Best regards.

Andi Haris Muhammad

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Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions

Put author name here[1*], Put author name here[1], Put author name here[1], Put author name here[2], Put author name here[2]

[1]*Put author's affiliation here, complete with address, postal code, and country*
[2]*Put author's affiliation here, complete with address, postal code, and country*
[2]*Put author's affiliation here, complete with address, postal code, and country*

Abstract. Ship course-keeping plays a vital role in navigation safety, especially when a ship is operating under windy conditions. A method to control ship movements through rudder-system configuration is necessary to stabilize a ship's course. This paper describes the twin-rudder-system configuration design's impact on a ship's course-keeping ability under windy conditions. A time-domain simulation using the MATLAB-Simulink program was developed for this purpose. A proportional integral derivative (PID) controller was used to adjust the ship's heading angle according to the desired path. Several parameters—such as relative wind velocity and directions—were accounted for in the simulation. The result shows that, at a wind direction of 88º, the ship's course-keeping speed decreased; however, increasing wind velocity caused a large deviation in the ship's heading angle. Meanwhile, the ship's course-keeping speed increased with rising windspeed directions of 219º. The ship's course-keeping time, at around 219º under the simulation's wind direction, was 11.84% lower than during a previous sea-trial. A possible reason for this difference is that the simulation excluded waves and currents.

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Keywords: Proportional integral derivative controller; Course-keeping; Ship-tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigation due to time-saving and reduced fuel consumption. To achieve quality ship course-keeping and generate accurate heading angles, a controller that considers ship hydrodynamics—including both internal and external disturbance parameters—should be installed. Keeping a ferry ship on course differs from sea-going ships due to navigation environments and ship particulars. The navigation environment's complexity, and especially wind-load forces and moment, makes ferry ships with large superstructures more susceptible to marine accidents. Many studies have related wind effects to ship maneuvering; wind's load-force and moment have significantly affected transversal and lateral projections of windage areas due to ships' large superstructures, as well as wind velocities and directions relative to ships (Fujiwara and Ueno, 2006). Paroka et al. (2016) simulated wind's effect on ferry ships' maneuvering, explaining that ship-speed changes caused by wind highly depend on wind velocity and direction. When the wind blows from the bow direction and passes to the ship's starboard (0 to 100º), ship speed tends to decrease. The corresponding decrease in ship speed is insignificant when the wind blows from a starboard direction and passes to the ship's

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doi: 10.14716/ijteusch.v0i0.0000

stern (100 to 180º). Meanwhile, when the wind blows from the side of a ship (20 to 140º), it tends to change the ship's direction. A ship's directional deviations due to wind vary by ship type, and a steering response is required. Ohtsu et al. (1996) reported that a wind blowing from starboard-bow quarters (45º) made a ship's steering becomes less sensitive, but steering became more sensitive when the wind came from the port-stern quarters (135º). Increasing a ship's speed as wind directions change is crucial. The information informing this behavior is essential to improve ships' course-keeping quality—especially when ships must take appropriate action to handle wind disturbances. The improving quality of a ship's course-keeping ability in windy conditions is strongly influenced by steering responses to wind-blowing loads through an appropriately configured rudder system design (Hasegawa et al., 2006). Steering control plays an essential role in responding to external forces to a ship's yaw motion stability and course-keeping ability during maneuvers (Paroka, 2020).

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Many efforts to improve ships' maneuvering have been conducted using twin-rudder ship controllers. Yoshimura and Sakurai (1989) investigated the effect of a ship-fitted, twin-rudder, twin-propeller configuration on ships' maneuvering. They found that a twin-rudder, twin-propeller configuration's hydrodynamic characteristics did not differ significantly from the corresponding characteristics of a single-propeller, single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ships' maneuvering when fitted with a twin-propeller, twin-rudder configuration. Furthermore, Khanfir et al. (2011) conducted captive model tests and free-running tests with a single-propeller, twin-rudder ship and a twin-propeller, twin-rudder ship. These tests aimed to evaluate drift angles' effect on rudder forces and the peculiar phenomena concerning a normal rudder force for twin-rudder ships.

Other parameters that affect ships' maneuvering performance include the distance of spacing between single rudders in twin-rudder ships. Gim (2013) conducted a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5–1.0 times the chord length of the rudder. He found that this spacing distance between rudders in twin-rudder configurations was also affected by interactions between rudders, and he also found that this critical distance should be less than 1.0 times the chord length of the rudder in order to decrease the turbulence flow and vortices. This result was similar to the findings of Chen et al. (2018), who used numerical simulation to confirming the excellent characteristics of twin-rudder ships compared to single-rudder ships. Chen et al. (2018) concluded that a ship fitted with a twin-rudder configuration would operate very well at 15º rudder angles. Additionally, the twin rudders' effective performance stopped at a lateral spacing equal to 1.3 times the chord length of the rudder.

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These previous studies have shown that a rudder system's configuration is the most crucial feature in achieving ship controllability goals. A rudder system must alter ship control to the desired heading angle, due to both internal and external disturbance parameters. The current paper focuses on applying the twin-rudder system to improve ferries' course-keeping quality under windy conditions. By simulating fluctuating wind velocity and directions according to a ship's operating route, quality course-keeping and accurate heading angles may be achieved, increasing the ship's safety.

2. Methods

2.1. Mathematical Model

This study's ship maneuvering analysis used computer simulation to employ modular mathematical models, including a consideration of hydrodynamic derivatives. This study's models were based on surge, sway, and yaw motions (Equation 1) using the coordinate system shown in Figure 1.

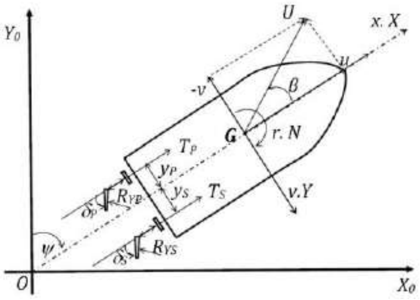

Figure 1 Coordinate ship system

$$
\begin{aligned}
&m(\dot{u}-rv)=X_H+X_P+X_R+X_W\\
&m(\dot{v}-ru)=Y_H+Y_P+Y_R+Y_W\\
&I_{ZZ}\ddot{\psi}=N_H+N_P+N_R+N_W
\end{aligned}
\qquad (1)
$$

The notations *u, v* and *r,* are velocity components at the ship's center of gravity (*G*). *m* and I_{ZZ} represent the ship's mass and moments of inertia. *X, Y*, and *N* represent the hydrodynamic forces and moment. The subscript *H*, *P, R,* and *W* refer to the ship's hull, propeller, rudder, and wind. In principle, the force and moment induced by hull (X_H, Y_H, and N_H) approximate *β* and *r'* polynomial function. These equations were expressed by Yoshimura et al. (2001) as Equation 2:

$$
\begin{aligned}
X_H &= \tfrac{1}{2}\rho LdU^2(X'_0+X'_{\beta\beta}\beta^2+(X'_{\beta r}-m'_y)\beta r'+X'_{rr}r'^2+X'_{\beta\beta\beta\beta}\beta^4)\\
Y_H &= \tfrac{1}{2}\rho LdU^2(Y'_\beta\beta+(Y'_r-m'_x)r'+Y'_{\beta\beta\beta}\beta^3+Y'_{\beta\beta r}\beta^2r'+Y'_{\beta rr}\beta r'^2+Y'_{rrr}r'^3)\\
N_H &= \tfrac{1}{2}\rho L^2dU^2(N'_\beta\beta+N'_rr'+N'_{\beta\beta\beta}\beta^3+N'_{\beta\beta r}\beta^2r'+N'_{\beta rr}\beta r'^2+N'_{rrr}r'^3)
\end{aligned}
\qquad (2),
$$

where *β* is the drift angle at the midship position by $\tan^{-1}(v/u)$ and *r'* non-dimensionalized yaw rate by *rL/U*. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} is the hydrodynamic derivatives on the ship's maneuvering. The force and moment induced by twin-propeller configurations (X_P, Y_P, and N_P) were expressed by Khanfir et al. (2011) in Equation 3:

$$
\begin{aligned}
X_P &= \rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2D_{P(S)}{}^4K_{T(S)}(J_{P(S)})+(1-t_{P(P)})y_{P(P)}n_{P(P)}{}^2D_{P(P)}{}^4K_{T(P)}(J_{P(P)})\Big)\\
N_P &= \rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2D_{P(S)}{}^4K_{T(S)}\Big)+\rho\Big((1-t_{P(P)})n_{P(P)}{}^2D_{P(P)}{}^4K_{T(P)}\Big)
\end{aligned}
\qquad (3),
$$

where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}})=k_0+k_1J_{P\substack{(S)\\(P)}}+k_2J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\substack{(S)\\(P)}}=(u-y_Pr(1-w_{P\substack{(S)\\(P)}}))/(n_{P\substack{(S)\\(P)}}D_{P\substack{(S)\\(P)}})$.

where t_P is the thrust deduction coefficient in straightforward moving, K_T is the thrust coefficient of the propeller force, and n_P is the propeller revolution. D_P is the propeller diameter, w_P is the effective wake fraction coefficient at the propeller's location, and J_P is the advance coefficient, while k_0, k_1, and k_2 are the constants for an open-water propeller. The sub-subscript *(S)* and *(P)* refer to starboard and portside.

Force and moment due to twin-rudder configurations (X_R, Y_R, and N_R) can be expressed by equations 4–8 (Khanfir et al., 2011).

$$\begin{aligned} X_R &= -(1-t_{R(S)}F_{RY(S)}\sin\delta_{(S)} - (1-t_{R(P)}F_{RY(P)}\sin\delta_{(P)} \\ Y_R &= -(1+a_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{R(YS)}\cos\delta_{(P)}\right) \\ N_R &= -(x_R + a_H x_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{RY(P)}\cos\delta_{(P)}\right) + f(x_R) \\ f(x_R) &= y_{P(S)}(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)} \end{aligned} \qquad (4),$$

where δ is the rudder angle, x_R and z_R are the rudder's location, and t_R, a_H, and x_H are the interactive force coefficients for the hull, propeller, and rudder as functions of the propeller's advance constant. The rudder's normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

$$F_{RY^{(S)}_{(P)}} = \tfrac{1}{2}\rho A_R U_{R^{(S)}_{(P)}}{}^2 f_\alpha \sin\alpha_{R^{(S)}_{(P)}} \qquad (5),$$

where A_R is the rudder area, and f_α is the gradient of the rudder's lift coefficient, which can be approximated by the function of the rudder's aspect ratio (f_α = 6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and the effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6:

$$U_{R^{(S)}_{(P)}} = \sqrt{u_{R^{(S)}_{(P)}}{}^2 + v_{R^{(S)}_{(P)}}{}^2} \qquad \text{and} \qquad \alpha_{R^{(S)}_{(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R^{(S)}_{(P)}}\left(\beta_{R^{(S)}_{(P)}}\right) \qquad (6)$$

The effective inflow velocity (u_R) to the rudder in the surge direction can be expressed by Equation 7:

$$u_{R^{(S)}_{(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P^{(S)}_{(P)}} \times \sqrt{\eta_{P^{(S)}_{(P)}}\left\{1+\kappa\left(\sqrt{1+8K_{T^{(S)}_{(P)}}\Big/\pi J_{P^{(S)}_{(P)}}{}^2} - 1\right)\right\}^2 + (1-\eta_{P^{(S)}_{(P)}})} \qquad (7),$$

where: $\varepsilon_{\substack{(S)\\(P)}} = 1 - w_{R^{(S)}_{(P)}} \Big/ 1 - w_{P^{(S)}_{(P)}}$; $\kappa = kx \Big/ \varepsilon_{\substack{(S)\\(P)}}$; $\eta_{P^{(S)}_{(P)}} = D_{P^{(S)}_{(P)}} \Big/ H_{R^{(S)}_{(P)}}$; $u_{P^{(S)}_{(P)}} = \left(1 - w_{P^{(S)}_{(P)}}\right)\left(u - y_{P^{(S)}_{(P)}} r\right)$.

Here, ε, κ, γ_R, and l_R are the parameters describing the rudder inflow velocity angle, while (1-w) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H) is the ratio of the propeller diameter to the rudder height.

The effective inflow velocity (v_R) to the rudder in the sway direction can be expressed by Equation 8:

$$v_{R^{(S)}_{(P)}} = u_{R^{(S)}_{(P)}} \tan\left(\delta_{R^{(S)}_{(P)}}\right) \qquad (8),$$

where: $\delta_{R^{(S)}_{(P)}} = \gamma_{R^{(S)}_{(P)}} \beta_{R^{(S)}_{(P)}} + \tan^{-1}\left(y_{R^{(S)}_{(P)}} \Big/ x_{R^{(S)}_{(P)}}\right)$ and $\beta_{R^{(S)}_{(P)}} = \beta - L_{R^{(S)}_{(P)}} r$.

Here, δ_R is the rudder angle, β_R is the effective drift angle at the rudder, and L_R is the flow-straightening coefficient of the yaw rate. For the case of a ship operating under windy conditions, the force and moment (X_W, Y_W, and N_W) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A) q_A A_F; \quad Y_W = C_{AY}(\psi_A) q_A A_L; \quad N_W = C_{AN}(\psi_A) q_A A_L L_{OA} \qquad (9),$$

where $\psi_A = \tan^{-1}\left[U_T\cos\psi + U\cos\beta / U_T\sin\psi - U\cos\beta\right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi+\beta)$.

C_{AX}, C_{AY}, and C_{AN} are the wind load forces and moments' coefficients, respectively, as a function of the wind direction relative to a ship (ψ_A). U_T and ψ are wind velocity and direction angles with reference to the coordinate system, q_A is wind pressure, q_T is wind pressure due to the elevation of the center of a windage area, and q_S is the wind pressure induced by wind velocity, without an elevation effect. A_F and A_L are the transversal and lateral projections of the windage area, respectively.

2.2. Autopilot Ship Steering

The rudder is the most critical feature in achieving controllability goals. The control system must alter the control surfaces to the desired heading angle. The schematic equation of the PID control system that a ship tracks can be expressed by Equation 10 (Lee et al., 2009).

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$$\delta = K_p(e) + K_d(\dot{e}) + K_i \int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \qquad (10),$$

where δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain, and integral gain respectively; and e is an error between the heading target (ψ_T) and the actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference heading angles. The reference heading angle equation and target zone correction can be expressed by Equation 11:

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t)/x_k - x(t)) \text{ and } (x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \qquad (11).$$

where x_k and y_k are the track-point coordinates, $x(t)$ and $y(t)$ are the ship's coordinates position, and R_0 is the target zone's radius.

2.3. Simulation Program

According to IMO (2002) criteria for ship maneuvering, a swept path should be used to analyze a ship's course-keeping prediction. A ship's swept path can be obtained by double-integrating the ship motion mathematical model's acceleration, including hydrodynamic derivatives. A numerical integration of the Dormand–Prince method (Maimun et al., 2011; Muhammad et al., 2015) then solved the equations of motion in this time-domain simulation using the MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for the acting hull force and moment in Equation 2—and the interaction force coefficient among the hull, propeller, and rudder—were predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). This regression equation is among the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circles and zigzag maneuvering for ships with twin-rudder and twin-propeller systems, as well as validation through model testing or free-running tests. In many cases, the regression equation has been used to predict ferry ships' maneuvering under active wind and wave conditions (Paroka et al., 2015, 2016, 2017b). A ship's resistance coefficients for simulation were predicted using the Holtrop method (Holtrop and Mennen, 1982; Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\, J_P - 0.1178\, J_P^{\,2}$) was predicted using polynomial regression, based on the open water test's statistical data for the B-series propeller (Carlton, 2007). The coefficient of the wind load force and moment in Equation 9 was predicted using the methodology proposed by Fujiwara et al. (2006). The control method used in the simulation was a proportional integrated derivative (PID) controller. The designed rudder angle (δ=±35 deg.) was calculated using Equation 10 with a PID gain (K_p = 2.208; K_i = 0.027 and K_d = 45.372), and it was selected using the pole placement method with the second-order linear Nomoto model of the ship (Nomoto et al., 1957). The methods used by Paroka et al. (2017a) in developing an automatic control system to predict and avoid ferry-ship collisions were compared using a free-running experiment.

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2.4. Ship and Sea-Trial Data

The study's object was the *KMP Bontoharu* ferry ship (1053 gross tonnage), owned by PT. ASDP Indonesia Ferry. The ship has twin propellers and twin rudders, and the distance between the rudders and propellers is 2.3 m. The ship's particulars are presented in Table 1. The ship's sea trial on the Selayar-to-Bulukumba route was 15.385 nautical miles long, involving a 7,268-second traveling time, around a 6.03 m/s wind velocity, and a 254º wind direction. The trial data were taken on September 20, 2015.

Table 1 Ship particulars

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m^2	182.87	*Z*	2 x 4
Lbp,m	47.45	A_F, m^2	129.20	*D, m*	1.450
B, m	14	A_{OD}, m	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_G, m	2.70	*n*	8.784
V, m/s²	6.618	H_L, m	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, m	10.48	*Chord, m*	0.900
				A_R, m^2	2 x 1.395
				BHP, HP	2 x 1000
				RPMME	1850

2.5. Wind Data

Monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years, from 2006 to 2018, at six-hour intervals. The model provided wind speed data with a resolution of 0.25 x 0.25 degrees. This model was validated by Dee et al. (2011). Furthermore, it was validated locally by Lina et al. (2015) using data from eight buoys deployed in the Yellow Sea and the East China Sea. This study's coordinate for its observation data was at 5.75ºS and 120.5ºE.

3. Results and Discussion

The wind speed trend peaked in January, with a maximum of 10.06 m/s (88º), as Figure 2 shows. Meanwhile, April's monthly wind speed trend decreased, with a minimum of 6.41 m/s (219º). The monthly wind speed movements varied, depending on the month occurring during the west or east monsoon seasons.

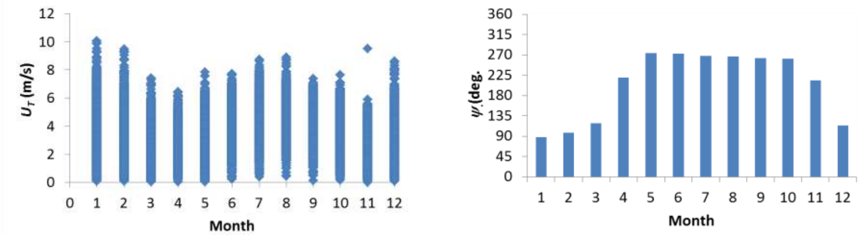

Figure 2 Significant wind velocity and direction on the Selayar–Bulukumba route

Based on the wind data characteristics in Figure 2, the *KMP Bontoharu*'s course-keeping was simulated for three conditions of wind direction parameters—the starboard bow (88º) and the portside stern of the ship (219 and 268º)—using the time domain simulation program of MATLAB-Simulink. This information is essential to ship navigation due to time-savings and reduced fuel consumption by controlling a twin-rudder configuration design. Figure 3 shows the historic result of the simulation for the course-keeping trajectory of the *KMP Bontoharu* (Selayar to Bulukumba) under wind velocities' effect. The horizontal axis expresses the time, while the vertical axis expresses the heading angle (ψ), rudder angle (δ), and ship speed (u), respectively. The wind blew from the starboard bow (88º) at wind velocities of 10.06 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory slowly deviated from the initial track with a low heading with significant course-keeping time compared to conditions without winds (U_T = 0 m/s). Meanwhile, the ship's course-keeping trajectory with increased wind velocities caused more deviations and low ship speeds.

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Figure 4 shows the simulation results for the *KMP Bontoharu*'s course-keeping with the wind blowing from the portside stern (219º) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory quickly deviated from the initial track with a high heading and short course-keeping time at each blown wind velocity, compared to conditions without winds (U_T = 0 m/s). These characteristics differed when the wind blew from the starboard side (88º). The wind direction angle caused these differences, as Ohtsu et al. (1996) found, relating to changes in a ship's heading and rudder angle as a result of wind velocity and ship direction in course-keeping. Figure 5 shows the historic results of the simulation for the course-keeping trajectory of the *KMP Bontoharu* with the wind blowing from the portside stern (268º) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed was 0.27% reduced compared to conditions without wind (U_T = 0 m/s), while the ship speed increased by 5.96% increases at a wind speed of 20 m/s. These changes in ship speed were caused by the ship's directional movements.

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Figure 6 shows the sea-trial simulation results for the ship course-keeping trajectory with a 6.03 m/s wind velocity and a 254º wind direction at an initial ship speed of 3.98 m/s. We found that the traveling time under these conditions stood at 6.407 seconds. The simulation's traveling time was 11.84% higher than the sea-trial result. A possible reason for this difference is that the simulation excluded waves and currents.

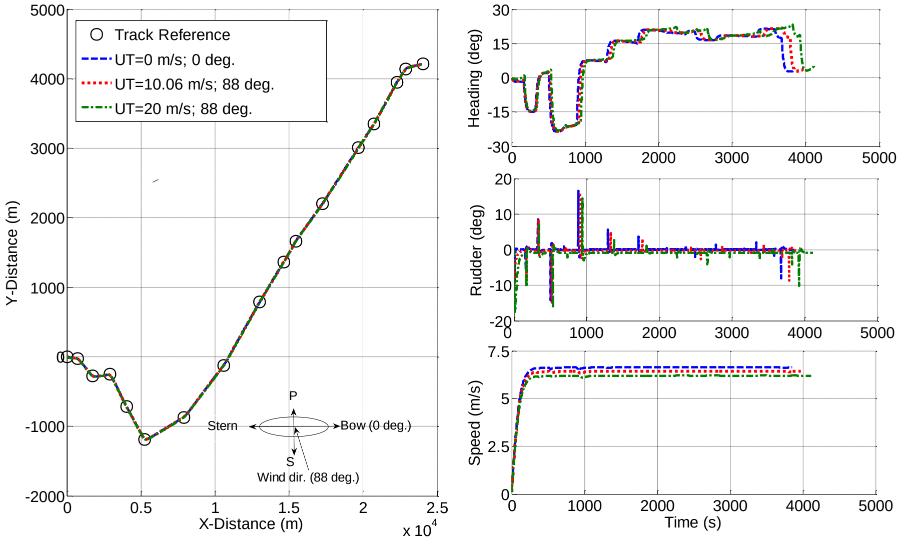

Figure 3 Ship trajectory with different wind speeds (U_T) at 88º

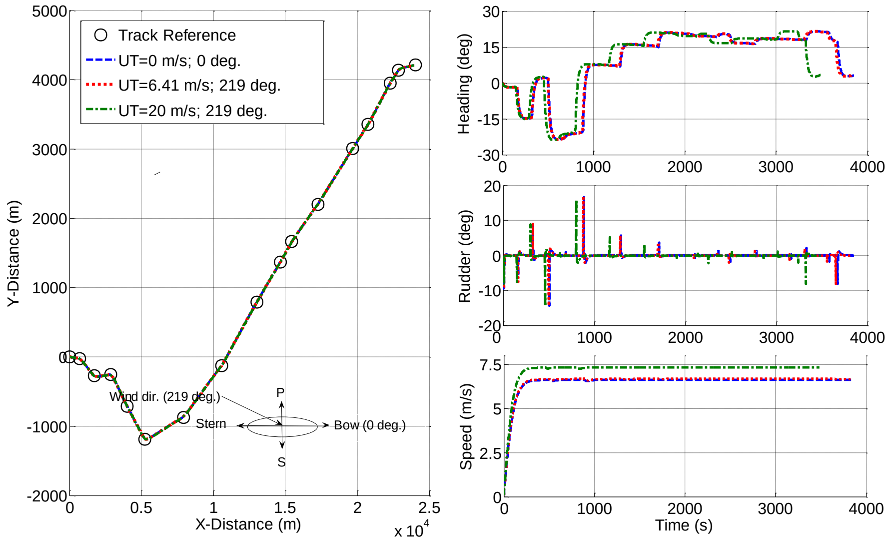

Figure 4 Ship trajectory with different wind speeds (U_T) at 219º

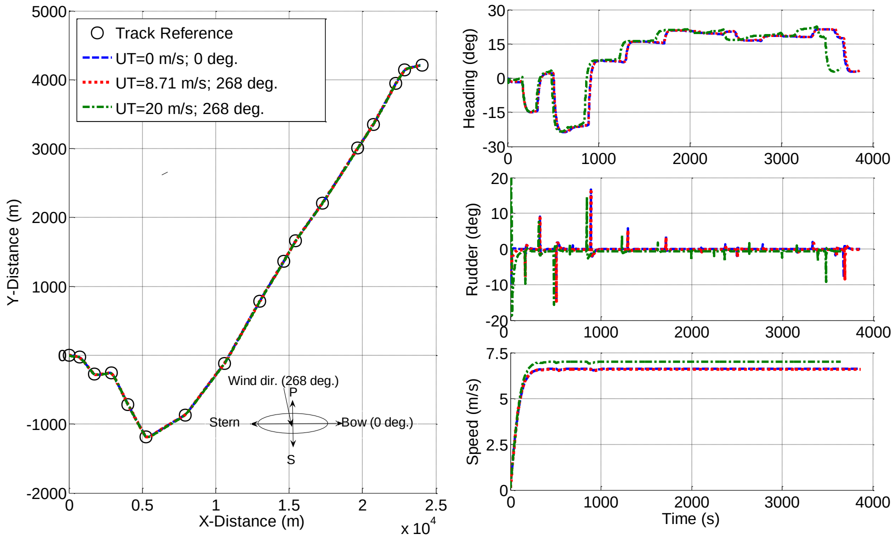

Figure 5 Ship trajectory with different wind speeds (U_T) at 268º

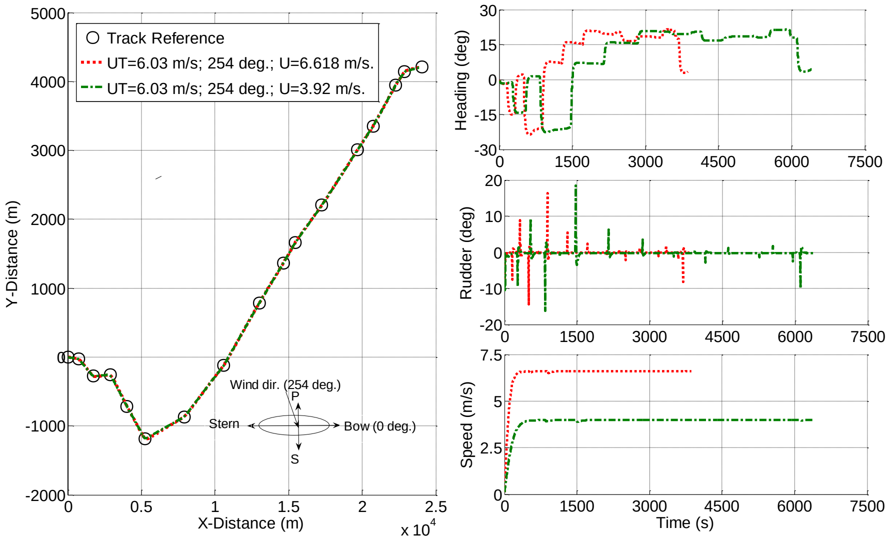

Figure 6 Sea-trial simulation result for ship trajectories with different initial ship speeds (*U*)

Figures 3, 4, and 5 also show the effects of winds velocity and direction on ship speed, with a course-keeping trajectory for an initial ship speed (*U*) of 6.618 m/s. We found that, when the wind blew from the starboard bow (88º) with a wind velocity of 20 m/s, the ship speed was 6.36% lower compared to conditions without wind (U_T = 0 m/s). Meanwhile, when the wind blew from the portside stern (219 and 268º), the ship speed was increased by 10.74% and 5.96%, respectively. The two latter speeds were beneficial because the track trajectory times were minimal. In general, when the wind blew from the starboard and portside to the stern (98 to 268º), the ship's track trajectory time tended to benefit compared to conditions with the wind blows from the bow to the starboard and portside, as the simulation results in Figure 7 show. The ship's reduced speed when the wind blew from the bow to the starboard (less than 100º) was similar to the findings of Paroka et al. (2016) related to ship-speed changes caused by wind speeds and directions' influence on ferry maneuvering.

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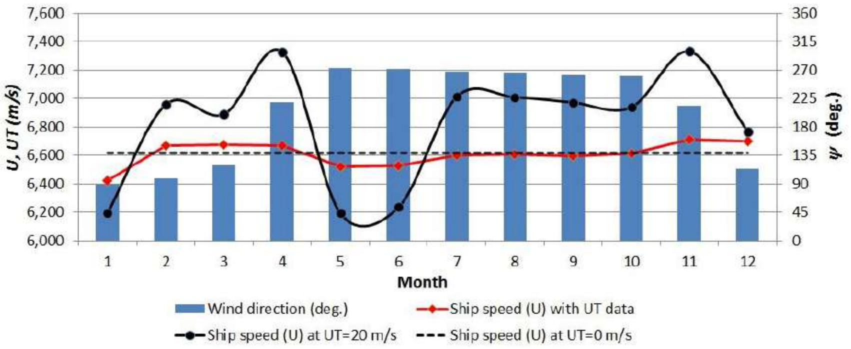

Figure 7 Tracking ship speed trajectories with different wind velocities and directions

4. Conclusions

This study has analyzed a twin-rudder-system configuration's influence on a ship's course-keeping ability under various wind speeds and directions through the MATLAB-Simulink computer-simulation program. The results indicated that applying a twin-rudder system to ferry ships' to improve their course-keeping ability under windy conditions is very effective using a PID controller, reducing ship deviation and increasing ship speed by adjusting the ship's heading angle to the desired path. The track trajectory time in the ferry's course-keeping highly depends on wind velocity and direction. When the wind blows from the starboard and portside to the stern (98 to 268º), a ship's travel time tends to benefit compared to when the wind blows from the bow to the side. This research shows that the PID controller method can be applied to assist ships' movements due to other environmental influences, such as waves and currents. However, ships' course-keeping quality highly depends on the selected PID parameters.

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Acknowledgments

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~~Configuration Design of~~ Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability ~~of A Ferry Ship Under Wind Condition~~under Windy Conditions

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Abstract. Ship course-keeping plays a vital role in navigation safety, ~~mainly~~especially when a ship is operating under windy conditions. A method ~~for controlling~~to control ship movements through ~~the~~ rudder-system configuration is necessary to ~~stabilise its ship's~~stabilize a ship's course. This paper describes the twin-rudder-system~~'s~~ configuration ~~design~~design's impact on ~~the ship~~a ship's course-keeping ability under windy conditions. ~~Time~~A time-domain simulation ~~of~~using the MATLAB-Simulink program was developed for this purpose. ~~The Proportional Integral Derivative~~A proportional integral derivative (PID) controller ~~is~~was used to adjust the ship's heading angle according to the desired path. Several parameters~~,~~ —such as relative wind velocity and directions~~, have been taken into account~~ —were accounted for in the simulation. The result shows that, at a wind direction of ~~88 deg.,~~88º, the ship's course-keeping speed ~~decreases. However, the~~decreased; however, increasing wind velocity cause~~s~~d a large deviation ~~of~~in the ship's heading angle. Meanwhile, the ship's course-keeping speed increased with ~~the~~ rising ~~wind speed direction of 219 deg. Ship~~windspeed directions of 219º. The ship's course-keeping time ~~with~~, at around ~~219 deg~~219º under the simulation's wind direction ~~of the simulation~~, was 11.84% lower than ~~the~~during a previous sea-trial. ~~The~~A possible reason for this difference is that the simulation ~~did not include wave~~excluded waves and currents.

Keywords: Proportional integral derivative controller; Course-keeping; Ship-tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigation~~s~~ due to time-saving ~~time~~ and ~~saving~~reduced fuel consumption. To achieve ~~the~~ quality ~~of~~ ship course-keeping and generate accurate heading angles, a controller that considers ship hydrodynamics~~,~~ —including both internal and external disturbance~~s~~ parameters~~,~~ —should be installed. Keeping ~~the Ferry~~a ferry ship on course ~~is different~~differs from ~~that of~~ sea-going ships due to ~~the~~ navigation environments and ship particulars. The navigation environment's complexity, and especially wind-load forces and moment, makes ferry ships with ~~the~~ large ~~superstructure, is~~superstructures more susceptible to marine accidents. Many studies ~~relate to~~have related wind ~~effect on~~effects to ship maneuvering; ~~the~~wind's load-force and moment ~~of wind~~ have significantly affected transversal and lateral projections of ~~the~~ windage areas due to ~~the~~ships' large ~~superstructure of the ship and~~superstructures, as well as wind velocit~~y~~ies and directions relative to ships (Fujiwara and Ueno, 2006). Paroka et al. (2016) ~~have~~ simulated ~~the~~wind's effect ~~of wind~~ on ferry ships' maneuvering~~. They explained~~, explaining that ship-speed changes ~~in ship speed~~ caused by wind ~~are~~ highly

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depend on wind velocity and direction. When the wind blows from the bow direction and passes to the ship's starboard (0 to 100º), ship speed tends to decrease. The corresponding decrease in ship speed is insignificant when the wind blows from a starboard direction and passes to the ship's stern (100 to ~~180 deg.). Whereas~~180º). Meanwhile, when the wind blow~~ing~~s from the side of ~~the~~a ship (20 to ~~140 deg.),~~140º), it tends to change ~~its~~the ship's direction. ~~The direction~~A ship's directional deviations ~~of the ship caused by~~ due to wind vary ~~for each~~by ship type~~ of ship~~, and ~~the~~a steering response is required. Ohtsu et al. (1996) reported that ~~the~~a wind blowing from starboard-bow quarters (~~45 deg.)~~45º) made ~~the~~a ship's steering becomes less sensitive, but steering became more sensitive when the wind ~~was coming~~came from the port-stern quarters (~~135 deg.). It~~ 135º). Increasing a ship's speed as wind directions change is crucial ~~to increase the ship speed to change due to the different direction of the wind. This behaviour~~ . The information informing this behavior is essential to improve ships' course-keeping quality~~,~~ —especially when ~~the~~ ships ~~need to~~must take appropriate action ~~in handling the~~to handle wind disturbances. The improving quality of ~~the~~a ship's course-keeping ability in windy conditions is strongly influenced by ~~the~~ steering responses to ~~the~~ wind-blowing loads through ~~the appropriate configuration design of the~~an appropriately configured rudder system design (Hasegawa et al., 2006). ~~The steering~~Steering control ~~h~~plays an essential role in responding to external forces to ~~the~~a ship's yaw motion stability and course-keeping ability during man~~o~~euvers (Paroka, 2020).

Many efforts to improve ships' maneuvering have been ~~carried out by~~ conducted using ~~a~~ twin-rudder ship controllers. Yoshimura and Sakurai (1989) investigated the effect of a ship-fitted, twin-rudder, twin-propeller configuration on ships' maneuvering. They found that a twin-rudder, twin-~~propeller's~~propeller configuration's hydrodynamic characteristics ~~are~~did not ~~so different~~differ significantly from ~~those of~~ the corresponding characteristics of a single-propeller, single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ~~ship maneuver~~ships' maneuvering when fitted with a twin-propeller, twin-rudder~~.~~ configuration. Furthermore, Khanfir et al. (2011)~~ have~~ conducted captive model tests and free-running tests with a single-propeller, twin-rudder ship and a twin-propeller, twin-rudder ship. ~~The tests' purpose is~~These tests aimed to evaluate ~~the~~ drift angle~~'~~s' effect on ~~the~~ rudder forces and ~~some~~the peculiar phenomena concerning a normal rudder force for twin-rudder ships.

Other parameters that affect ~~ship maneuver~~ships' maneuvering performance ~~are from~~include the distance of spacing between single rudders in ~~the~~ twin-rudder ships. Gim (2013) ~~carried out~~conducted a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5~~ – ~~–1.0 times the chord length of the rudder. ~~It was~~ He found that this spacing distance between rudders in twin-rudder configurations ~~is~~was also affected by ~~the interaction~~interactions between ~~the~~ rudders, and ~~the~~ he also found that this critical distance should be less than 1.0 times the chord length of the rudder in order to decrease the turbulence flow and vortices. This result ~~is~~was similar to the findings of Chen et al. (2018~~) by using~~), who used numerical simulation~~,~~ to confirming the excellent characteristics of ~~the~~ twin-rudder ships compared ~~with those of a~~to single-rudder ships. Chen et al. (2018) concluded that a ship fitted with a twin-rudder configuration would operate very well at ~~15 deg. of~~15º rudder angles. Additionally, the ~~effectiveness of the~~ twin

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rudders’ ~~stopping~~effective performance stopped at ~~the~~a lateral spacing ~~equals~~equal to 1.3 times the chord length of the rudder.

These previous studies have shown that a rudder system’s configuration is the most crucial feature in achieving ship controllability goals. A rudder system must alter ship control to the desired heading angle, due to both internal and external disturbance parameters. The current paper focuses on applying the twin-rudder system to improve ferries’ course-keeping quality under windy conditions. By simulating fluctuating wind velocity and directions according to a ship’s operating route, quality course-keeping and accurate heading angles may be achieved, increasing the ship’s safety.

2. Methods

2.1. Mathematical Model

This study’s ship maneuvering analysis used computer simulation to employ modular mathematical models, including a consideration of hydrodynamic derivatives. This study’s models were based on surge, sway, and yaw motions (Equation 1) using the coordinate system shown in Figure 1.

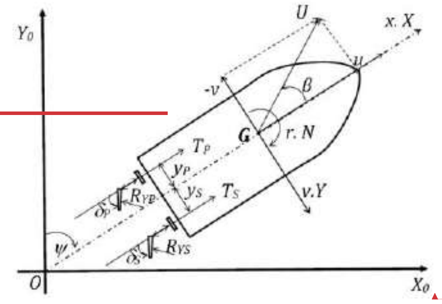

Figure 1 Coordinate ship system

$$m(\dot{u}-rv)=X_H+X_P+X_R+X_W \quad m(\dot{u}-rv)=X_H+X_P+X_R+X_W$$
$$m(\dot{v}-ru)=Y_H+Y_P+Y_R+Y_W \quad m(\dot{v}-ru)=Y_H+Y_P+Y_R+Y_W$$
$$I_{ZZ}\ddot{\psi}=N_H+N_P+N_R+N_W \quad I_{ZZ}\ddot{\psi}=N_H+N_P+N_R+N_W$$
(1)

The notations *u, v* and *r,* are velocity components at the ship’s center of gravity (*G*). *m* and I_{ZZ} represent the ship’s mass and moments of inertia. *X, Y,* and *N* represent the hydrodynamic forces and moment. The subscript *H, P, R,* and *W* refer to the ship’s hull, propeller, rudder, and wind. In principle, the force and moment induced by hull (X_H, Y_H, and N_H) approximate *β* and *r’* polynomial function. These equations were expressed by Yoshimura et al. (2001) as Equation 2:

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$$
\begin{aligned}
X_H &= \tfrac{1}{2}\rho L d U^2 (X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr} r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\
Y_H &= \tfrac{1}{2}\rho L d U^2 (Y'_\beta \beta + (Y'_r - m'_x) r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr} r'^3) \\
N_H &= \tfrac{1}{2}\rho L^2 d U^2 (N'_\beta \beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr} r'^3)
\end{aligned}
\qquad (2).
$$

where β is the drift angle at the midship position by tan^{-1}(v/u) and r' non-dimensionalized yaw rate by rL/U. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} is the hydrodynamic derivatives on the ship's maneuvering. The force and moment induced by twin-propeller configurations (X_P, Y_P, and N_P) were expressed by Khanfir et al. (2011) in Equation 3:

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\begin{aligned}
X_P &= \rho\left((1-t_{P(S)}) y_{P(S)} n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}(J_{P(S)}) + (1-t_{P(P)}) y_{P(P)} n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}(J_{P(P)})\right) \\
N_P &= \rho\left((1-t_{P(S)}) y_{P(S)} n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}\right) + \rho\left((1-t_{P(P)}) n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}\right)
\end{aligned}
\qquad (3).
$$

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where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}}) = k_0 + k_1 J_{P\substack{(S)\\(P)}} + k_2 J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\substack{(S)\\(P)}} = (u - y_P r(1 - w_{P\substack{(S)\\(P)}}))/(n_{P\substack{(S)\\(P)}} D_{P\substack{(S)\\(P)}})$.

where t_P is the thrust deduction coefficient in straightforward moving, K_T is the thrust coefficient of the propeller force, and n_P is the propeller revolution. D_P is the propeller diameter, w_P is the effective wake fraction coefficient at the propeller's location, and J_P is the advance coefficient, while k_0, k_1, and k_2 are the constants for an open-water propeller. The sub-subscript (S) and (P) refer to starboard and portside.

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Force and moment due to twin-rudder configurations (X_R, Y_R, and N_R) can be expressed by equations 4–8 (Khanfir et al., 2011).

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$$
\begin{aligned}
X_R &= -(1-t_{R(S)} F_{RY(S)} \sin\delta_{(S)} - (1-t_{R(P)} F_{RY(P)} \sin\delta_{(P)} \\
Y_R &= -(1+a_H)\left(F_{RY(S)} \cos\delta_{(S)} + F_{R(YS)} \cos\delta_{(P)}\right) \\
N_R &= -(x_R + a_H x_H)\left(F_{RY(S)} \cos\delta_{(S)} + F_{RY(P)} \cos\delta_{(P)}\right) + f(x_R) \\
f(x_R) &= y_{P(S)}(1-t_{R(S)}) F_{RY(S)} \sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)}) F_{RY(P)} \sin\delta_{(P)}
\end{aligned}
\qquad (4).
$$

where δ is the rudder angle, x_R and z_R are the rudder's location, and t_R, a_H, and x_H are the interactive force coefficients for the hull, propeller, and rudder as functions of the propeller's advance constant. The rudder's normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

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$$
F_{RY\substack{(S)\\(P)}} = \tfrac{1}{2}\rho A_R U_{R\substack{(S)\\(P)}}{}^2 f_\alpha \sin\alpha_{R\substack{(S)\\(P)}} \qquad (5).
$$

where A_R is the rudder area, and f_α is the gradient of the rudder's lift coefficient, which can be approximated by the function of the rudder's aspect ratio (f_α = 6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and the effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6:

$$
U_{R\substack{(S)\\(P)}} = \sqrt{u_{R\substack{(S)\\(P)}}{}^2 + v_{R\substack{(S)\\(P)}}{}^2} \qquad \text{and} \qquad \alpha_{R\substack{(S)\\(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R\substack{(S)\\(P)}}\left(\beta_{R\substack{(S)\\(P)}}\right) \qquad (6)
$$

The effective inflow velocity (u_R) to the rudder in the surge direction can be expressed by Equation 7:

$$u_{R\substack{(S)\\(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P\substack{(S)\\(P)}} \times \sqrt{\eta_{P\substack{(S)\\(P)}} \left\{1+\kappa\left(\sqrt{1+8K_{T\substack{(S)\\(P)}} \Big/ \pi J_{P\substack{(S)\\(P)}}^{\,2}} -1\right)\right\}^2 + (1-\eta_{P\substack{(S)\\(P)}})}$$

$$u_{R\substack{(S)\\(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P\substack{(S)\\(P)}} \times \sqrt{\eta_{P\substack{(S)\\(P)}} \left\{1+\kappa\left(\sqrt{1+8K_{T\substack{(S)\\(P)}} \Big/ \pi J_{P\substack{(S)\\(P)}}^{\,2}} -1\right)\right\}^2 + (1-\eta_{P\substack{(S)\\(P)}})} \qquad (7~~)~~).$$

where: $\varepsilon_{\substack{(S)\\(P)}} = 1-w_{R\substack{(S)\\(P)}} \Big/ 1-w_{P\substack{(S)\\(P)}}\,;\ \kappa = kx\Big/\varepsilon_{\substack{(S)\\(P)}}\,;\ \eta_{P\substack{(S)\\(P)}} = D_{P\substack{(S)\\(P)}} \Big/ H_{R\substack{(S)\\(P)}}\,;\ u_{P\substack{(S)\\(P)}} = \left(1-w_{P\substack{(S)\\(P)}}\right)\left(u-y_{P\substack{(S)\\(P)}}r\right)$

$$\varepsilon_{\substack{(S)\\(P)}} = 1-w_{R\substack{(S)\\(P)}} \Big/ 1-w_{P\substack{(S)\\(P)}}\,;\ \kappa = kx\Big/\varepsilon_{\substack{(S)\\(P)}}\,;\ \eta_{P\substack{(S)\\(P)}} = D_{P\substack{(S)\\(P)}} \Big/ H_{R\substack{(S)\\(P)}}\,;\ u_{P\substack{(S)\\(P)}} = \left(1-w_{P\substack{(S)\\(P)}}\right)\left(u-y_{P\substack{(S)\\(P)}}r\right).$$

Here, *ε, κ, γ*$_R$, and *l*$_R$ are the parameters describing the rudder inflow velocity angle, while (*1*-*w*) and *η* are the propeller wake fraction and effective efficiency, respectively. (*D*$_P$/*H*) is the ratio of the propeller diameter to the rudder height.

The effective inflow velocity (*v*$_R$) to the rudder in the sway direction can be expressed by Equation 8:

$$v_{R\substack{(S)\\(P)}} = u_{R\substack{(S)\\(P)}} \tan\left(\delta_{R\substack{(S)\\(P)}}\right) \quad v_{R\substack{(S)\\(P)}} = u_{R\substack{(S)\\(P)}} \tan\left(\delta_{R\substack{(S)\\(P)}}\right)$$

(8~~)~~).

where: $\delta_{R\substack{(S)\\(P)}} = \gamma_{R\substack{(S)\\(P)}} \beta_{R\substack{(S)\\(P)}} + \tan^{-1}\left(y_{R\substack{(S)\\(P)}} \Big/ x_{R\substack{(S)\\(P)}}\right)$ $\delta_{R\substack{(S)\\(P)}} = \gamma_{R\substack{(S)\\(P)}} \beta_{R\substack{(S)\\(P)}} + \tan^{-1}\left(y_{R\substack{(S)\\(P)}} \Big/ x_{R\substack{(S)\\(P)}}\right)$ and

$$\beta_{R\substack{(S)\\(P)}} = \beta - L_{R\substack{(S)\\(P)}} r \quad \beta_{R\substack{(S)\\(P)}} = \beta - L_{R\substack{(S)\\(P)}} r\,.$$

Here, *δ*$_R$ is the rudder angle, *β*$_R$ is the effective drift angle at the rudder, and *L*$_R$ is the flow-straightening coefficient of the yaw rate. For the case of a ship operating under windy conditions, the force and moment (*X*$_W$, *Y*$_W$, and *N*$_W$) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A) q_A A_F\,; \quad Y_W = C_{AY}(\psi_A) q_A A_L\,; \quad N_W = C_{AN}(\psi_A) q_A A_L L_{OA}$$

$$X_W = C_{AX}(\psi_A) q_A A_F\,; \quad Y_W = C_{AY}(\psi_A) q_A A_L\,; \quad N_W = C_{AN}(\psi_A) q_A A_L L_{OA} \qquad (9~~)~~).$$

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

$\psi_A = \tan^{-1}\left[U_T\cos\psi + U\cos\beta / U_T\sin\psi - U\cos\beta\right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi+\beta)$

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

C$_{AX}$, *C*$_{AY}$, and *C*$_{AN}$ are the wind load forces and moments' coefficients, respectively, as a function of the wind direction relative to a ship (*ψ*$_A$). *U*$_T$ and *ψ* are wind velocity and direction angles with reference to the coordinate system, *q*$_A$ is wind pressure, *q*$_T$ is wind pressure due to the elevation of the center of a windage area, and *q*$_S$ is the wind pressure induced by wind velocity, without an elevation effect. *A*$_F$ and *A*$_L$ are the transversal and lateral projections of the windage area, respectively.

2.2. Autopilot Ship Steering

The rudder is the most critical feature in achieving controllability goals. The control system must alter the control surfaces to the desired heading angle. The schematic equation

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of the PID control system that a ship tracks can be expressed by Equation 10 (Lee et al., 2009).

$$\delta = K_p(e) + K_d(\dot{e}) + K_i\int_0^T e(t)dt \ \text{and} \ e = (\psi_T - \psi_P) \qquad (10).$$

where, δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain, and integral gain respectively; and e is an error between the heading target (ψ_T) and the actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference heading angles. The reference heading angle equation and target zone correction can be expressed by Equation 11:

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t)/x_k - x(t)) \ \text{and} \ (x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \qquad (11).$$

where, x_k and y_k are the track-point coordinates, $x(t)$ and $y(t)$ are the ship's coordinates position, and R_0 is the target zone's radius.

2.3. Simulation Program

According to IMO (2002) criteria for ship maneuvering, a swept path should be used to analyze a ship's course-keeping prediction. A ship's swept path can be obtained by double-integrating the ship motion mathematical model's acceleration, including hydrodynamic derivatives. A numerical integration of the Dormand–Prince method (Maimun et al., 2011; Muhammad et al., 2015) then solved the equations of motion in this time-domain simulation using the MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for the acting hull force and moment in Equation 2—and the interaction force coefficient among the hull, propeller, and rudder—were predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). This regression equation is among the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circles and zigzag maneuvering for ships with twin-rudder and twin-propeller systems, as well as validation through model testing or free-running tests. In many cases, the regression equation has been used to predict ferry ships' maneuvering under active wind and wave conditions (Paroka et al., 2015, 2016, 2017b). A ship's resistance coefficients for simulation were predicted using the Holtrop method (Holtrop and Mennen, 1982; Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\ J_P - 0.1178\ J_P{}^2$) was predicted using polynomial regression, based on the open water test's statistical data for the B-series propeller (Carlton, 2007). The coefficient of the wind load force and moment in Equation 9 was predicted using the methodology proposed by Fujiwara et al. (2006). The control method used in the simulation was a proportional integrated derivative (PID) controller. The designed rudder angle (δ=±35 deg.) was calculated using Equation 10 with a PID gain (K_p = 2.208; K_i = 0.027 and K_d = 45.372), and it was selected using the pole placement method with the second-order linear Nomoto model of the ship (Nomoto et al., 1957). The methods used by Paroka et al. (2017a) in developing an automatic control system to predict and avoid ferry-ship collisions were compared using a free-running experiment.

2.4. Ship and Sea-Trial Data

The study's object was the *KMP Bontoharu* ferry ship (1053 gross tonnage), owned by PT. ASDP Indonesia Ferry. The ship has twin propellers and twin rudders, and the distance between the rudders and propellers is 2.3 m. The ship's particulars are presented in Table 1. The ship's sea trial on the Selayar-to-Bulukumba route was 15.385 nautical miles long,

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involving a 7,268-second trave~~l~~ling time, around a 6.03 m/s wind velocity, and ~~254 deg~~a 254º wind direction. The trial data ~~was~~were taken on ~~20th~~ September 20, 2015.

Table 1 Ship particulars

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m^2	182.87	*Z*	2 x 4
Lbp,m	47.45	A_F, m^2	129.20	*D, m*	1.450
B, m	14	A_{OD}, m	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_C, m	2.70	*n*	8.784
V, m/s^2	6.618	H_L, m	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, m	10.48	*Chord, m*	0.900
				A_R, m^2	2 x 1.395
				BHP, HP	2 x 1000
				RPMME	1850

2.5. Wind Data

~~The monthly~~Monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years, from 2006~~-~~ to 2018, at ~~6-hourly~~six-hour intervals. The model provide~~s~~d wind speed data with a resolution of 0.25 x 0.25 degrees. This model ~~has been~~was validated by Dee et al. (2011). Furthermore, it ~~has been~~was validated locally by Lina et al. (2015) using data from eight buoys ~~data~~ deployed in the Yellow Sea and the East China ~~Seas. In this study, the~~Sea. This study's coordinate for ~~the~~its observation data ~~is on~~was at 5~~,~~.75ºS and 120.5ºE.

3. Results and Discussion

The wind speed ~~show peak~~ trend peaked in January, with a maximum of 10.06 m/s (~~88 deg.) trend~~88º), as ~~shown in~~ Figure 2 shows. Meanwhile, April's monthly wind speed trend ~~has decreasing trends~~decreased, with ~~the~~a minimum ~~trend~~ of 6.41 m/s (~~219 deg.).~~219º). The ~~movements of~~ monthly wind speed ~~are varying~~movements varied, depending on the month occurring during ~~West~~the west or ~~E~~east monsoon seasons.

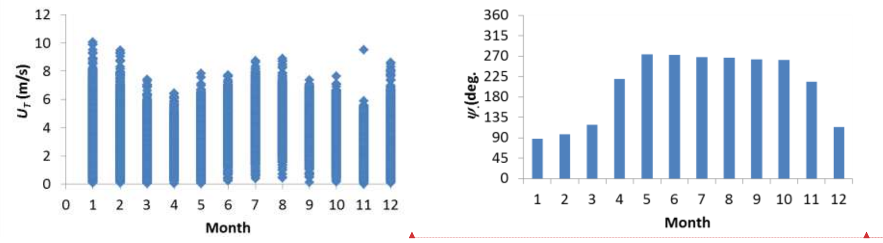

Figure 2 Significant wind velocity and direction ~~in~~on the Selayar~~-~~–Bulukumba route

Based on the wind data characteristics in Figure 2, the *KMP Bontoharu's* course-keeping ~~of a KMP Bontoharu has been~~was simulated for three conditions of wind direction parameters~~, namely,~~—the starboard bow (~~88 deg.)~~88º) and the portside stern of the ship (219 and ~~268 deg.) by~~ 268º)—using the time domain simulation program of MATLAB-Simulink. Th~~e~~is information is essential ~~in~~to ship navigation due to ~~saving~~ time-savings and ~~saving~~reduced fuel consumption by controlling a twin-rudder configuration design. Figure 3 shows the histor~~y~~ic result of the simulation for the ~~track~~course-keeping trajectory of ~~a~~the *KMP Bontoharu* (Selayar to Bulukumba) under wind velocities' effect. The horizontal axis expresses the time, while the vertical axis expresses the heading angle (ψ), rudder angle

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(δ), and ship speed (u), respectively. The wind blew from the starboard bow (88º) at wind velocities of 10.06 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory slowly deviated from the initial track with a low heading with significant course-keeping time compared to conditions without winds ($U_T = 0$ m/s). Meanwhile, the ship's course-keeping trajectory with increased wind velocities caused more deviations and low ship speeds.

Figure 4 shows the simulation results for the *KMP Bontoharu*'s course-keeping with the wind blowing from the portside stern (219º) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory quickly deviated from the initial track with a high heading and short course-keeping time at each blown wind velocity, compared to conditions without winds ($U_T = 0$ m/s). These characteristics differed when the wind blew from the starboard side (88º). The wind direction angle caused these differences, as Ohtsu et al. (1996) found, relating to changes in a ship's heading and rudder angle as a result of wind velocity and ship direction in course-keeping. Figure 5 shows the historic results of the simulation for the course-keeping trajectory of the *KMP Bontoharu* with the wind blowing from the portside stern (268º) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed was 0.27% reduced compared to conditions without wind ($U_T = 0$ m/s), while the ship speed increased by 5.96% increases at a wind speed of 20 m/s. These changes in ship speed were caused by the ship's directional movements.

Figure 6 shows the sea-trial simulation results for the ship course-keeping trajectory with a 6.03 m/s wind velocity and a 254º wind direction at an initial ship speed of 3.98 m/s. We found that the traveling time under these conditions stood at 6.407 seconds. The simulation's traveling time was 11.84% higher than the sea-trial result. A possible reason for this difference is that the simulation excluded waves and currents.

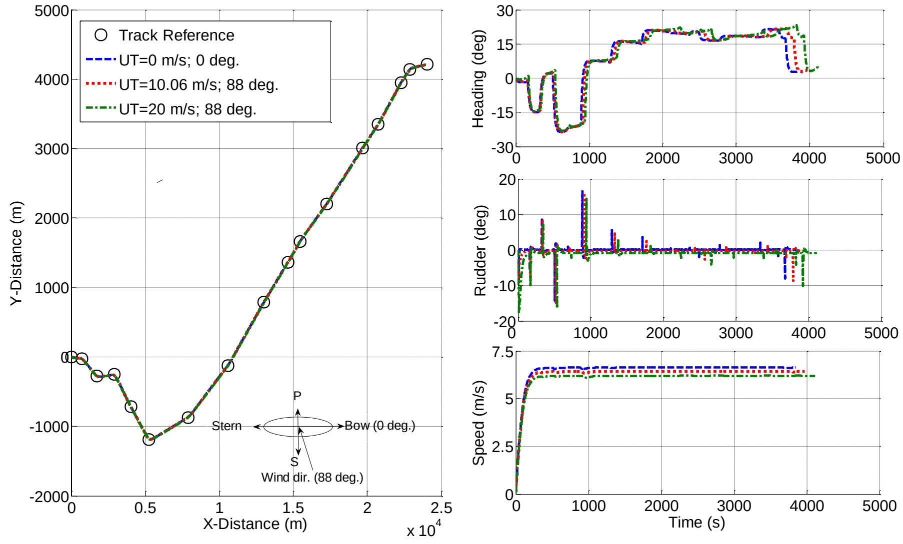

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Figure 3 Ship trajectory with different wind speeds (U_T) at 88º

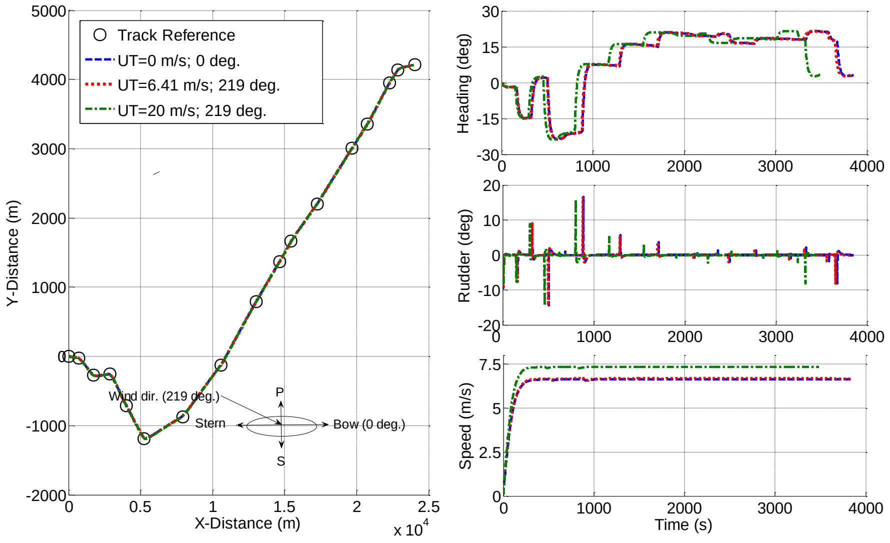

Figure 4 Ship trajectory with different wind speeds (U_T) at 219º

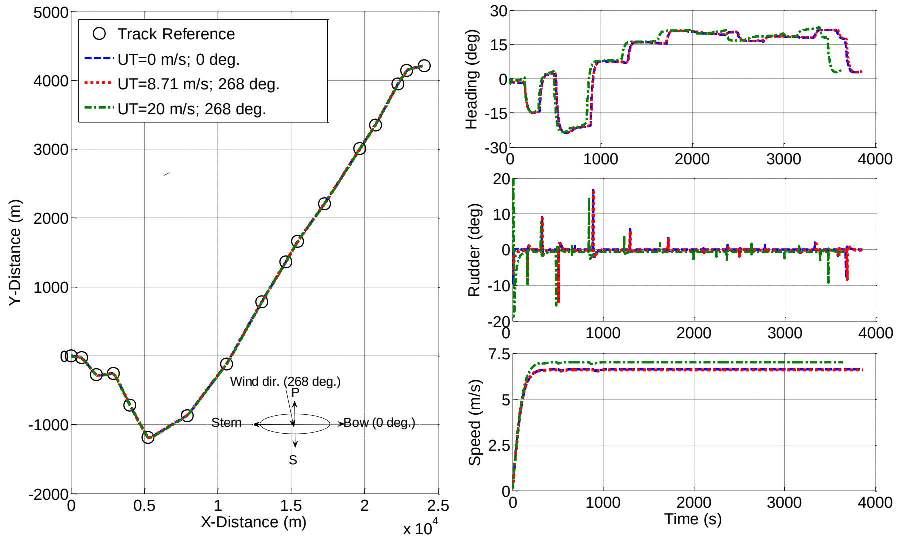

Figure 5 Ship trajectory with different wind speeds (U_T) at 268º

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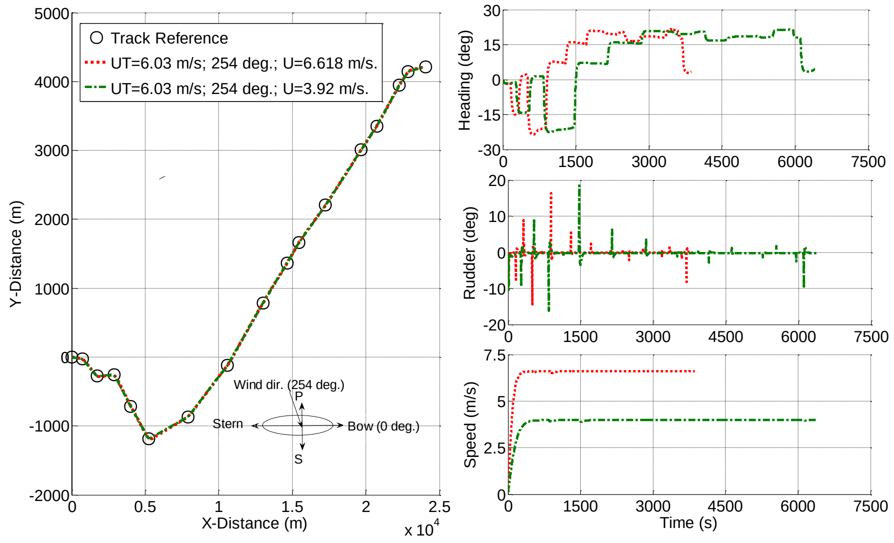

Figure 6 Sea-trial simulation result for ship trajectories with different initial ship speeds (U)

Figures 3, 4, and 5 also show the effects of winds velocity and direction on ship speed, with a course-keeping trajectory for an initial ship speed (U) of 6.618 m/s. We found that, when the wind blew from the starboard bow (88º) with a wind velocity of 20 m/s, the ship speed was 6.36% lower compared to conditions without wind (U_T = 0 m/s). Meanwhile, when the wind blew from the portside stern (219 and 268º), the ship speed was increased by 10.74% and 5.96%, respectively. The two latter speeds were beneficial because the track trajectory times were minimal. In general, when the wind blew from the starboard and portside to the stern (98 to 268º), the ship's track trajectory time tended to benefit compared to conditions with the wind blows from the bow to the starboard and portside, as the simulation results in Figure 7 show. The ship's reduced speed when the wind blew from the bow to the starboard (less than 100º) was similar to the findings of Paroka et al. (2016) related to ship-speed changes caused by wind speeds and directions' influence on ferry maneuvering.

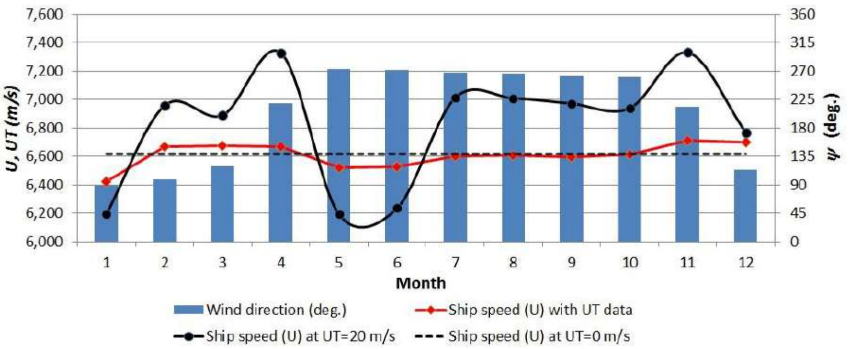

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Figure 7 Tracking ship speed trajectories with different wind velocities and directions

4. Conclusions

This study has analyzed a twin-rudder-system configuration's influence on a ship's course-keeping ability under various wind speeds and directions through the MATLAB-Simulink computer-simulation program. The results indicated that applying a twin-rudder system to ferry ships' to improve their course-keeping ability under windy conditions is very effective using a PID controller, reducing ship deviation and increasing ship speed by adjusting the ship's heading angle to the desired path. The track trajectory time in the ferry's course-keeping highly depends on wind velocity and direction. When the wind blows from the starboard and portside to the stern (98 to 268º), a ship's travel time tends to benefit compared to when the wind blows from the bow to the side. This research shows that the PID controller method can be applied to assist ships' movements due to other environmental influences, such as waves and currents. However, ships' course-keeping quality highly depends on the selected PID parameters.

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Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions

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Abstract. Ship course-keeping plays a vital role in navigation safety, especially when a ship is operating under windy conditions. A method to control ship movements through rudder-system configuration is necessary to stabilize a ship's course. This paper describes the twin-rudder-system configuration design's impact on a ship's course-keeping ability under windy conditions. A time-domain simulation using the MATLAB-Simulink program was developed for this purpose. A proportional integral derivative (PID) controller was used to adjust the ship's heading angle according to the desired path. Several parameters—such as relative wind velocity and directions—were accounted for in the simulation. The result shows that, at a wind direction of 88º, the ship's course-keeping speed decreased; however, increasing wind velocity caused a large deviation in the ship's heading angle. Meanwhile, the ship's course-keeping speed increased with rising windspeed directions of 219º. The ship's course-keeping time, at around 219º under the simulation's wind direction, was 11.84% lower than during a previous sea-trial. A possible reason for this difference is that the simulation excluded waves and currents.

Keywords: Proportional integral derivative controller; Course-keeping; Ship-tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigation due to time-saving and reduced fuel consumption (Prpic-Orsic et al., 2015). To achieve quality ship course-keeping and generate accurate heading angles, a controller that considers ship hydrodynamics—including both internal and external disturbance parameters—should be installed (Lee et al, 2009). Keeping a ferry ship on course differs from sea-going ships due to navigation environments and ship particulars (Prpic-Orsic et al., 2015). The navigation environment's complexity, and especially wind-load forces and moment, makes ferry ships with large superstructures more susceptible to marine accidents (Fujiwara and Ueno, 2006). Many studies have related wind effects to ship maneuvering; wind's load-force and moment have significantly affected transversal and lateral projections of windage areas due to ships' large superstructures, as well as wind velocities and directions relative to ships (Fujiwara and Ueno, 2006). Paroka et al. (2016) simulated wind's effect on ferry ships' maneuvering, explaining that ship-speed changes caused by wind highly depend on wind velocity and direction. When the wind blows from the bow direction and passes to the ship's starboard (0 to 100º), ship speed tends to decrease. The corresponding decrease in ship speed is insignificant when the wind blows from a starboard direction and passes to the ship's

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stern (100 to 180º). Meanwhile, when the wind blows from the side of a ship (20 to 140º), it tends to change the ship's direction. A ship's directional deviations due to wind vary by ship type, and a steering response is required. Ohtsu et al. (1996) reported that a wind blowing from starboard-bow quarters (45º) made a ship's steering becomes less sensitive, but steering became more sensitive when the wind came from the port-stern quarters (135º). Increasing a ship's speed as wind directions change is crucial (Paroka et al., 2016 and Ohtsu et al., 1996). The information informing this behavior is essential to improve ships' course-keeping quality—especially when ships must take appropriate action to handle wind disturbances. The improving quality of a ship's course-keeping ability in windy conditions is strongly influenced by steering responses to wind-blowing loads through an appropriately configured rudder system design (Hasegawa et al., 2006). Steering control plays an essential role in responding to external forces to a ship's yaw motion stability and course-keeping ability during maneuvers (Paroka, 2020).

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Many efforts to improve ships' maneuvering have been conducted using twin-rudder ship controllers. Yoshimura and Sakurai (1989) investigated the effect of a ship-fitted, twin-rudder, twin-propeller configuration on ships' maneuvering. They found that a twin-rudder, twin-propeller configuration's hydrodynamic characteristics did not differ significantly from the corresponding characteristics of a single-propeller, single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ships' maneuvering when fitted with a twin-propeller, twin-rudder configuration. Furthermore, Khanfir et al. (2011) conducted captive model tests and free-running tests with a single-propeller, twin-rudder ship and a twin-propeller, twin-rudder ship. These tests aimed to evaluate drift angles' effect on rudder forces and the peculiar phenomena concerning a normal rudder force for twin-rudder ships.

Other parameters that affect ships' maneuvering performance include the distance of spacing between single rudders in twin-rudder ships. Gim (2013) conducted a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5–1.0 times the chord length of the rudder. He found that this spacing distance between rudders in twin-rudder configurations was also affected by interactions between rudders, and he also found that this critical distance should be less than 1.0 times the chord length of the rudder in order to decrease the turbulence flow and vortices. This result was similar to the findings of Chen et al. (2018), who used numerical simulation to confirming the excellent characteristics of twin-rudder ships compared to single-rudder ships. Chen et al. (2018) concluded that a ship fitted with a twin-rudder configuration would operate very well at 15º rudder angles. Additionally, the twin rudders' effective performance stopped at a lateral spacing equal to 1.3 times the chord length of the rudder.

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These previous studies have shown that a rudder system's configuration is the most crucial feature in achieving ship controllability goals. A rudder system must alter ship control to the desired heading angle, due to both internal and external disturbance parameters. The current paper focuses on applying the twin-rudder system to improve ferries' course-keeping quality under windy conditions. By simulating fluctuating wind velocity and directions according to a ship's operating route, quality course-keeping and accurate heading angles may be achieved, increasing the ship's safety.

2. Methods

2.1. *Mathematical Model*

This study's ship maneuvering analysis used computer simulation to employ modular mathematical models, including a consideration of hydrodynamic derivatives. This study's models were based on surge, sway, and yaw motions (Equation 1) using the coordinate system shown in Figure 1.

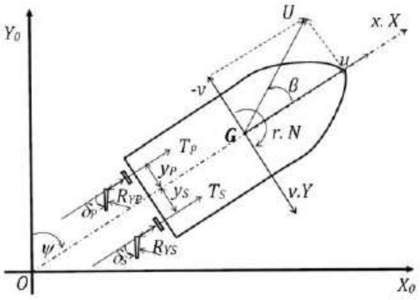

Figure 1 Coordinate ship system

$$
\begin{aligned}
&m(\dot{u}-rv)=X_H+X_P+X_R+X_W\\
&m(\dot{v}-ru)=Y_H+Y_P+Y_R+Y_W\\
&I_{ZZ}\ddot{\psi}=N_H+N_P+N_R+N_W
\end{aligned}
\qquad (1)
$$

The notations *u, v* and *r,* are velocity components at the ship's center of gravity (*G*). *m* and I_{ZZ} represent the ship's mass and moments of inertia. *X, Y,* and *N* represent the hydrodynamic forces and moment. The subscript *H*, *P, R,* and *W* refer to the ship's hull, propeller, rudder, and wind. In principle, the force and moment induced by hull (X_H, Y_H, and N_H) approximate *β* and *r'* polynomial function. These equations were expressed by Yoshimura et al. (2001) as Equation 2:

$$
\begin{aligned}
X_H&=\tfrac{1}{2}\rho LdU^2(X'_0+X'_{\beta\beta}\beta^2+(X'_{\beta r}-m'_y)\beta r'+X'_{rr}r'^2+X'_{\beta\beta\beta\beta}\beta^4)\\
Y_H&=\tfrac{1}{2}\rho LdU^2(Y'_\beta\beta+(Y'_r-m'_x)r'+Y'_{\beta\beta\beta}\beta^3+Y'_{\beta\beta r}\beta^2 r'+Y'_{\beta rr}\beta r'^2+Y'_{rrr}r'^3)\\
N_H&=\tfrac{1}{2}\rho L^2dU^2(N'_\beta\beta+N'_r r'+N'_{\beta\beta\beta}\beta^3+N'_{\beta\beta r}\beta^2 r'+N'_{\beta rr}\beta r'^2+N'_{rrr}r'^3)
\end{aligned}
\qquad (2),
$$

where *β* is the drift angle at the midship position by $\tan^{-1}(v/u)$ and *r'* non-dimensionalized yaw rate by *rL/U*. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} is the hydrodynamic derivatives on the ship's maneuvering. The force and moment induced by twin-propeller configurations (X_P, Y_P, and N_P) were expressed by Khanfir et al. (2011) in Equation 3:

$$
\begin{aligned}
X_P&=\rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2D_{P(S)}{}^4K_{T(S)}(J_{P(S)})+(1-t_{P(P)})y_{P(P)}n_{P(P)}{}^2D_{P(P)}{}^4K_{T(P)}(J_{P(P)})\Big)\\
N_P&=\rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2D_{P(S)}{}^4K_{T(S)}\Big)+\rho\Big((1-t_{P(P)})n_{P(P)}{}^2D_{P(P)}{}^4K_{T(P)}\Big)
\end{aligned}
\qquad (3),
$$

where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}})=k_0+k_1J_{P\substack{(S)\\(P)}}+k_2J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\substack{(S)\\(P)}}=(u-y_Pr(1-w_{P\substack{(S)\\(P)}})/(n_{P\substack{(S)\\(P)}}D_{P\substack{(S)\\(P)}})$.

where t_P is the thrust deduction coefficient in straightforward moving, K_T is the thrust coefficient of the propeller force, and n_P is the propeller revolution. D_P is the propeller diameter, w_P is the effective wake fraction coefficient at the propeller's location, and J_P is the advance coefficient, while k_0, k_1, and k_2 are the constants for an open-water propeller. The sub-subscript *(S)* and *(P)* refer to starboard and portside.

Force and moment due to twin-rudder configurations (X_R, Y_R, and N_R) can be expressed by equations 4–8 (Khanfir et al., 2011).

$$\begin{aligned}
X_R &= -(1-t_{R(S)}F_{RY(S)}\sin\delta_{(S)} - (1-t_{R(P)}F_{RY(P)}\sin\delta_{(P)} \\
Y_R &= -(1+a_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{R(YS)}\cos\delta_{(P)}\right) \\
N_R &= -(x_R + a_H x_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{RY(P)}\cos\delta_{(P)}\right) + f\left(x_R\right) \\
f\left(x_R\right) &= y_{P(S)}(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)}
\end{aligned} \qquad (4),$$

where δ is the rudder angle, x_R is the rudder's location, and t_R, a_H, and x_H are the interactive force coefficients for the hull, propeller, and rudder as functions of the propeller's advance constant. The rudder's normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

$$F_{RY\substack{(S)\\(P)}} = \tfrac{1}{2}\rho A_R U_{R\substack{(S)\\(P)}}^{\;2} f_\alpha \sin\alpha_{R\substack{(S)\\(P)}} \qquad (5),$$

where A_R is the rudder area, and f_α is the gradient of the rudder's lift coefficient, which can be approximated by the function of the rudder's aspect ratio (f_α = 6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and the effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6:

$$U_{R\substack{(S)\\(P)}} = \sqrt{u_{R\substack{(S)\\(P)}}^{\;2} + v_{R\substack{(S)\\(P)}}^{\;2}} \qquad \text{and} \qquad \alpha_{R\substack{(S)\\(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R\substack{(S)\\(P)}}\left(\beta_{R\substack{(S)\\(P)}}\right) \qquad (6)$$

The effective inflow velocity (u_R) to the rudder in the surge direction can be expressed by Equation 7:

$$u_{R\substack{(S)\\(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P\substack{(S)\\(P)}} \times \sqrt{\eta_{P\substack{(S)\\(P)}}\left\{1+\kappa\left(\sqrt{1+8K_{T\substack{(S)\\(P)}} \Big/ \pi J_{P\substack{(S)\\(P)}}^{\;2}} - 1\right)\right\}^2 + (1-\eta_{P\substack{(S)\\(P)}})} \qquad (7),$$

where: $\varepsilon_{\substack{(S)\\(P)}} = 1 - w_{R\substack{(S)\\(P)}} \Big/ 1 - w_{P\substack{(S)\\(P)}}$; $\kappa = kx \Big/ \varepsilon_{\substack{(S)\\(P)}}$; $\eta_{P\substack{(S)\\(P)}} = D_{P\substack{(S)\\(P)}} \Big/ H_{R\substack{(S)\\(P)}}$; $u_{P\substack{(S)\\(P)}} = \left(1 - w_{P\substack{(S)\\(P)}}\right)\left(u - y_{P\substack{(S)\\(P)}} r\right)$.

Here, ε, κ, γ_R, and l_R are the parameters describing the rudder inflow velocity angle, while (1-w) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H) is the ratio of the propeller diameter to the rudder height.

The effective inflow velocity (v_R) to the rudder in the sway direction can be expressed by Equation 8:

$$v_{R\substack{(S)\\(P)}} = u_{R\substack{(S)\\(P)}} \tan\left(\delta_{R\substack{(S)\\(P)}}\right) \qquad (8),$$

where: $\delta_{R\substack{(S)\\(P)}} = \gamma_{R\substack{(S)\\(P)}} \beta_{R\substack{(S)\\(P)}} + \tan^{-1}\left(y_{R\substack{(S)\\(P)}} \Big/ x_{R\substack{(S)\\(P)}}\right)$ and $\beta_{R\substack{(S)\\(P)}} = \beta - L_{R\substack{(S)\\(P)}} r$.

Here, δ_R is the rudder angle, β_R is the effective drift angle at the rudder, and L_R is the flow-straightening coefficient of the yaw rate. For the case of a ship operating under windy conditions, the force and moment (X_W, Y_W, and N_W) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A) q_A A_F; \quad Y_W = C_{AY}(\psi_A) q_A A_L; \quad N_W = C_{AN}(\psi_A) q_A A_L L_{OA} \qquad (9),$$

where $\psi_A = \tan^{-1}\left[U_T\cos\psi + U\cos\beta / U_T\sin\psi - U\cos\beta\right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi+\beta)$.

C_{AX}, C_{AY}, and C_{AN} are the wind load forces and moments' coefficients, respectively, as a function of the wind direction relative to a ship (ψ_A). U_T and ψ are wind velocity and direction angles with reference to the coordinate system, q_A is wind pressure, q_T is wind pressure due to the elevation of the center of a windage area, and q_S is the wind pressure induced by wind velocity, without an elevation effect. A_F and A_L are the transversal and lateral projections of the windage area, respectively.

2.2. Autopilot Ship Steering

The rudder is the most critical feature in achieving controllability goals (Lee et al., 2019). The control system must alter the control surfaces to the desired heading angle. The schematic equation of the PID control system that a ship tracks can be expressed by Equation 10 (Lee et al., 2009).

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$$\delta = K_p(e) + K_d(\dot{e}) + K_i\int_0^T e(t)dt \ \text{ and } \ e = (\psi_T - \psi_P) \qquad (10),$$

where δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain, and integral gain respectively; and e is an error between the heading target (ψ_T) and the actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference heading angles. The reference heading angle equation and target zone correction can be expressed by Equation 11:

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t)/x_k - x(t)) \ \text{ and } \ (x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \qquad (11).$$

where x_k and y_k are the track-point coordinates, $x(t)$ and $y(t)$ are the ship's coordinates position, and R_0 is the target zone's radius.

2.3. Simulation Program

According to IMO (2002) criteria for ship maneuvering, a swept path should be used to analyze a ship's course-keeping prediction. A ship's swept path can be obtained by double-integrating the ship motion mathematical model's acceleration, including hydrodynamic derivatives. A numerical integration of the Dormand–Prince method (Maimun et al., 2011; Muhammad et al., 2015) then solved the equations of motion in this time-domain simulation using the MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for the acting hull force and moment in Equation 2—and the interaction force coefficient among the hull, propeller, and rudder—were predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). This regression equation is among the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circles and zigzag maneuvering for ships with twin-rudder and twin-propeller systems, as well as validation through model testing or free-running tests. In many cases, the regression equation has been used to predict ferry ships' maneuvering under active wind and wave conditions (Paroka et al., 2015, 2016, 2017b). A ship's resistance coefficients for simulation were predicted using the Holtrop method (Holtrop and Mennen, 1982; Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\, J_P - 0.1178\, J_P^{\,2}$) was predicted using polynomial regression, based on the open water test's statistical data for the B-series propeller (Carlton, 2007). The coefficient of the wind load force and moment in Equation 9 was predicted using the methodology proposed by Fujiwara et al. (2006). The control method used in the simulation was a proportional integrated derivative (PID) controller. The designed rudder angle (δ=±35 deg.) was calculated using Equation 10 with a PID gain (K_p = 2.208; K_i = 0.027 and K_d = 45.372), and it was selected using the pole placement method with the second-order linear Nomoto model of the ship (Nomoto et al., 1957). The methods used by Paroka et al. (2017a) in developing an automatic control system to predict and avoid ferry-ship collisions were compared using a free-running experiment.

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2.4. Ship and Sea-Trial Data

The study's object was the *KMP Bontoharu* ferry ship (1053 gross tonnage), owned by PT. ASDP Indonesia Ferry. The ship has twin propellers and twin rudders, and the distance between the rudders and propellers is 2.3 m. The ship's particulars are presented in Table 1. The ship's sea trial on the Selayar-to-Bulukumba route was 15.385 nautical miles long, involving a 7,268-second traveling time, around a 6.03 m/s wind velocity, and a 254º wind direction. The trial data were taken on September 20, 2015.

Table 1 Ship particulars

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m^2	182.87	*Z*	2 x 4
Lbp,m	47.45	A_F, m^2	129.20	*D, m*	1.450
B, m	14	A_{OD}, m	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_C, m	2.70	*n*	8.784
V, m/s^2	6.618	H_L, m	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, m	10.48	*Chord, m*	0.900
				A_R, m^2	2 x 1.395
				BHP, HP	2 x 1000
				RPMME	1850

2.5. Wind Data

Monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years, from 2006 to 2018, at six-hour intervals. The model provided wind speed data with a resolution of 0.25 x 0.25 degrees. This model was validated by Dee et al. (2011). Furthermore, it was validated locally by Lina et al. (2015) using data from eight buoys deployed in the Yellow Sea and the East China Sea. This study's coordinate for its observation data was at 5.75°S and 120.5°E.

3. Results and Discussion

The wind speed trend peaked in January, with a maximum of 10.06 m/s (88º), as Figure 2 shows. Meanwhile, April's monthly wind speed trend decreased, with a minimum of 6.41 m/s (219º). The monthly wind speed movements varied, depending on the month occurring during the west or east monsoon seasons.

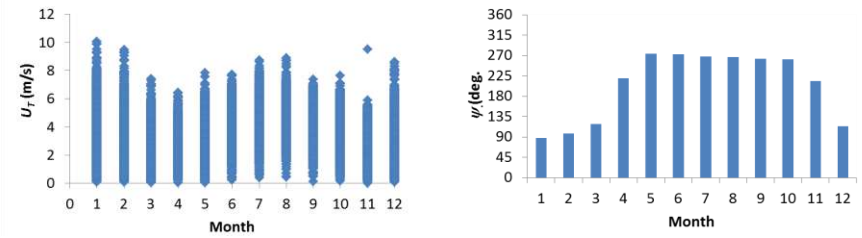

Figure 2 Significant wind velocity and direction on the Selayar–Bulukumba route

Based on the wind data characteristics in Figure 2, the *KMP Bontoharu*'s course-keeping was simulated for three conditions of wind direction parameters—the starboard bow (88º) and the portside stern of the ship (219 and 268º)—using the time domain simulation program of MATLAB-Simulink. This information is essential to ship navigation due to time-savings and reduced fuel consumption by controlling a twin-rudder configuration design. Figure 3 shows the historic result of the simulation for the course-keeping trajectory of the *KMP Bontoharu* (Selayar to Bulukumba) under wind velocities' effect. The horizontal axis expresses the time, while the vertical axis expresses the heading angle (ψ), rudder angle (δ), and ship speed (u), respectively. The wind blew from the starboard bow (88º) at wind velocities of 10.06 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory slowly deviated from the initial track with a low heading with significant course-keeping time compared to conditions without winds (U_T = 0 m/s). Meanwhile, the ship's course-keeping trajectory with increased wind velocities caused more deviations and low ship speeds.

Figure 4 shows the simulation results for the *KMP Bontoharu*'s course-keeping with the wind blowing from the portside stern (219º) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory quickly deviated from the initial track with a high heading and short course-keeping time at each blown wind velocity, compared to conditions without winds (U_T = 0 m/s). These characteristics differed when the wind blew from the starboard side (88º). The wind direction angle caused these differences, as Ohtsu et al. (1996) found, relating to changes in a ship's heading and rudder angle as a result of wind velocity and ship direction in course-keeping. Figure 5 shows the historic results of the simulation for the course-keeping trajectory of the *KMP Bontoharu* with the wind blowing from the portside stern (268º) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed was 0.27% reduced compared to conditions without wind (U_T = 0 m/s), while the ship speed increased by 5.96% increases at a wind speed of 20 m/s. These changes in ship speed were caused by the ship's directional movements.

Figure 6 shows the sea-trial simulation results for the ship course-keeping trajectory with a 6.03 m/s wind velocity and a 254º wind direction at an initial ship speed of 3.98 m/s. We found that the traveling time under these conditions stood at 6.407 seconds. The simulation's traveling time was 11.84% higher than the sea-trial result. A possible reason for this difference is that the simulation excluded waves and currents.

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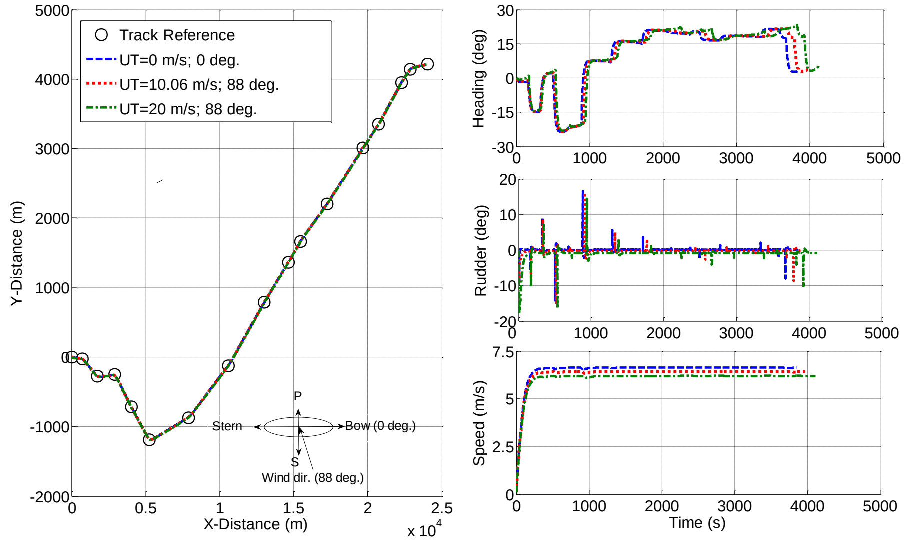

Figure 3 Ship trajectory with different wind speeds (U_T) at 88º

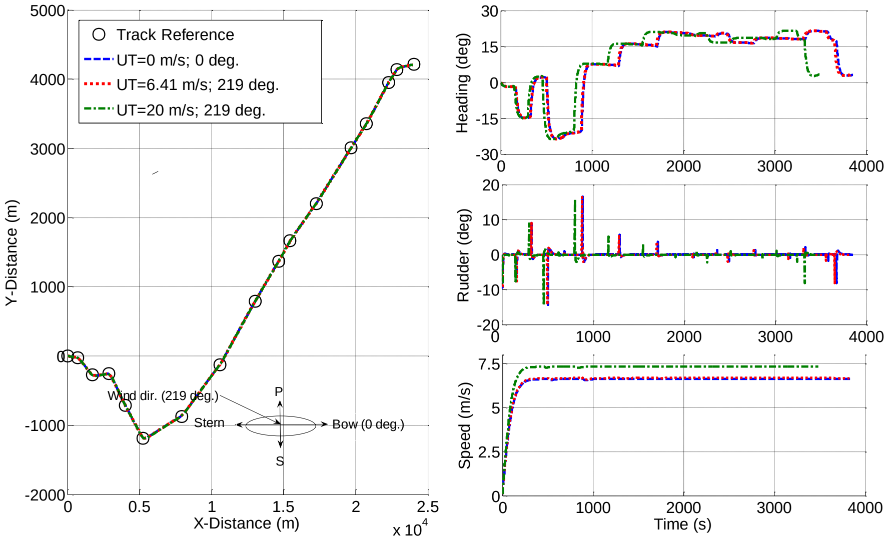

Figure 4 Ship trajectory with different wind speeds (U_T) at 219º

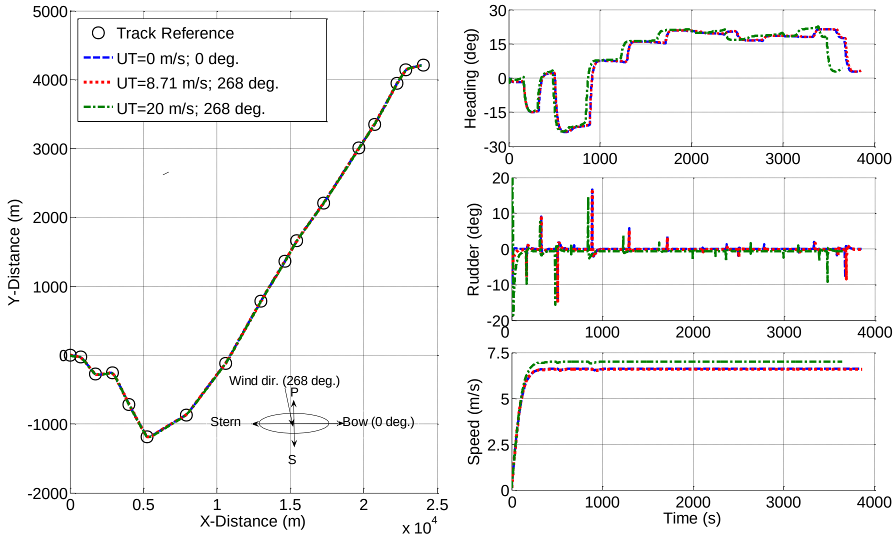

Figure 5 Ship trajectory with different wind speeds (U_T) at 268º

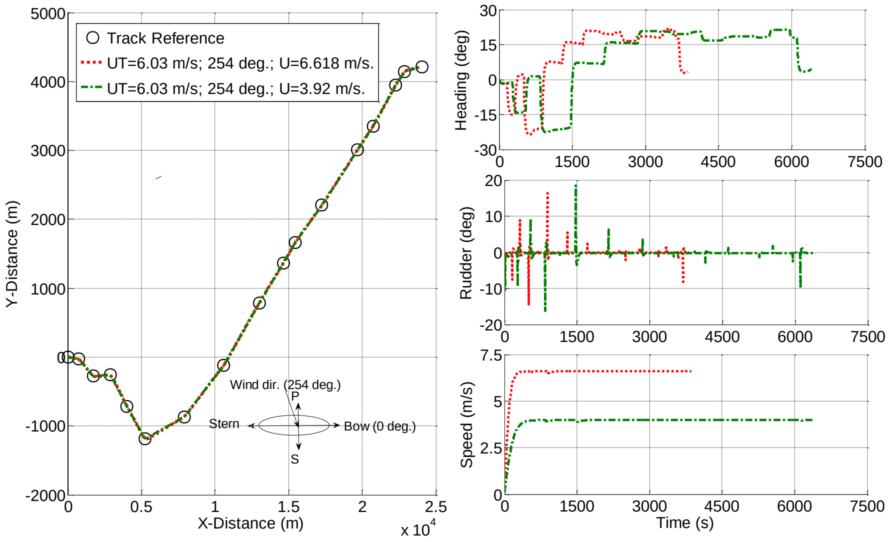

Figure 6 Sea-trial simulation result for ship trajectories with different initial ship speeds (U)

Figures 3, 4, and 5 also show the effects of winds velocity and direction on ship speed, with a course-keeping trajectory for an initial ship speed (U) of 6.618 m/s. We found that, when the wind blew from the starboard bow (88º) with a wind velocity of 20 m/s, the ship speed was 6.36% lower compared to conditions without wind ($U_T = 0$ m/s). Meanwhile, when the wind blew from the portside stern (219 and 268º), the ship speed was increased by 10.74% and 5.96%, respectively. The two latter speeds were beneficial because the track trajectory times were minimal. In general, when the wind blew from the starboard and portside to the stern (98 to 268º), the ship's track trajectory time tended to benefit compared to conditions with the wind blows from the bow to the starboard and portside, as the simulation results in Figure 7 show. The ship's reduced speed when the wind blew from the bow to the starboard (less than 100º) was similar to the findings of Paroka et al. (2016) related to ship-speed changes caused by wind speeds and directions' influence on ferry maneuvering.

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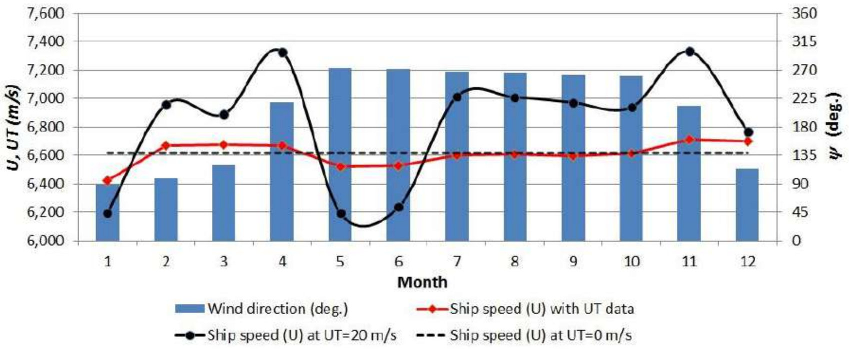

Figure 7 Tracking ship speed trajectories with different wind velocities and directions

4. Conclusions

This study has analyzed a twin-rudder-system configuration’s influence on a ship’s course-keeping ability under various wind speeds and directions through the MATLAB-Simulink computer-simulation program. The results indicated that applying a twin-rudder system to ferry ships’ to improve their course-keeping ability under windy conditions is very effective using a PID controller, reducing ship deviation and increasing ship speed by adjusting the ship's heading angle to the desired path. The track trajectory time in the ferry’s course-keeping highly depends on wind velocity and direction. When the wind blows from the starboard and portside to the stern (98 to 268º), a ship’s travel time tends to benefit compared to when the wind blows from the bow to the side. This research shows that the PID controller method can be applied to assist ships’ movements due to other environmental influences, such as waves and currents. However, ships’ course-keeping quality highly depends on the selected PID parameters.

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Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions

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Abstract. Ship course-keeping plays a vital role in navigation safety, especially when a ship is operating under windy conditions. A method to control ship movements through rudder-system configuration is necessary to stabilize a ship's course. This paper describes the twin-rudder-system configuration design's impact on a ship's course-keeping ability under windy conditions. A time-domain simulation using the MATLAB-Simulink program was developed for this purpose. A proportional integral derivative (PID) controller was used to adjust the ship's heading angle according to the desired path. Several parameters—such as relative wind velocity and directions—were accounted for in the simulation. The result shows that, at a wind direction of 88°, the ship's course-keeping speed decreased; however, increasing wind velocity caused a large deviation in the ship's heading angle. Meanwhile, the ship's course-keeping speed increased with rising windspeed directions of 219°. The ship's course-keeping time, at around 219° under the simulation's wind direction, was 11.84% lower than during a previous sea-trial. A possible reason for this difference is that the simulation excluded waves and currents.

Keywords: Course-keeping; Proportional integral derivative controller; Ship-tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigation due to time-saving and reduced fuel consumption (Prpic-Orsic et al., 2016). To achieve quality ship course-keeping and generate accurate heading angles, a controller that considers ship hydrodynamics—including both internal and external disturbance parameters—should be installed (Lee et al, 2009). Keeping a ferry ship on course differs from sea-going ships due to navigation environments and ship particulars (Prpic-Orsic et al., 2016). The navigation environment's complexity, and especially wind-load forces and moment, makes ferry ships with large superstructures more susceptible to marine accidents (Fujiwara and Ueno, 2006). Many studies have related wind effects to ship maneuvering; wind's load-force and moment have significantly affected transversal and lateral projections of windage areas due to ships' large superstructures, as well as wind velocities and directions relative to ships (Fujiwara and Ueno, 2006). Paroka et al. (2016) simulated wind's effect on ferry ships' maneuvering,

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explaining that ship-speed changes caused by wind highly depend on wind velocity and direction. When the wind blows from the bow direction and passes to the ship's starboard (0 to 100°), ship speed tends to decrease. The corresponding decrease in ship speed is insignificant when the wind blows from a starboard direction and passes to the ship's stern (100 to 180°). Meanwhile, when the wind blows from the side of a ship (20 to 140°), it tends to change the ship's direction. A ship's directional deviations due to wind vary by ship type, and a steering response is required. Ohtsu et al. (1996) reported that a wind blowing from starboard-bow quarters (45°) made a ship's steering becomes less sensitive, but steering became more sensitive when the wind came from the port-stern quarters (135°). Increasing a ship's speed as wind directions change is crucial (Ohtsu et al., 1996; Paroka et al., 2016). The information informing this behavior is essential to improve ships' course-keeping quality—especially when ships must take appropriate action to handle wind disturbances. The improving quality of a ship's course-keeping ability in windy conditions is strongly influenced by steering responses to wind-blowing loads through an appropriately configured rudder system design (Hasegawa et al., 2006). Steering control plays an essential role in responding to external forces to a ship's yaw motion stability and course-keeping ability during maneuvers (Paroka, 2020).

Many efforts to improve ships' maneuvering have been conducted using twin-rudder ship controllers. Yoshimura and Sakurai (1989) investigated the effect of a ship-fitted, twin-rudder, twin-propeller configuration on ships' maneuvering. They found that a twin-rudder, twin-propeller configuration's hydrodynamic characteristics did not differ significantly from the corresponding characteristics of a single-propeller, single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ships' maneuvering when fitted with a twin-propeller, twin-rudder configuration. Furthermore, Khanfir et al. (2011) conducted captive model tests and free-running tests with a single-propeller, twin-rudder ship and a twin-propeller, twin-rudder ship. These tests aimed to evaluate drift angles' effect on rudder forces and the peculiar phenomena concerning a normal rudder force for twin-rudder ships.

Other parameters that affect ships' maneuvering performance include the distance of spacing between single rudders in twin-rudder ships. Gim (2013) conducted a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5–1.0 times the chord length of the rudder. He found that this spacing distance between rudders in twin-rudder configurations was also affected by interactions between rudders, and he also found that this critical distance should be less than 1.0 times the chord length of the rudder in order to decrease the turbulence flow and vortices. This result was similar to the findings of Chen et al. (2018), who used numerical simulation to confirming the excellent characteristics of twin-rudder ships compared to single-rudder ships. Chen et al. (2018) concluded that a ship fitted with a twin-rudder configuration would operate very well at 15° rudder angles. Additionally, the twin rudders' effective performance stopped at a lateral spacing equal to 1.3 times the chord length of the rudder.

These previous studies have shown that a rudder system's configuration is the most crucial feature in achieving ship controllability goals. A rudder system must alter ship control to the desired heading angle, due to both internal and external disturbance parameters. The current paper focuses on applying the twin-rudder system to improve ferries' course-keeping quality under windy conditions. By simulating fluctuating wind velocity and directions according to a ship's operating route, quality course-keeping and accurate heading angles may be achieved, increasing the ship's safety.

2. Methods

2.1. Mathematical Model

This study's ship maneuvering analysis used computer simulation to employ modular mathematical models, including a consideration of hydrodynamic derivatives. This study's models were based on surge, sway, and yaw motions (Equation 1) using the coordinate system shown in Figure 1.

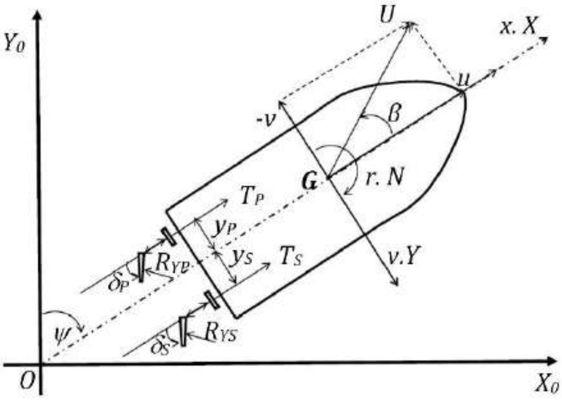

Figure 1 Coordinate ship system

$$\begin{aligned} m(\dot{u}-rv) &= X_H + X_P + X_R + X_W \\ m(\dot{v}-ru) &= Y_H + Y_P + Y_R + Y_W \\ I_{ZZ}\ddot{\psi} &= N_H + N_P + N_R + N_W \end{aligned} \tag{1}$$

The notations *u, v* and *r,* are velocity components at the ship's center of gravity (*G*). *m* and I_{ZZ} represent the ship's mass and moments of inertia. *X, Y*, and *N* represent the hydrodynamic forces and moment. The subscript *H, P, R,* and *W* refer to the ship's hull, propeller, rudder, and wind. In principle, the force and moment induced by hull (X_H, Y_H, and N_H) approximate β and r' polynomial function. These equations were expressed by Yoshimura (2001) as Equation 2:

$$\begin{aligned} X_H &= \tfrac{1}{2}\rho L d U^2 (X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr}r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\ Y_H &= \tfrac{1}{2}\rho L d U^2 (Y'_\beta\beta + (Y'_r - m'_x)r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr}r'^3) \\ N_H &= \tfrac{1}{2}\rho L^2 d U^2 (N'_\beta\beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr}r'^3) \end{aligned} \tag{2}$$

where β is the drift angle at the midship position by $\tan^{-1}(v/u)$ and r' non-dimensionalized yaw rate by rL/U. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} is the hydrodynamic derivatives on the ship's maneuvering. The force and moment induced by twin-propeller configurations (X_P, Y_P, and N_P) were expressed by Khanfir et al. (2011) in Equation 3:

$$\begin{aligned} X_P &= \rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}(J_{P(S)}) + (1-t_{P(P)})y_{P(P)}n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}(J_{P(P)})\Big) \\ N_P &= \rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}\Big) + \rho\Big((1-t_{P(P)})n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}\Big) \end{aligned} \tag{3}$$

where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}}) = k_0 + k_1 J_{P\substack{(S)\\(P)}} + k_2 J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\substack{(S)\\(P)}} = (u - y_P r(1 - w_{P\substack{(S)\\(P)}})/(n_{P\substack{(S)\\(P)}} D_{P\substack{(S)\\(P)}})$

where t_P is the thrust deduction coefficient in straightforward moving, K_T is the thrust coefficient of the propeller force, and n_P is the propeller revolution. D_P is the propeller

diameter, w_P is the effective wake fraction coefficient at the propeller's location, and J_P is the advance coefficient, while k_0, k_1, and k_2 are the constants for an open-water propeller. The sub-subscript *(S)* and *(P)* refer to starboard and portside.

Force and moment due to twin-rudder configurations (X_R, Y_R, and N_R) can be expressed by Equations 4–8 (Khanfir et al., 2011).

$$\begin{aligned}
X_R &= -(1-t_{R(S)}F_{RY(S)}\sin\delta_{(S)} - (1-t_{R(P)}F_{RY(P)}\sin\delta_{(P)} \\
Y_R &= -(1+a_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{R(YS)}\cos\delta_{(P)}\right) \\
N_R &= -(x_R + a_H x_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{RY(P)}\cos\delta_{(P)}\right) + f\left(x_R\right) \\
f\left(x_R\right) &= y_{P(S)}(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)}
\end{aligned} \tag{4}$$

where δ is the rudder angle, x_R is the rudder's location, and t_R, a_H, and x_H are the interactive force coefficients for the hull, propeller, and rudder as functions of the propeller's advance constant. The rudder's normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

$$F_{RY\substack{(S)\\(P)}} = \tfrac{1}{2}\rho A_R U_{R\substack{(S)\\(P)}}^{\;2} f_\alpha \sin\alpha_{R\substack{(S)\\(P)}} \tag{5}$$

where A_R is the rudder area, and f_α is the gradient of the rudder's lift coefficient, which can be approximated by the function of the rudder's aspect ratio (f_α = 6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and the effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6:

$$U_{R\substack{(S)\\(P)}} = \sqrt{u_{R\substack{(S)\\(P)}}^{\;2} + v_{R\substack{(S)\\(P)}}^{\;2}} \qquad \text{and} \qquad \alpha_{R\substack{(S)\\(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R\substack{(S)\\(P)}}\left(\beta_{R\substack{(S)\\(P)}}\right) \tag{6}$$

The effective inflow velocity (u_R) to the rudder in the surge direction can be expressed by Equation 7:

$$u_{R\substack{(S)\\(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P\substack{(S)\\(P)}} \times \sqrt{\eta_{P\substack{(S)\\(P)}}\left\{1+\kappa\left(\sqrt{1+8K_{T\substack{(S)\\(P)}} \Big/ \pi J_{P\substack{(S)\\(P)}}^{\;2}} - 1\right)\right\}^2 + (1-\eta_{P\substack{(S)\\(P)}})} \tag{7}$$

where: $\varepsilon_{\substack{(S)\\(P)}} = 1 - w_{R\substack{(S)\\(P)}} \Big/ 1 - w_{P\substack{(S)\\(P)}}$; $\kappa = kx \Big/ \varepsilon_{\substack{(S)\\(P)}}$; $\eta_{P\substack{(S)\\(P)}} = D_{P\substack{(S)\\(P)}} \Big/ H_{R\substack{(S)\\(P)}}$; $u_{P\substack{(S)\\(P)}} = \left(1 - w_{P\substack{(S)\\(P)}}\right)\left(u - y_{P\substack{(S)\\(P)}} r\right)$

Here, ε, κ, γ_R, and l_R are the parameters describing the rudder inflow velocity angle, while (*1-w*) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H) is the ratio of the propeller diameter to the rudder height.

The effective inflow velocity (v_R) to the rudder in the sway direction can be expressed by Equation 8:

$$v_{R\substack{(S)\\(P)}} = u_{R\substack{(S)\\(P)}} \tan\left(\delta_{R\substack{(S)\\(P)}}\right) \tag{8}$$

where: $\delta_{R\substack{(S)\\(P)}} = \gamma_{R\substack{(S)\\(P)}} \beta_{R\substack{(S)\\(P)}} + \tan^{-1}\left(y_{R\substack{(S)\\(P)}} \Big/ x_{R\substack{(S)\\(P)}}\right)$ and $\beta_{R\substack{(S)\\(P)}} = \beta - L_{R\substack{(S)\\(P)}} r$

Here, δ_R is the rudder angle, β_R is the effective drift angle at the rudder, and L_R is the flow-straightening coefficient of the yaw rate. For the case of a ship operating under windy conditions, the force and moment (X_W, Y_W, and N_W) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A) q_A A_F; \quad Y_W = C_{AY}(\psi_A) q_A A_L; \quad N_W = C_{AN}(\psi_A) q_A A_L L_{OA} \tag{9}$$

where $\psi_A = \tan^{-1}\left[U_T \cos\psi + U\cos\beta / U_T \sin\psi - U\cos\beta\right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi + \beta)$

C_{AX}, C_{AY}, and C_{AN} are the wind load forces and moments' coefficients, respectively, as a function of the wind direction relative to a ship (ψ_A). U_T and ψ are wind velocity and direction angles with reference to the coordinate system, q_A is wind pressure, q_T is wind pressure due to the elevation of the center of a windage area, and q_S is the wind pressure induced by wind velocity, without an elevation effect. A_F and A_L are the transversal and lateral projections of the windage area, respectively.

2.2. *Autopilot Ship Steering*

The rudder is the most critical feature in achieving controllability goals (Lee et al., 2009). The control system must alter the control surfaces to the desired heading angle. The schematic equation of the PID control system that a ship tracks can be expressed by Equation 10 (Lee et al., 2009).

$$\delta = K_p(e) + K_d(\dot{e}) + K_i \int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \tag{10}$$

where δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain, and integral gain respectively; and *e* is an error between the heading target (ψ_T) and the actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference heading angles. The reference heading angle equation and target zone correction can be expressed by Equation 11:

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t)/x_k - x(t)) \text{ and } (x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \tag{11}$$

where x_k and y_k are the track-point coordinates, $x(t)$ and $y(t)$ are the ship's coordinates position, and R_0 is the target zone's radius.

2.3. *Simulation Program*

According to IMO (2002) criteria for ship maneuvering, a swept path should be used to analyze a ship's course-keeping prediction. A ship's swept path can be obtained by double-integrating the ship motion mathematical model's acceleration, including hydrodynamic derivatives. A numerical integration of the Dormand–Prince method (Maimun et al., 2011; Muhammad et al., 2015) then solved the equations of motion in this time-domain simulation using the MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for the acting hull force and moment in Equation 2—and the interaction force coefficient among the hull, propeller, and rudder—were predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). This regression equation is among the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circles and zigzag maneuvering for ships with twin-rudder and twin-propeller systems, as well as validation through model testing or free-running tests. In many cases, the regression equation has been used to predict ferry ships' maneuvering under active wind and wave conditions (Paroka et al., 2015, 2016, 2017b). A ship's resistance coefficients for simulation were predicted using the Holtrop method (Holtrop and Mennen, 1982; Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\,J_P - 0.1178\,J_P^{\,2}$) was predicted using polynomial regression, based on the open water test's statistical data for the B-series propeller (Carlton, 2007). The coefficient of the wind load force and moment in Equation 9 was predicted using the methodology proposed by Fujiwara and Ueno (2006). The control method used in the simulation was a proportional integrated derivative (PID) controller. The designed rudder angle (δ=±35 deg.) was calculated using Equation 10 with a PID gain (K_p = 2.208; K_i = 0.027 and K_d = 45.372), and it was selected using the pole placement method with the second-order linear Nomoto model of the ship (Nomoto et al., 1957). The methods used by Paroka et al. (2017a) in developing an automatic control system to predict and avoid ferry-ship collisions were compared using a free-running experiment.

2.4. *Ship and Sea-Trial Data*

The study's object was the *KMP Bontoharu* ferry ship (1053 gross tonnage), owned by PT. ASDP Indonesia Ferry. The ship has twin propellers and twin rudders, and the distance between the rudders and propellers is 2.3 m. The ship's particulars are presented in Table 1. The ship's sea trial on the Selayar-to-Bulukumba route was 15.385 nautical miles long, involving a 7,268-second traveling time, around a 6.03 m/s wind velocity, and a 254^o wind direction. The trial data were taken on September 20, 2015.

Table 1 Ship particulars

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m^2	182.87	*Z*	2×4
Lbp,m	47.45	A_F, m^2	129.20	*D, m*	1.450
B, m	14	A_{OD}, m	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_C, m	2.70	*n*	8.784
V, m/s^2	6.618	H_L, m	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, m	10.48	*Chord, m*	0.900
				A_R, m^2	2×1.395
				BHP, HP RPMME	2×1000
					1850

2.5. *Wind Data*

Monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years, from 2006 to 2018, at six-hour intervals. The model provided wind speed data with a resolution of 0.25 × 0.25 degrees. This model was validated by Dee et al. (2011). Furthermore, it was validated locally by Lina et al. (2015) using data from eight buoys deployed in the Yellow Sea and the East China Sea. This study's coordinate for its observation data was at 5.75^{o}S and 120.5^{o}E.

3. Results and Discussion

The wind speed trend peaked in January, with a maximum of 10.06 m/s (88^o), as Figure 2 shows. Meanwhile, April's monthly wind speed trend decreased, with a minimum of 6.41 m/s (219^o). The monthly wind speed movements varied, depending on the month occurring during the west or east monsoon seasons.

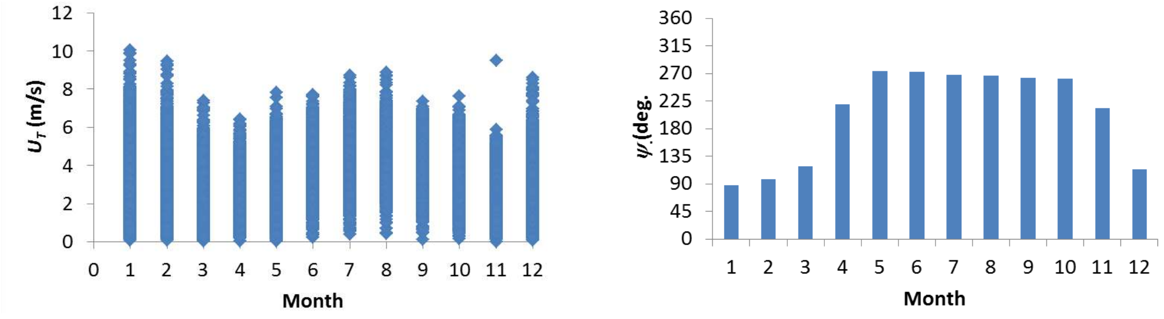

Figure 2 Significant wind velocity and direction on the Selayar–Bulukumba route

Based on the wind data characteristics in Figure 2, the *KMP Bontoharu*'s course-keeping was simulated for three conditions of wind direction parameters—the starboard bow (88°) and the portside stern of the ship (219° and 268°)—using the time domain simulation program of MATLAB-Simulink. This information is essential to ship navigation due to time-savings and reduced fuel consumption by controlling a twin-rudder configuration design. Figure 3 shows the historic result of the simulation for the course-keeping trajectory of the *KMP Bontoharu* (Selayar to Bulukumba) under wind velocities' effect.

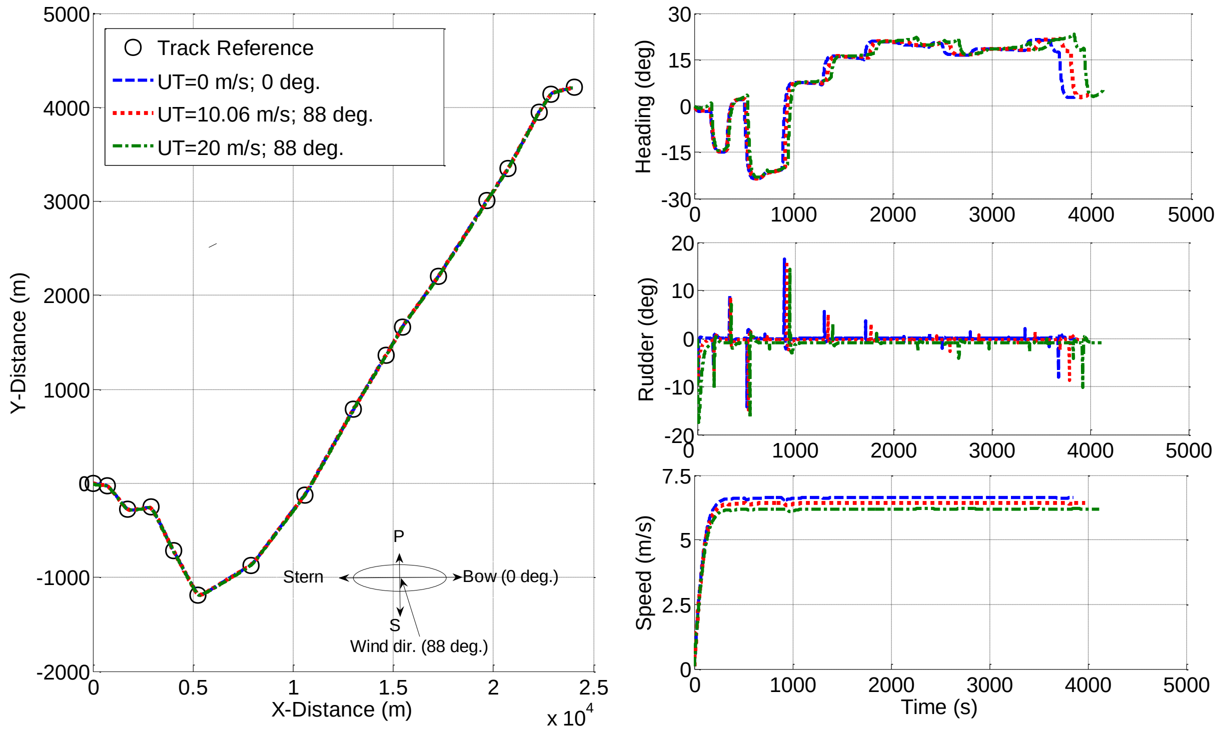

Figure 3 Ship trajectory with different wind speeds (U_T) at 88°

The horizontal axis expresses the time, while the vertical axis expresses the heading angle (ψ), rudder angle (δ), and ship speed (u), respectively. The wind blew from the starboard bow (88°) at wind velocities of 10.06 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory slowly deviated from the initial track with a low heading with significant course-keeping time compared to conditions without winds ($U_T =$ 0 m/s). Meanwhile, the ship's course-keeping trajectory with increased wind velocities caused more deviations and low ship speeds.

Figure 4 shows the simulation results for the *KMP Bontoharu*'s course-keeping with the wind blowing from the portside stern (219°) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory quickly deviated from the initial track with a high heading and short course-keeping time at each blown wind velocity, compared to conditions without winds (U_T = 0 m/s). These characteristics differed when the wind blew from the starboard side (88°). The wind direction angle caused these differences, as Ohtsu et al. (1996) found, relating to changes in a ship's heading and rudder angle as a result of wind velocity and ship direction in course-keeping.

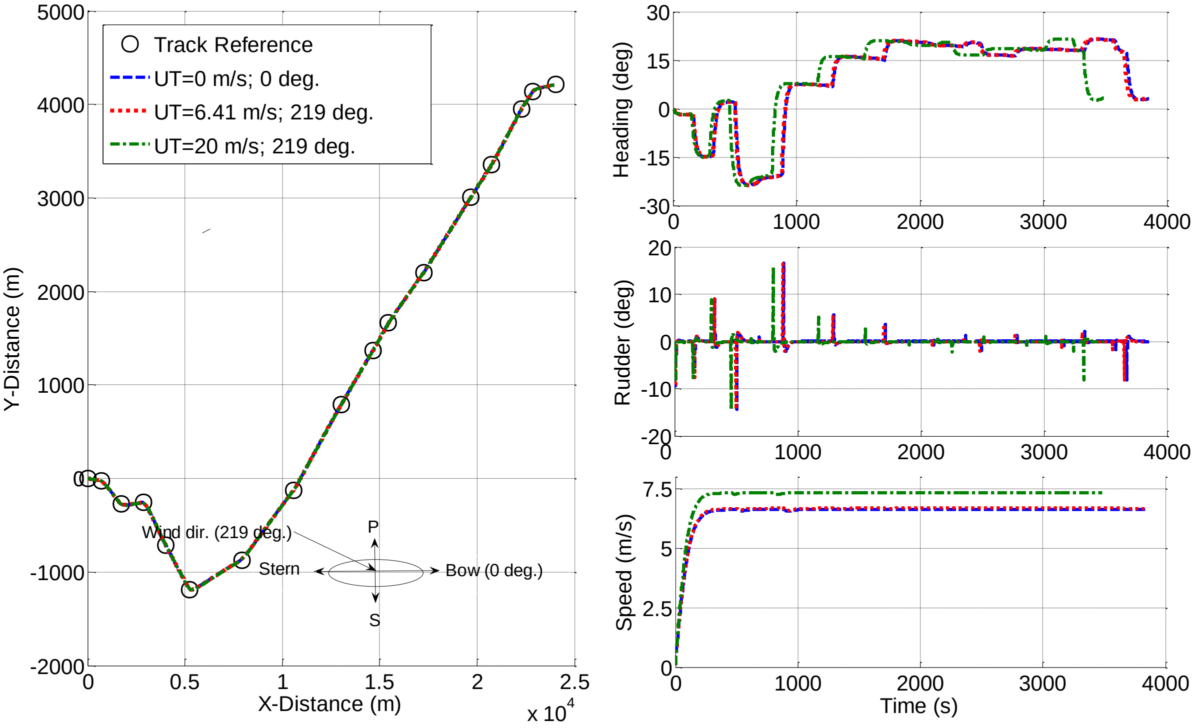

Figure 4 Ship trajectory with different wind speeds (U_T) at 219°

Figure 5 shows the historic results of the simulation for the course-keeping trajectory of the *KMP Bontoharu* with the wind blowing from the portside stern (268°) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed was 0.27% reduced compared to conditions without wind (U_T = 0 m/s), while the ship speed increased by 5.96% increases at a wind speed of 20 m/s. These changes in ship speed were caused by the ship's directional movements.

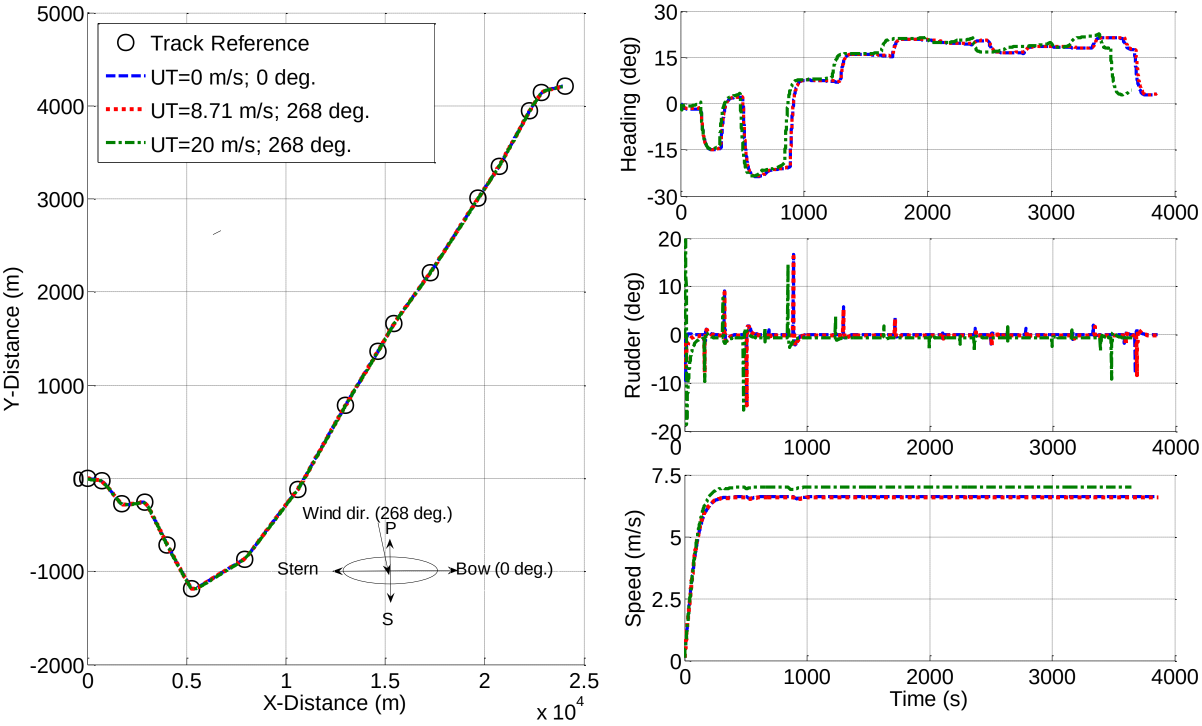

Figure 5 Ship trajectory with different wind speeds (U_T) at 268°

Figure 6 shows the sea-trial simulation results for the ship course-keeping trajectory with a 6.03 m/s wind velocity and a 254° wind direction at an initial ship speed of 3.98 m/s. We found that the traveling time under these conditions stood at 6.407 seconds. The simulation's traveling time was 11.84% higher than the sea-trial result. A possible reason for this difference is that the simulation excluded waves and currents.

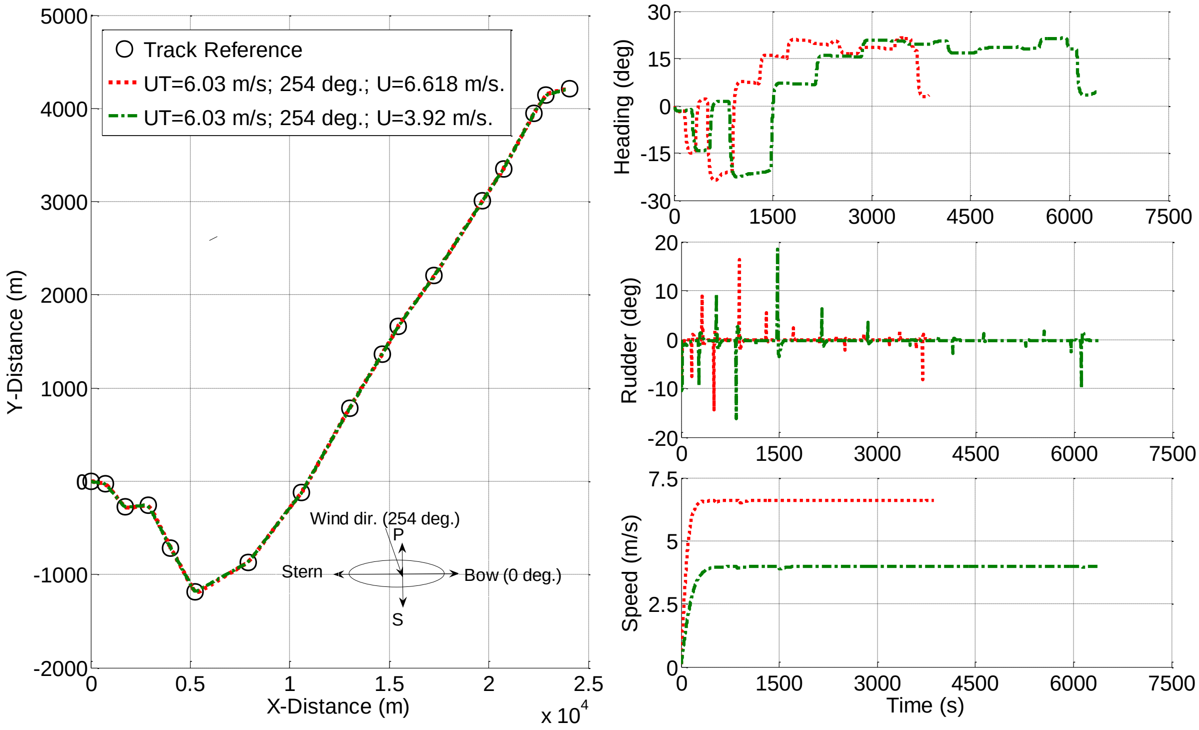

Figure 6 Sea-trial simulation result for ship trajectories with different initial ship speeds (*U*)

Figures 3, 4, and 5 also show the effects of winds velocity and direction on ship speed, with a course-keeping trajectory for an initial ship speed (*U*) of 6.618 m/s. We found that, when the wind blew from the starboard bow (88º) with a wind velocity of 20 m/s, the ship speed was 6.36% lower compared to conditions without wind (U_T = 0 m/s). Meanwhile, when the wind blew from the portside stern (219° and 268°), the ship speed was increased by 10.74% and 5.96%, respectively. The two latter speeds were beneficial because the track trajectory times were minimal.

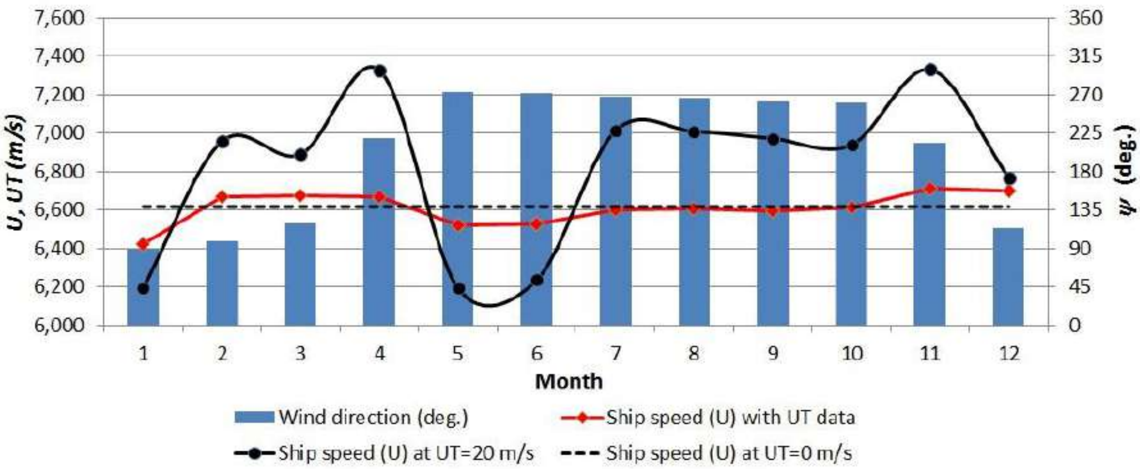

Figure 7 Tracking ship speed trajectories with different wind velocities and directions

In general, when the wind blew from the starboard and portside to the stern (98° to 268°), the ship's track trajectory time tended to benefit compared to conditions with the wind blows from the bow to the starboard and portside, as the simulation results in Figure 7. The ship's reduced speed when the wind blew from the bow to the starboard (less than 100°) was similar to the findings of Paroka et al. (2016) related to ship-speed changes caused by wind speeds and directions' influence on ferry maneuvering.

4. Conclusions

This study has analyzed a twin-rudder-system configuration's influence on a ship's course-keeping ability under various wind speeds and directions through the MATLAB-Simulink computer-simulation program. The results indicated that applying a twin-rudder system to ferry ships' to improve their course-keeping ability under windy conditions is very effective using a PID controller, reducing ship deviation and increasing ship speed by adjusting the ship's heading angle to the desired path. The track trajectory time in the ferry's course-keeping highly depends on wind velocity and direction. When the wind blows from the starboard and portside to the stern (98 to 268º), a ship's travel time tends to benefit compared to when the wind blows from the bow to the side. This research shows that the PID controller method can be applied to assist ships' movements due to other environmental influences, such as waves and currents. However, ships' course-keeping quality highly depends on the selected PID parameters.

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Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions

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Abstract. Ship course-keeping plays a vital role in navigation safety, especially when a ship is operating under windy conditions. A method to control ship movements through rudder-system configuration is necessary to stabilize a ship's course. This paper describes the twin-rudder-system configuration design's impact on a ship's course-keeping ability under windy conditions. A time-domain simulation using the MATLAB-Simulink program was developed for this purpose. A proportional integral derivative (PID) controller was used to adjust the ship's heading angle according to the desired path. Several parameters—such as relative wind velocity and directions—were accounted for in the simulation. The result shows that, at a wind direction of 88°, the ship's course-keeping speed decreased; however, increasing wind velocity caused a large deviation in the ship's heading angle. Meanwhile, the ship's course-keeping speed increased with rising windspeed directions of 219°. The ship's course-keeping time, at around 219° under the simulation's wind direction, was 11.84% lower than during a previous sea-trial. A possible reason for this difference is that the simulation excluded waves and currents.

Keywords: Course-keeping; Proportional integral derivative controller; Ship-tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigation due to time-saving and reduced fuel consumption (Prpic-Orsic et al., 2016). To achieve quality ship course-keeping and generate accurate heading angles, a controller that considers ship hydrodynamics—including both internal and external disturbance parameters—should be installed (Lee et al, 2009). Keeping a ferry ship on course differs from sea-going ships due to navigation environments and ship particulars (Prpic-Orsic et al., 2016). The navigation environment's complexity, and especially wind-load forces and moment, makes ferry ships with large superstructures more susceptible to marine accidents (Fujiwara and Ueno, 2006). Many studies have related wind effects to ship maneuvering; wind's load-force and moment have significantly affected transversal and lateral projections of windage areas due to ships' large superstructures, as well as wind velocities and directions relative to ships (Fujiwara and Ueno, 2006). Paroka et al. (2016) simulated wind's effect on ferry ships' maneuvering,

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explaining that ship-speed changes caused by wind highly depend on wind velocity and direction. When the wind blows from the bow direction and passes to the ship's starboard (0 to 100°), ship speed tends to decrease. The corresponding decrease in ship speed is insignificant when the wind blows from a starboard direction and passes to the ship’s stern (100 to 180°). Meanwhile, when the wind blows from the side of a ship (20 to 140°), it tends to change the ship’s direction. A ship’s directional deviations due to wind vary by ship type, and a steering response is required. Ohtsu et al. (1996) reported that a wind blowing from starboard-bow quarters (45°) made a ship’s steering becomes less sensitive, but steering became more sensitive when the wind came from the port-stern quarters (135°). Increasing a ship’s speed as wind directions change is crucial (Ohtsu et al., 1996; Paroka et al., 2016). The information informing this behavior is essential to improve ships’ course-keeping quality—especially when ships must take appropriate action to handle wind disturbances. The improving quality of a ship’s course-keeping ability in windy conditions is strongly influenced by steering responses to wind-blowing loads through an appropriately configured rudder system design (Hasegawa et al., 2006). Steering control plays an essential role in responding to external forces to a ship’s yaw motion stability and course-keeping ability during maneuvers (Paroka, 2020).

Many efforts to improve ships’ maneuvering have been conducted using twin-rudder ship controllers. Yoshimura and Sakurai (1989) investigated the effect of a ship-fitted, twin-rudder, twin-propeller configuration on ships’ maneuvering. They found that a twin-rudder, twin-propeller configuration’s hydrodynamic characteristics did not differ significantly from the corresponding characteristics of a single-propeller, single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ships’ maneuvering when fitted with a twin-propeller, twin-rudder configuration. Furthermore, Khanfir et al. (2011) conducted captive model tests and free-running tests with a single-propeller, twin-rudder ship and a twin-propeller, twin-rudder ship. These tests aimed to evaluate drift angles’ effect on rudder forces and the peculiar phenomena concerning a normal rudder force for twin-rudder ships.

Other parameters that affect ships’ maneuvering performance include the distance of spacing between single rudders in twin-rudder ships. Gim (2013) conducted a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5–1.0 times the chord length of the rudder. He found that this spacing distance between rudders in twin-rudder configurations was also affected by interactions between rudders, and he also found that this critical distance should be less than 1.0 times the chord length of the rudder in order to decrease the turbulence flow and vortices. This result was similar to the findings of Chen et al. (2018), who used numerical simulation to confirming the excellent characteristics of twin-rudder ships compared to single-rudder ships. Chen et al. (2018) concluded that a ship fitted with a twin-rudder configuration would operate very well at 15° rudder angles. Additionally, the twin rudders’ effective performance stopped at a lateral spacing equal to 1.3 times the chord length of the rudder.

These previous studies have shown that a rudder system’s configuration is the most crucial feature in achieving ship controllability goals. A rudder system must alter ship control to the desired heading angle, due to both internal and external disturbance parameters. The current paper focuses on applying the twin-rudder system to improve ferries’ course-keeping quality under windy conditions. By simulating fluctuating wind velocity and directions according to a ship’s operating route, quality course-keeping and accurate heading angles may be achieved, increasing the ship’s safety.

2. Methods

2.1. *Mathematical Model*

This study's ship maneuvering analysis used computer simulation to employ modular mathematical models, including a consideration of hydrodynamic derivatives. This study's models were based on surge, sway, and yaw motions (Equation 1) using the coordinate system shown in Figure 1.

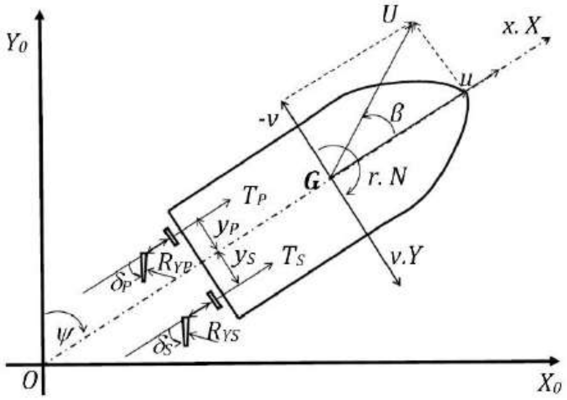

Figure 1 Coordinate ship system

$$\begin{aligned} m(\dot{u}-rv) &= X_H + X_P + X_R + X_W \\ m(\dot{v}-ru) &= Y_H + Y_P + Y_R + Y_W \\ I_{ZZ}\ddot{\psi} &= N_H + N_P + N_R + N_W \end{aligned} \tag{1}$$

The notations *u, v* and *r,* are velocity components at the ship's center of gravity (*G*). *m* and I_{ZZ} represent the ship's mass and moments of inertia. *X, Y*, and *N* represent the hydrodynamic forces and moment. The subscript *H, P, R,* and *W* refer to the ship's hull, propeller, rudder, and wind. In principle, the force and moment induced by hull (X_H, Y_H, and N_H) approximate β and r' polynomial function. These equations were expressed by Yoshimura (2001) as Equation 2:

$$\begin{aligned} X_H &= \tfrac{1}{2}\rho LdU^2(X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr}r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\ Y_H &= \tfrac{1}{2}\rho LdU^2(Y'_\beta\beta + (Y'_r - m'_x)r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr}r'^3) \\ N_H &= \tfrac{1}{2}\rho L^2dU^2(N'_\beta\beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr}r'^3) \end{aligned} \tag{2}$$

where β is the drift angle at the midship position by $\tan^{-1}(v/u)$ and r' non-dimensionalized yaw rate by rL/U. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} is the hydrodynamic derivatives on the ship's maneuvering. The force and moment induced by twin-propeller configurations (X_P, Y_P, and N_P) were expressed by Khanfir et al. (2011) in Equation 3:

$$\begin{aligned} X_P &= \rho\left((1-t_{P(S)})n_{P(S)}{}^2D_{P(S)}{}^4K_{T(S)}(J_{P(S)}) + (1-t_{P(P)})n_{P(P)}{}^2D_{P(P)}{}^4K_{T(P)}(J_{P(P)})\right) \\ N_P &= \rho\left((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2D_{P(S)}{}^4K_{T(S)}(J_{P(S)}) + (1-t_{P(P)})y_{P(P)}n_{P(P)}{}^2D_{P(P)}{}^4K_{T(P)}(J_{P(P)})\right) \end{aligned} \tag{3}$$

where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}}) = k_0 + k_1J_{P\substack{(S)\\(P)}} + k_2J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\substack{(S)\\(P)}} = (u - y_{P\substack{(S)\\(P)}}r(1-w_{P\substack{(S)\\(P)}})/(n_{P\substack{(S)\\(P)}}D_{P\substack{(S)\\(P)}})$

where t_P is the thrust deduction coefficient in straightforward moving, K_T is the thrust coefficient of the propeller force, and n_P is the propeller revolution. D_P is the propeller

diameter, w_P is the effective wake fraction coefficient at the propeller's location, and J_P is the advance coefficient, while k_0, k_1, and k_2 are the constants for an open-water propeller. The sub-subscript *(S)* and *(P)* refer to starboard and portside.

Force and moment due to twin-rudder configurations (X_R, Y_R, and N_R) can be expressed by Equations 4–8 (Khanfir et al., 2011).

$$\begin{aligned}
X_R &= -(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} - (1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)} \\
Y_R &= -(1+a_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{R(YS)}\cos\delta_{(P)}\right) \\
N_R &= -(x_R + a_H x_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{RY(P)}\cos\delta_{(P)}\right) + f\left(x_R\right) \\
f\left(x_R\right) &= y_{P(S)}(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)}
\end{aligned} \tag{4}$$

where δ is the rudder angle, x_R is the rudder's location, and t_R, a_H, and x_H are the interactive force coefficients for the hull, propeller, and rudder as functions of the propeller's advance constant. The rudder's normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

$$F_{RY\substack{(S)\\(P)}} = \tfrac{1}{2}\rho A_R U_{R\substack{(S)\\(P)}}^{\,2} f_\alpha \sin\alpha_{R\substack{(S)\\(P)}} \tag{5}$$

where A_R is the rudder area, and f_α is the gradient of the rudder's lift coefficient, which can be approximated by the function of the rudder's aspect ratio (f_α = 6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and the effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6:

$$U_{R\substack{(S)\\(P)}} = \sqrt{u_{R\substack{(S)\\(P)}}^{\,2} + v_{R\substack{(S)\\(P)}}^{\,2}} \qquad \text{and} \qquad \alpha_{R\substack{(S)\\(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R\substack{(S)\\(P)}}\left(\beta_{R\substack{(S)\\(P)}}\right) \tag{6}$$

The effective inflow velocity (u_R) to the rudder in the surge direction can be expressed by Equation 7:

$$u_{R\substack{(S)\\(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P\substack{(S)\\(P)}} \times \sqrt{\eta_{P\substack{(S)\\(P)}}\left\{1+\kappa\left(\sqrt{1+8K_{T\substack{(S)\\(P)}} \Big/ \pi J_{P\substack{(S)\\(P)}}^{\,2}} - 1\right)\right\}^2 + (1-\eta_{P\substack{(S)\\(P)}})} \tag{7}$$

where: $\varepsilon_{\substack{(S)\\(P)}} = 1 - w_{R\substack{(S)\\(P)}} \Big/ 1 - w_{P\substack{(S)\\(P)}}$; $\kappa = kx \Big/ \varepsilon_{\substack{(S)\\(P)}}$; $\eta_{P\substack{(S)\\(P)}} = D_{P\substack{(S)\\(P)}} \Big/ H_{R\substack{(S)\\(P)}}$; $u_{P\substack{(S)\\(P)}} = \left(1 - w_{P\substack{(S)\\(P)}}\right)\left(u - y_{P\substack{(S)\\(P)}} r\right)$

Here, ε, κ, γ_R, and l_R are the parameters describing the rudder inflow velocity angle, while (1-w_R) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H_R) is the ratio of the propeller diameter to the rudder height.

The effective inflow velocity (v_R) to the rudder in the sway direction can be expressed by Equation 8:

$$v_{R\substack{(S)\\(P)}} = u_{R\substack{(S)\\(P)}} \tan\left(\delta_{R\substack{(S)\\(P)}}\right) \tag{8}$$

where: $\delta_{R\substack{(S)\\(P)}} = \gamma_{R\substack{(S)\\(P)}} \beta_{R\substack{(S)\\(P)}} + \tan^{-1}\left(y_{R\substack{(S)\\(P)}} \Big/ x_{R\substack{(S)\\(P)}}\right)$ and $\beta_{R\substack{(S)\\(P)}} = \beta - L_{R\substack{(S)\\(P)}} r$

Here, δ_R is the rudder angle, β_R is the effective drift angle at the rudder, and L_R is the flow-straightening coefficient of the yaw rate. For the case of a ship operating under windy conditions, the force and moment (X_W, Y_W, and N_W) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A) q_A A_F ; \quad Y_W = C_{AY}(\psi_A) q_A A_L ; \quad N_W = C_{AN}(\psi_A) q_A A_L L_{OA} \tag{9}$$

where $\psi_A = \tan^{-1}\left[U_T \cos\psi + U\cos\beta / U_T \sin\psi - U\cos\beta \right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi + \beta)$

C_{AX}, C_{AY}, and C_{AN} are the wind load forces and moments' coefficients, respectively, as a function of the wind direction relative to a ship (ψ_A). U_T and ψ are wind velocity and direction angles with reference to the coordinate system, q_A is wind pressure, q_T is wind pressure due to the elevation of the center of a windage area, and q_S is the wind pressure induced by wind velocity, without an elevation effect. A_F and A_L are the transversal and lateral projections of the windage area, respectively.

2.2. Autopilot Ship Steering

The rudder is the most critical feature in achieving controllability goals (Lee et al., 2009). The control system must alter the control surfaces to the desired heading angle. The schematic equation of the PID control system that a ship tracks can be expressed by Equation 10 (Lee et al., 2009).

$$\delta = K_p(e) + K_d(\dot{e}) + K_i \int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \tag{10}$$

where δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain, and integral gain respectively; and e is an error between the heading target (ψ_T) and the actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference heading angles. The reference heading angle equation and target zone correction can be expressed by Equation 11:

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t)/x_k - x(t)) \text{ and } (x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \tag{11}$$

where x_k and y_k are the track-point coordinates, $x(t)$ and $y(t)$ are the ship's coordinates position, and R_0 is the target zone's radius.

2.3. Simulation Program

According to IMO (2002) criteria for ship maneuvering, a swept path should be used to analyze a ship's course-keeping prediction. A ship's swept path can be obtained by double-integrating the ship motion mathematical model's acceleration, including hydrodynamic derivatives. A numerical integration of the Dormand–Prince method (Maimun et al., 2013; Muhammad et al., 2015) then solved the equations of motion in this time-domain simulation using the MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for the acting hull force and moment in Equation 2—and the interaction force coefficient among the hull, propeller, and rudder—were predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). This regression equation is among the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circles and zigzag maneuvering for ships with twin-rudder and twin-propeller systems, as well as validation through model testing or free-running tests. In many cases, the regression equation has been used to predict ferry ships' maneuvering under active wind and wave conditions (Paroka et al., 2015, 2016, 2017b). A ship's resistance coefficients for simulation were predicted using the Holtrop method (Holtrop and Mennen, 1982; Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\, J_P - 0.1178\, J_P{}^2$) was predicted using polynomial regression, based on the open water test's statistical data for the B-series propeller (Carlton, 2007). The coefficient of the wind load force and moment in Equation 9 was predicted using the methodology proposed by Fujiwara and Ueno (2006). The control method used in the simulation was a proportional integrated derivative (PID) controller. The designed rudder angle (δ=±35 deg.) was

calculated using Equation 10 with a PID gain ($K_p = 2.208$; $K_i = 0.027$ and $K_d = 45.372$), and it was selected using the pole placement method with the second-order linear Nomoto model of the ship (Nomoto et al., 1957). The methods used by Paroka et al. (2017a) in developing an automatic control system to predict and avoid ferry-ship collisions were compared using a free-running experiment.

2.4. *Ship and Sea-Trial Data*

The study's object was the *KMP Bontoharu* ferry ship (1053 gross tonnage), owned by PT. ASDP Indonesia Ferry. The ship has twin propellers and twin rudders, and the distance between the rudders and propellers is 2.3 m. The ship's particulars are presented in Table 1. The ship's sea trial on the Selayar-to-Bulukumba route was 15.385 nautical miles long, involving a 7,268-second traveling time, around a 6.03 m/s wind velocity, and a 254° wind direction. The trial data were taken on September 20, 2015.

Table 1 Ship particulars

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m^2	182.87	*Z*	2×4
Lbp,m	47.45	A_F, m^2	129.20	*D, m*	1.450
B, m	14	A_{OD}, m	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_C, m	2.70	*n*	8.784
V, m/s²	6.618	H_L, m	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, m	10.48	*Chord, m*	0.900
				A_R, m^2	2×1.395
				BHP, HP	2×1000
				RPMME	1850

2.5. *Wind Data*

Monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years, from 2006 to 2018, at six-hour intervals. The model provided wind speed data with a resolution of 0.25 × 0.25 degrees. This model was validated by Dee et al. (2011). Furthermore, it was validated locally by Lina et al. (2015) using data from eight buoys deployed in the Yellow Sea and the East China Sea. This study's coordinate for its observation data was at 5.75°S and 120.5°E.

3. Results and Discussion

The wind speed trend peaked in January, with a maximum of 10.06 m/s (88°), as Figure 2 shows. Meanwhile, April's monthly wind speed trend decreased, with a minimum of 6.41 m/s (219°). The monthly wind speed movements varied, depending on the month occurring during the west or east monsoon seasons.

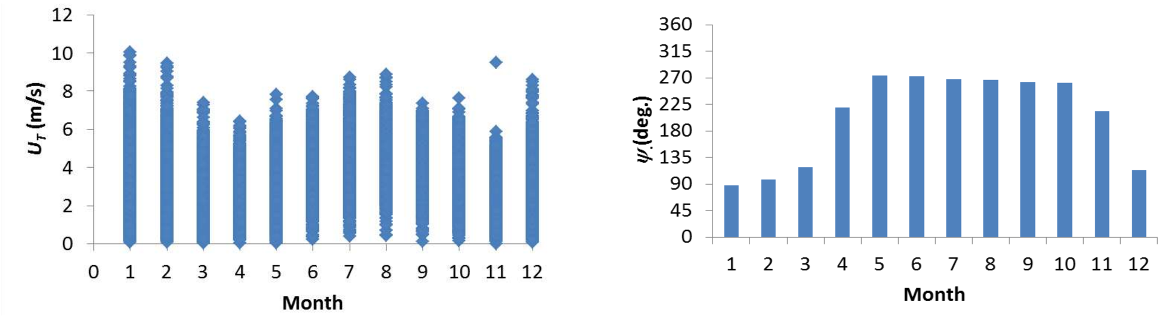

Figure 2 Significant wind velocity and direction on the Selayar–Bulukumba route

Based on the wind data characteristics in Figure 2, the *KMP Bontoharu*'s course-keeping was simulated for three conditions of wind direction parameters—the starboard bow (88°) and the portside stern of the ship (219° and 268°)—using the time domain simulation program of MATLAB-Simulink. This information is essential to ship navigation due to time-savings and reduced fuel consumption by controlling a twin-rudder configuration design. Figure 3 shows the historic result of the simulation for the course-keeping trajectory of the *KMP Bontoharu* (Selayar to Bulukumba) under wind velocities' effect.

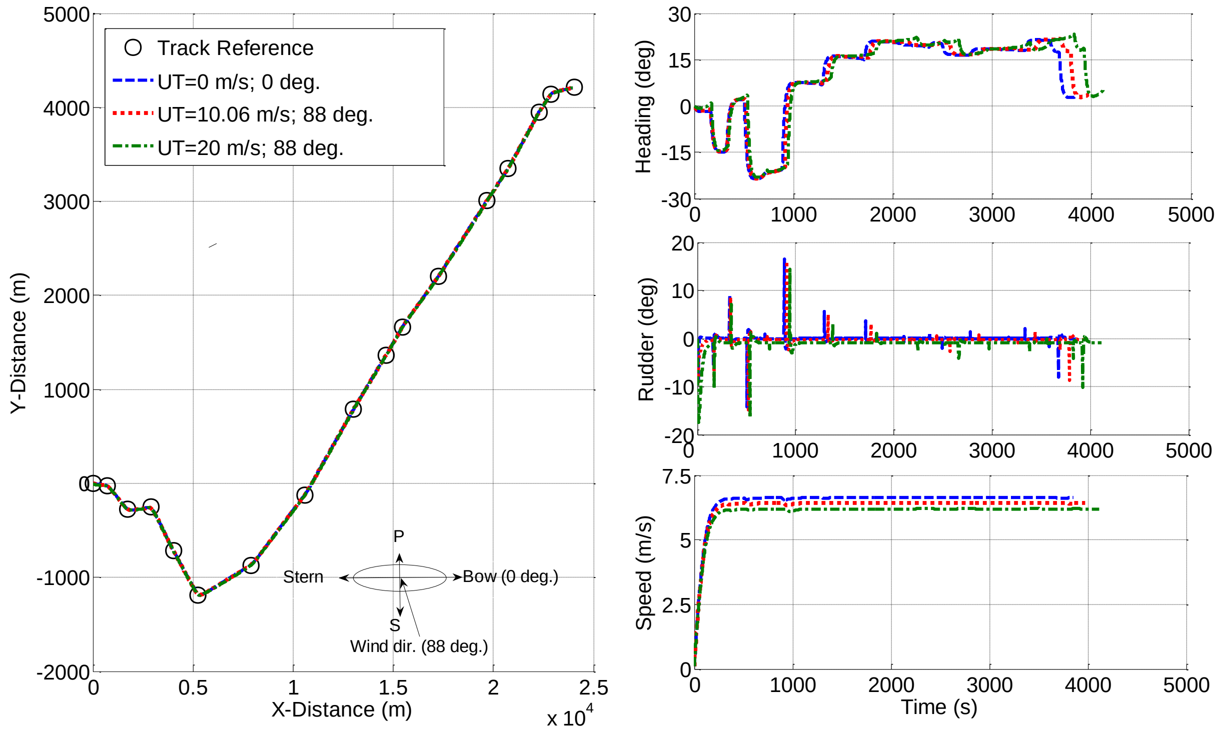

Figure 3 Ship trajectory with different wind speeds (U_T) at 88°

The horizontal axis expresses the time, while the vertical axis expresses the heading angle (ψ), rudder angle (δ), and ship speed (u), respectively. The wind blew from the starboard bow (88°) at wind velocities of 10.06 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory slowly deviated from the initial track with a low heading with significant course-keeping time compared to conditions without winds (U_T = 0 m/s). Meanwhile, the ship's course-keeping trajectory with increased wind velocities caused more deviations and low ship speeds.

Figure 4 shows the simulation results for the *KMP Bontoharu*'s course-keeping with the wind blowing from the portside stern (219°) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory quickly deviated from the initial track with a high heading and short course-keeping time at each blown wind velocity, compared to conditions without winds (U_T = 0 m/s). These characteristics differed when the wind blew from the starboard side (88°). The wind direction angle caused these differences, as Ohtsu et al. (1996) found, relating to changes in a ship's heading and rudder angle as a result of wind velocity and ship direction in course-keeping.

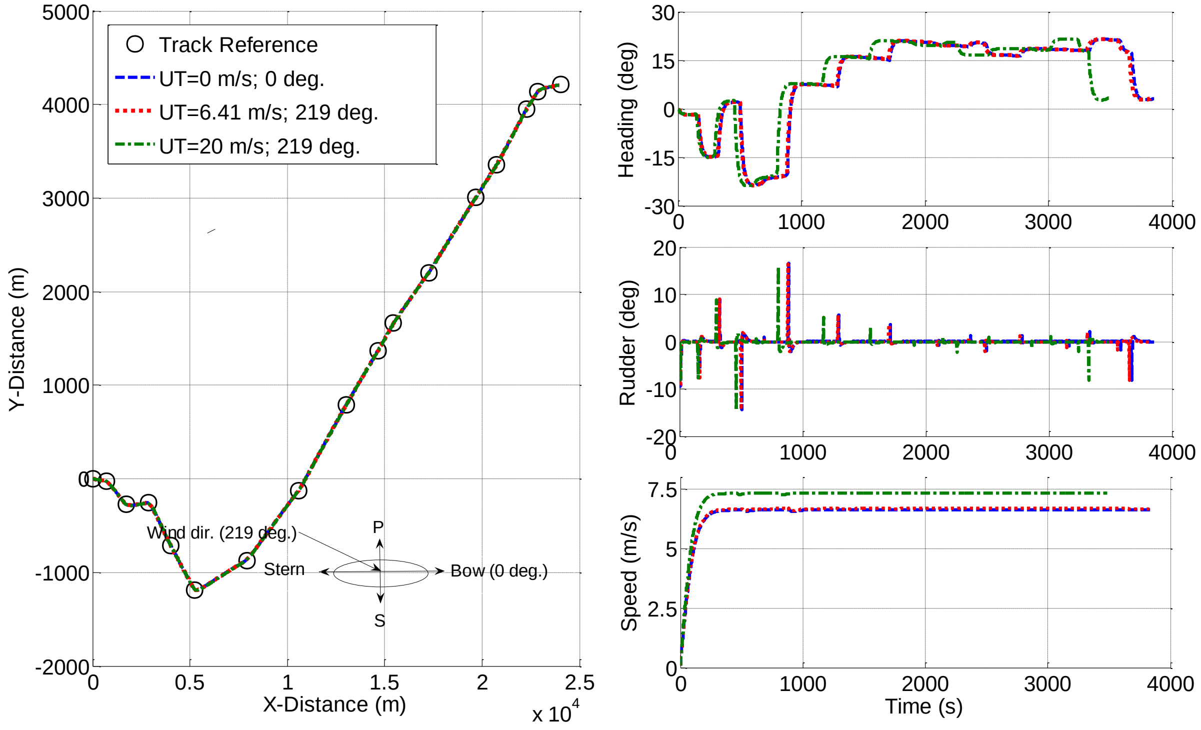

Figure 4 Ship trajectory with different wind speeds (U_T) at 219°

Figure 5 shows the historic results of the simulation for the course-keeping trajectory of the *KMP Bontoharu* with the wind blowing from the portside stern (268°) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed was 0.27% reduced compared to conditions without wind (U_T = 0 m/s), while the ship speed increased by 5.96% increases at a wind speed of 20 m/s. These changes in ship speed were caused by the ship's directional movements.

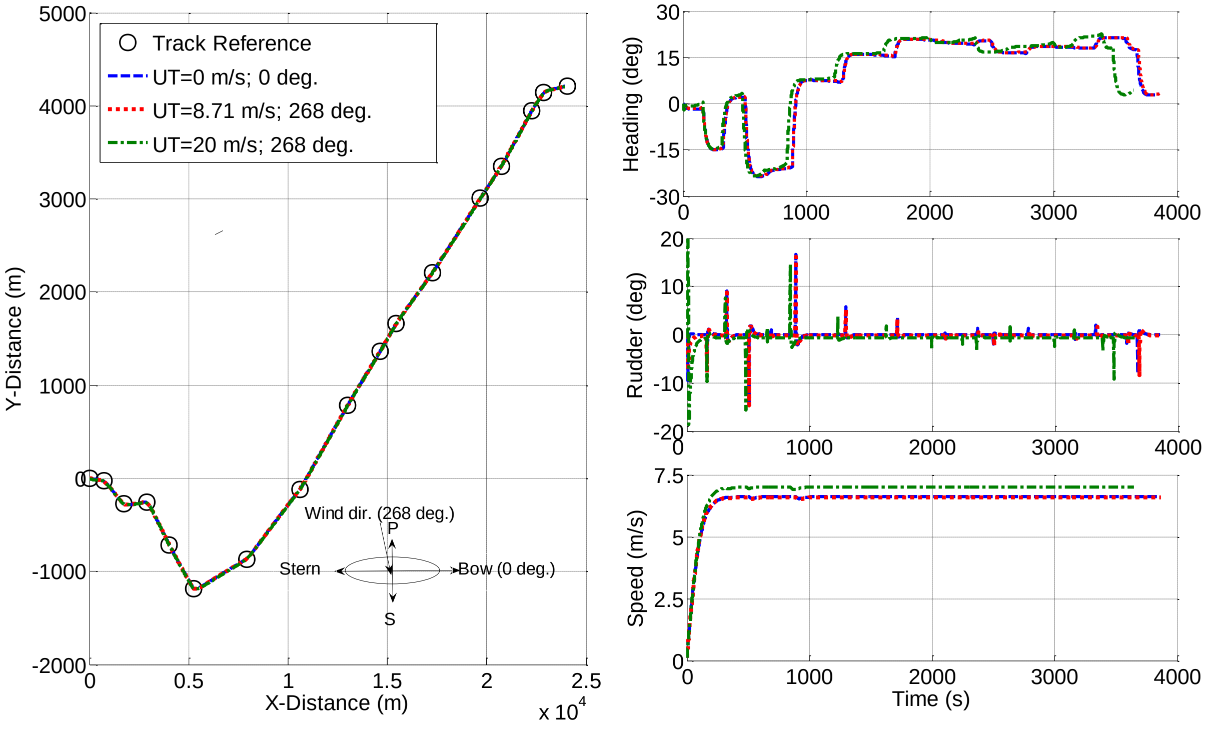

Figure 5 Ship trajectory with different wind speeds (U_T) at 268°

Figure 6 shows the sea-trial simulation results for the ship course-keeping trajectory with a 6.03 m/s wind velocity and a 254° wind direction at an initial ship speed of 3.98 m/s. We found that the traveling time under these conditions stood at 6,407 seconds. The simulation's traveling time was 11.84% higher than the sea-trial result. A possible reason for this difference is that the simulation excluded waves and currents.

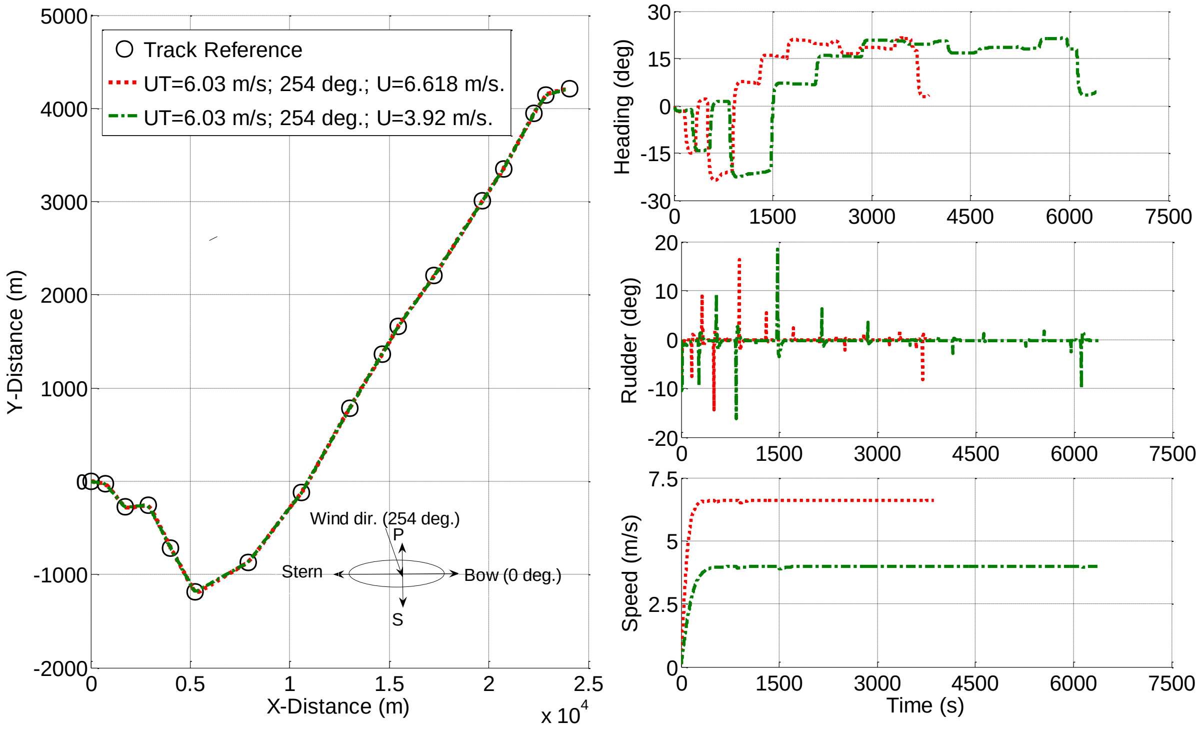

Figure 6 Sea-trial simulation result for ship trajectories with different initial ship speeds (U)

Figures 3, 4, and 5 also show the effects of winds velocity and direction on ship speed, with a course-keeping trajectory for an initial ship speed (U) of 6.618 m/s. We found that, when the wind blew from the starboard bow (88°) with a wind velocity of 20 m/s, the ship speed was 6.36% lower compared to conditions without wind ($U_T = 0$ m/s). Meanwhile, when the wind blew from the portside stern (219° and 268°), the ship speed was increased by 10.74% and 5.96%, respectively. The two latter speeds were beneficial because the track trajectory times were minimal.

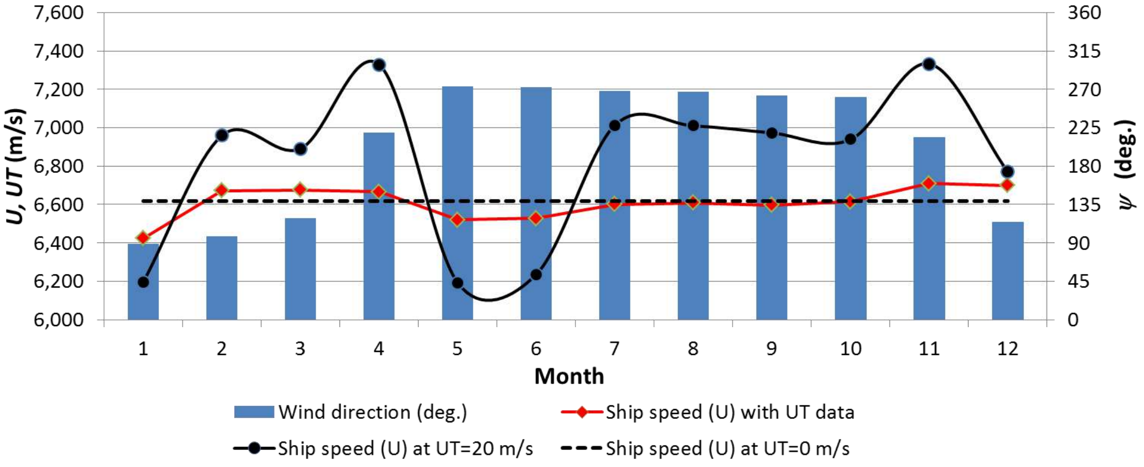

Figure 7 Tracking ship speed trajectories with different wind velocities and directions

In general, when the wind blew from the starboard and portside to the stern (98° to 268°), the ship's track trajectory time tended to benefit compared to conditions with the wind blows from the bow to the starboard and portside, as the simulation results in Figure 7. The ship's reduced speed when the wind blew from the bow to the starboard (less than 100°) was similar to the findings of Paroka et al. (2016) related to ship-speed changes caused by wind speeds and directions' influence on ferry maneuvering.

4. Conclusions

This study has analyzed a twin-rudder-system configuration's influence on a ship's course-keeping ability under various wind speeds and directions through the MATLAB-Simulink computer-simulation program. The results indicated that applying a twin-rudder system to ferry ships' to improve their course-keeping ability under windy conditions is very effective using a PID controller, reducing ship deviation and increasing ship speed by adjusting the ship's heading angle to the desired path. The track trajectory time in the ferry's course-keeping highly depends on wind velocity and direction. When the wind blows from the starboard and portside to the stern (98 to 268°), a ship's travel time tends to benefit compared to when the wind blows from the bow to the side. This research shows that the PID controller method can be applied to assist ships' movements due to other environmental influences, such as waves and currents. However, ships' course-keeping quality highly depends on the selected PID parameters.

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On behalf of the Editorial Board, I am pleased to inform you that your article entitled **Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions** has been published online in *Volume 12 Issue 2, Apr 2021*. You can check the online version at: https://ijtech.eng.ui.ac.id/issue/70

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Thank you for your contribution to IJTech and we look forward to a good collaboration in the next future.

Yours sincerely,

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Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions

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Abstract. Ship course-keeping plays a vital role in navigation safety, especially when a ship is operating under windy conditions. A method to control ship movements through rudder-system configuration is necessary to stabilize a ship's course. This paper describes the twin-rudder-system configuration design's impact on a ship's course-keeping ability under windy conditions. A time-domain simulation using the MATLAB-Simulink program was developed for this purpose. A proportional integral derivative (PID) controller was used to adjust the ship's heading angle according to the desired path. Several parameters—such as relative wind velocity and directions—were accounted for in the simulation. The result shows that, at a wind direction of 88°, the ship's course-keeping speed decreased; however, increasing wind velocity caused a large deviation in the ship's heading angle. Meanwhile, the ship's course-keeping speed increased with rising windspeed directions of 219°. The ship's course-keeping time, at around 219° under the simulation's wind direction, was 11.84% lower than during a previous sea-trial. A possible reason for this difference is that the simulation excluded waves and currents.

Keywords: Course-keeping; Proportional integral derivative controller; Ship-tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigation due to time-saving and reduced fuel consumption (Prpic-Orsic et al., 2016). To achieve quality ship course-keeping and generate accurate heading angles, a controller that considers ship hydrodynamics—including both internal and external disturbance parameters—should be installed (Lee et al, 2009). Keeping a ferry ship on course differs from sea-going ships due to navigation environments and ship particulars (Prpic-Orsic et al., 2016). The navigation environment's complexity, and especially wind-load forces and moment, makes ferry ships with large superstructures more susceptible to marine accidents (Fujiwara and Ueno, 2006). Many studies have related wind effects to ship maneuvering; wind's load-force and moment have significantly affected transversal and lateral projections of windage areas due to ships' large superstructures, as well as wind velocities and directions relative to ships (Fujiwara and Ueno, 2006). Paroka et al. (2016) simulated wind's effect on ferry ships' maneuvering,

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explaining that ship-speed changes caused by wind highly depend on wind velocity and direction. When the wind blows from the bow direction and passes to the ship's starboard (0 to 100^{o}), ship speed tends to decrease. The corresponding decrease in ship speed is insignificant when the wind blows from a starboard direction and passes to the ship’s stern (100 to 180^{o}). Meanwhile, when the wind blows from the side of a ship (20 to 140^{o}), it tends to change the ship’s direction. A ship’s directional deviations due to wind vary by ship type, and a steering response is required. Ohtsu et al. (1996) reported that a wind blowing from starboard-bow quarters (45^{o}) made a ship’s steering becomes less sensitive, but steering became more sensitive when the wind came from the port-stern quarters (135^{o}). Increasing a ship’s speed as wind directions change is crucial (Ohtsu et al., 1996; Paroka et al., 2016). The information informing this behavior is essential to improve ships’ course-keeping quality—especially when ships must take appropriate action to handle wind disturbances. The improving quality of a ship’s course-keeping ability in windy conditions is strongly influenced by steering responses to wind-blowing loads through an appropriately configured rudder system design (Hasegawa et al., 2006). Steering control plays an essential role in responding to external forces to a ship’s yaw motion stability and course-keeping ability during maneuvers (Paroka, 2020).

Many efforts to improve ships’ maneuvering have been conducted using twin-rudder ship controllers. Yoshimura and Sakurai (1989) investigated the effect of a ship-fitted, twin-rudder, twin-propeller configuration on ships’ maneuvering. They found that a twin-rudder, twin-propeller configuration’s hydrodynamic characteristics did not differ significantly from the corresponding characteristics of a single-propeller, single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ships’ maneuvering when fitted with a twin-propeller, twin-rudder configuration. Furthermore, Khanfir et al. (2011) conducted captive model tests and free-running tests with a single-propeller, twin-rudder ship and a twin-propeller, twin-rudder ship. These tests aimed to evaluate drift angles’ effect on rudder forces and the peculiar phenomena concerning a normal rudder force for twin-rudder ships.

Other parameters that affect ships’ maneuvering performance include the distance of spacing between single rudders in twin-rudder ships. Gim (2013) conducted a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5–1.0 times the chord length of the rudder. He found that this spacing distance between rudders in twin-rudder configurations was also affected by interactions between rudders, and he also found that this critical distance should be less than 1.0 times the chord length of the rudder in order to decrease the turbulence flow and vortices. This result was similar to the findings of Chen et al. (2018), who used numerical simulation to confirming the excellent characteristics of twin-rudder ships compared to single-rudder ships. Chen et al. (2018) concluded that a ship fitted with a twin-rudder configuration would operate very well at 15^{o} rudder angles. Additionally, the twin rudders’ effective performance stopped at a lateral spacing equal to 1.3 times the chord length of the rudder.

These previous studies have shown that a rudder system’s configuration is the most crucial feature in achieving ship controllability goals. A rudder system must alter ship control to the desired heading angle, due to both internal and external disturbance parameters. The current paper focuses on applying the twin-rudder system to improve ferries’ course-keeping quality under windy conditions. By simulating fluctuating wind velocity and directions according to a ship’s operating route, quality course-keeping and accurate heading angles may be achieved, increasing the ship’s safety.

2. Methods

2.1. Mathematical Model

This study's ship maneuvering analysis used computer simulation to employ modular mathematical models, including a consideration of hydrodynamic derivatives. This study's models were based on surge, sway, and yaw motions (Equation 1) using the coordinate system shown in Figure 1.

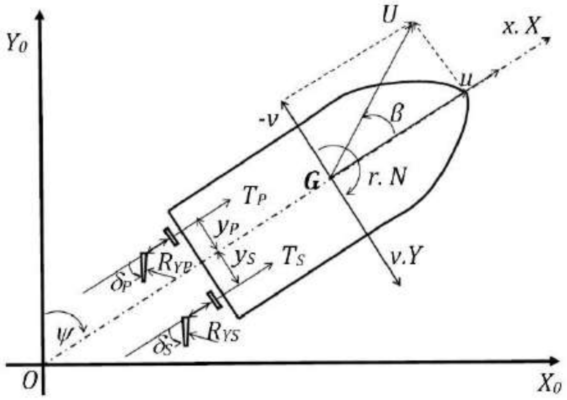

Figure 1 Coordinate ship system

$$\begin{aligned} m(\dot{u}-rv) &= X_H + X_P + X_R + X_W \\ m(\dot{v}-ru) &= Y_H + Y_P + Y_R + Y_W \\ I_{ZZ}\dot{r} &= N_H + N_P + N_R + N_W \end{aligned} \tag{1}$$

The notations *u*, *v* and *r*, are velocity components at the ship's center of gravity (*G*). *m* and I_{ZZ} represent the ship's mass and moments of inertia. *X*, *Y*, and *N* represent the hydrodynamic forces and moment. The subscript *H*, *P*, *R*, and *W* refer to the ship's hull, propeller, rudder, and wind. In principle, the force and moment induced by hull (X_H, Y_H, and N_H) approximate β and r' polynomial function. These equations were expressed by Yoshimura (2001) as Equation 2:

$$\begin{aligned} X_H &= \tfrac{1}{2}\rho LdU^2(X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr}r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\ Y_H &= \tfrac{1}{2}\rho LdU^2(Y'_\beta\beta + (Y'_r - m'_x)r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr}r'^3) \\ N_H &= \tfrac{1}{2}\rho L^2dU^2(N'_\beta\beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr}r'^3) \end{aligned} \tag{2}$$

where β is the drift angle at the midship position by $\tan^{-1}(v/u)$ and r' non-dimensionalized yaw rate by rL/U. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} is the hydrodynamic derivatives on the ship's maneuvering. The force and moment induced by twin-propeller configurations (X_P, Y_P, and N_P) were expressed by Khanfir et al. (2011) in Equation 3:

$$\begin{aligned} X_P &= \rho\Big((1-t_{P(S)})n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}(J_{P(S)}) + (1-t_{P(P)})n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}(J_{P(P)})\Big) \\ N_P &= \rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}(J_{P(S)}) + (1-t_{P(P)})y_{P(P)}n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}(J_{P(P)})\Big) \end{aligned} \tag{3}$$

where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}}) = k_0 + k_1 J_{P\substack{(S)\\(P)}} + k_2 J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\substack{(S)\\(P)}} = (u - y_{P\substack{(S)\\(P)}}r(1 - w_{P\substack{(S)\\(P)}})/(n_{P\substack{(S)\\(P)}}D_{P\substack{(S)\\(P)}})$

where t_P is the thrust deduction coefficient in straightforward moving, K_T is the thrust coefficient of the propeller force, and n_P is the propeller revolution. D_P is the propeller

diameter, w_P is the effective wake fraction coefficient at the propeller's location, and J_P is the advance coefficient, while k_0, k_1, and k_2 are the constants for an open-water propeller. The sub-subscript *(S)* and *(P)* refer to starboard and portside.

Force and moment due to twin-rudder configurations (X_R, Y_R, and N_R) can be expressed by Equations 4–8 (Khanfir et al., 2011).

$$\begin{aligned}
X_R &= -(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} - (1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)} \\
Y_R &= -(1+a_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{R(YS)}\cos\delta_{(P)}\right) \\
N_R &= -(x_R + a_H x_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{RY(P)}\cos\delta_{(P)}\right) + f\left(x_R\right) \\
f\left(x_R\right) &= y_{P(S)}(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)}
\end{aligned} \tag{4}$$

where δ is the rudder angle, x_R is the rudder's location, and t_R, a_H, and x_H are the interactive force coefficients for the hull, propeller, and rudder as functions of the propeller's advance constant. The rudder's normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

$$F_{RY\substack{(S)\\(P)}} = \tfrac{1}{2}\rho A_R U_{R\substack{(S)\\(P)}}^{\,2} f_\alpha \sin\alpha_{R\substack{(S)\\(P)}} \tag{5}$$

where A_R is the rudder area, and f_α is the gradient of the rudder's lift coefficient, which can be approximated by the function of the rudder's aspect ratio (f_α = 6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and the effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6:

$$U_{R\substack{(S)\\(P)}} = \sqrt{u_{R\substack{(S)\\(P)}}^{\,2} + v_{R\substack{(S)\\(P)}}^{\,2}} \qquad \text{and} \qquad \alpha_{R\substack{(S)\\(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R\substack{(S)\\(P)}}\left(\beta_{R\substack{(S)\\(P)}}\right) \tag{6}$$

The effective inflow velocity (u_R) to the rudder in the surge direction can be expressed by Equation 7:

$$u_{R\substack{(S)\\(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P\substack{(S)\\(P)}} \times \sqrt{\eta_{P\substack{(S)\\(P)}}\left\{1+\kappa\left(\sqrt{1+8K_{T\substack{(S)\\(P)}}\Big/\pi J_{P\substack{(S)\\(P)}}^{\,2}}-1\right)\right\}^2 + (1-\eta_{P\substack{(S)\\(P)}})} \tag{7}$$

where: $\varepsilon_{\substack{(S)\\(P)}} = 1 - w_{R\substack{(S)\\(P)}}\Big/1 - w_{P\substack{(S)\\(P)}}$; $\kappa = kx\Big/\varepsilon_{\substack{(S)\\(P)}}$; $\eta_{P\substack{(S)\\(P)}} = D_{P\substack{(S)\\(P)}}\Big/H_{R\substack{(S)\\(P)}}$; $u_{P\substack{(S)\\(P)}} = \left(1 - w_{P\substack{(S)\\(P)}}\right)\left(u - y_{P\substack{(S)\\(P)}} r\right)$

Here, ε, κ, γ_R, and l_R are the parameters describing the rudder inflow velocity angle, while (1-w_R) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H_R) is the ratio of the propeller diameter to the rudder height.

The effective inflow velocity (v_R) to the rudder in the sway direction can be expressed by Equation 8:

$$v_{R\substack{(S)\\(P)}} = u_{R\substack{(S)\\(P)}} \tan\left(\delta_{R\substack{(S)\\(P)}}\right) \tag{8}$$

where: $\delta_{R\substack{(S)\\(P)}} = \gamma_{R\substack{(S)\\(P)}}\beta_{R\substack{(S)\\(P)}} + \tan^{-1}\left(y_{R\substack{(S)\\(P)}}\Big/x_{R\substack{(S)\\(P)}}\right)$ and $\beta_{R\substack{(S)\\(P)}} = \beta - L_{R\substack{(S)\\(P)}} r$

Here, δ_R is the rudder angle, β_R is the effective drift angle at the rudder, and L_R is the flow-straightening coefficient of the yaw rate. For the case of a ship operating under windy conditions, the force and moment (X_W, Y_W, and N_W) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A)q_A A_F; \quad Y_W = C_{AY}(\psi_A)q_A A_L; \quad N_W = C_{AN}(\psi_A)q_A A_L L_{OA} \tag{9}$$

where $\psi_A = \tan^{-1}\left[U_T \cos\psi + U\cos\beta / U_T \sin\psi - U\cos\beta\right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi + \beta)$

C_{AX}, C_{AY}, and C_{AN} are the wind load forces and moments' coefficients, respectively, as a function of the wind direction relative to a ship (ψ_A). U_T and ψ are wind velocity and direction angles with reference to the coordinate system, q_A is wind pressure, q_T is wind pressure due to the elevation of the center of a windage area, and q_S is the wind pressure induced by wind velocity, without an elevation effect. A_F and A_L are the transversal and lateral projections of the windage area, respectively.

2.2. Autopilot Ship Steering

The rudder is the most critical feature in achieving controllability goals (Lee et al., 2009). The control system must alter the control surfaces to the desired heading angle. The schematic equation of the PID control system that a ship tracks can be expressed by Equation 10 (Lee et al., 2009).

$$\delta = K_p(e) + K_d(\dot{e}) + K_i\int_0^T e(t)dt \quad \text{and} \quad e = (\psi_T - \psi_P) \tag{10}$$

where δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain, and integral gain respectively; and e is an error between the heading target (ψ_T) and the actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference heading angles. The reference heading angle equation and target zone correction can be expressed by Equation 11:

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t)/x_k - x(t)) \quad \text{and} \quad (x_k - x(t))^2 + (y_k - y(t))^2 \leq R_0^2 \tag{11}$$

where x_k and y_k are the track-point coordinates, $x(t)$ and $y(t)$ are the ship's coordinates position, and R_0 is the target zone's radius.

2.3. Simulation Program

According to IMO (2002) criteria for ship maneuvering, a swept path should be used to analyze a ship's course-keeping prediction. A ship's swept path can be obtained by double-integrating the ship motion mathematical model's acceleration, including hydrodynamic derivatives. A numerical integration of the Dormand–Prince method (Maimun et al., 2013; Muhammad et al., 2015) then solved the equations of motion in this time-domain simulation using the MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for the acting hull force and moment in Equation 2—and the interaction force coefficient among the hull, propeller, and rudder—were predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). This regression equation is among the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circles and zigzag maneuvering for ships with twin-rudder and twin-propeller systems, as well as validation through model testing or free-running tests. In many cases, the regression equation has been used to predict ferry ships' maneuvering under active wind and wave conditions (Paroka et al., 2015, 2016, 2017b). A ship's resistance coefficients for simulation were predicted using the Holtrop method (Holtrop and Mennen, 1982; Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\, J_P - 0.1178\, J_P{}^2$) was predicted using polynomial regression, based on the open water test's statistical data for the B-series propeller (Carlton, 2007). The coefficient of the wind load force and moment in Equation 9 was predicted using the methodology proposed by Fujiwara and Ueno (2006). The control method used in the simulation was a proportional integrated derivative (PID) controller. The designed rudder angle (δ=±35 deg.) was

calculated using Equation 10 with a PID gain ($K_p = 2.208$; $K_i = 0.027$ and $K_d = 45.372$), and it was selected using the pole placement method with the second-order linear Nomoto model of the ship (Nomoto et al., 1957). The methods used by Paroka et al. (2017a) in developing an automatic control system to predict and avoid ferry-ship collisions were compared using a free-running experiment.

2.4. *Ship and Sea-Trial Data*

The study's object was the *KMP Bontoharu* ferry ship (1053 gross tonnage), owned by PT. ASDP Indonesia Ferry. The ship has twin propellers and twin rudders, and the distance between the rudders and propellers is 2.3 m. The ship's particulars are presented in Table 1. The ship's sea trial on the Selayar-to-Bulukumba route was 15.385 nautical miles long, involving a 7,268-second traveling time, around a 6.03 m/s wind velocity, and a 254^o wind direction. The trial data were taken on September 20, 2015.

Table 1 Ship particulars

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m^2	182.87	*Z*	2×4
Lbp,m	47.45	A_F, m^2	129.20	*D, m*	1.450
B, m	14	A_{OD}, *m*	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_C, *m*	2.70	*n*	8.784
V, m/s²	6.618	H_L, *m*	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, *m*	10.48	*Chord, m*	0.900
				A_R, m^2	2×1.395
				BHP, HP	2×1000
				RPMME	1850

2.5. *Wind Data*

Monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years, from 2006 to 2018, at six-hour intervals. The model provided wind speed data with a resolution of 0.25 × 0.25 degrees. This model was validated by Dee et al. (2011). Furthermore, it was validated locally by Lina et al. (2015) using data from eight buoys deployed in the Yellow Sea and the East China Sea. This study's coordinate for its observation data was at 5.75^{o}S and 120.5^{o}E.

3. Results and Discussion

The wind speed trend peaked in January, with a maximum of 10.06 m/s (88^o), as Figure 2 shows. Meanwhile, April's monthly wind speed trend decreased, with a minimum of 6.41 m/s (219^o). The monthly wind speed movements varied, depending on the month occurring during the west or east monsoon seasons.

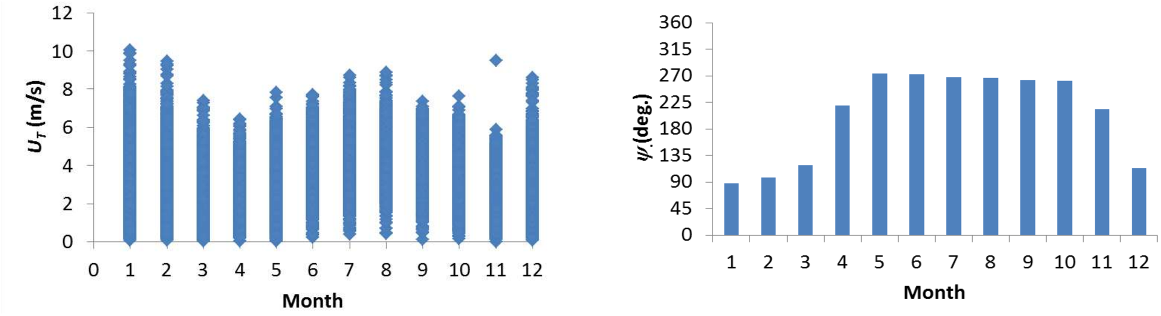

Figure 2 Significant wind velocity and direction on the Selayar–Bulukumba route

Based on the wind data characteristics in Figure 2, the *KMP Bontoharu*'s course-keeping was simulated for three conditions of wind direction parameters—the starboard bow (88°) and the portside stern of the ship (219° and 268°)—using the time domain simulation program of MATLAB-Simulink. This information is essential to ship navigation due to time-savings and reduced fuel consumption by controlling a twin-rudder configuration design. Figure 3 shows the historic result of the simulation for the course-keeping trajectory of the *KMP Bontoharu* (Selayar to Bulukumba) under wind velocities' effect.

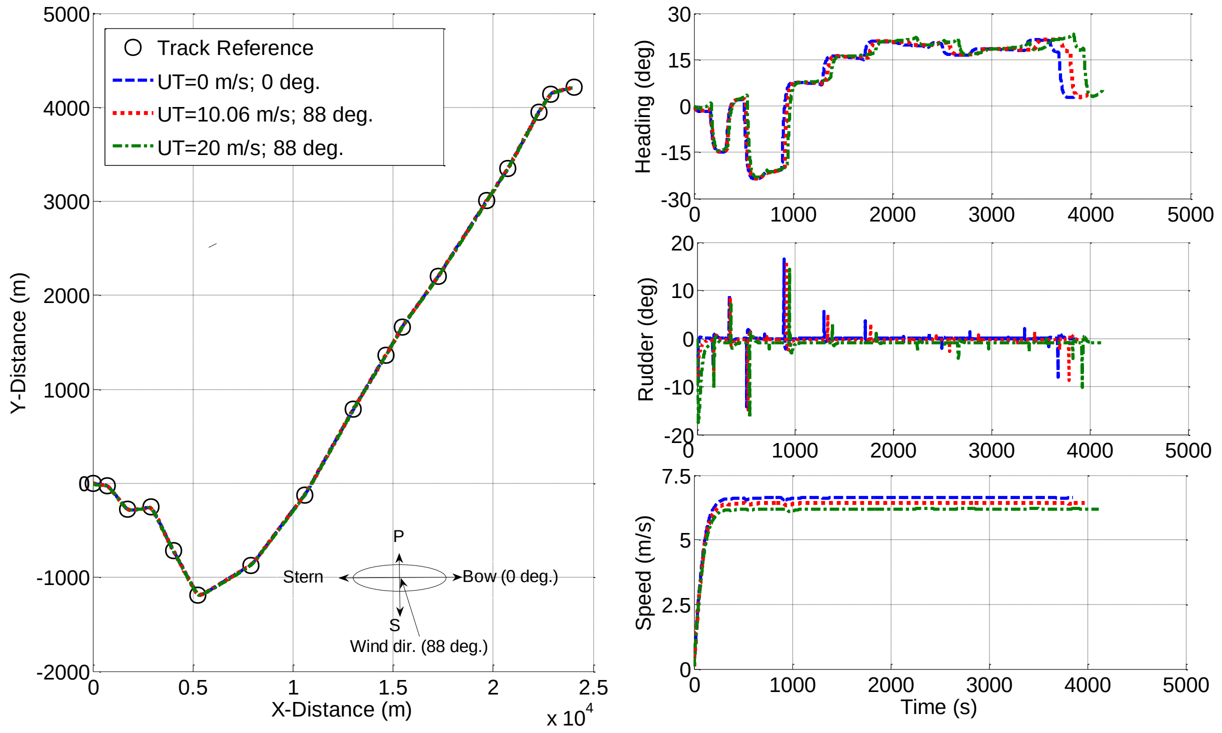

Figure 3 Ship trajectory with different wind speeds (U_T) at 88°

The horizontal axis expresses the time, while the vertical axis expresses the heading angle (ψ), rudder angle (δ), and ship speed (u), respectively. The wind blew from the starboard bow (88°) at wind velocities of 10.06 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory slowly deviated from the initial track with a low heading with significant course-keeping time compared to conditions without winds (U_T = 0 m/s). Meanwhile, the ship's course-keeping trajectory with increased wind velocities caused more deviations and low ship speeds.

Figure 4 shows the simulation results for the *KMP Bontoharu*'s course-keeping with the wind blowing from the portside stern (219°) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory quickly deviated from the initial track with a high heading and short course-keeping time at each blown wind velocity, compared to conditions without winds (U_T = 0 m/s). These characteristics differed when the wind blew from the starboard side (88°). The wind direction angle caused these differences, as Ohtsu et al. (1996) found, relating to changes in a ship's heading and rudder angle as a result of wind velocity and ship direction in course-keeping.

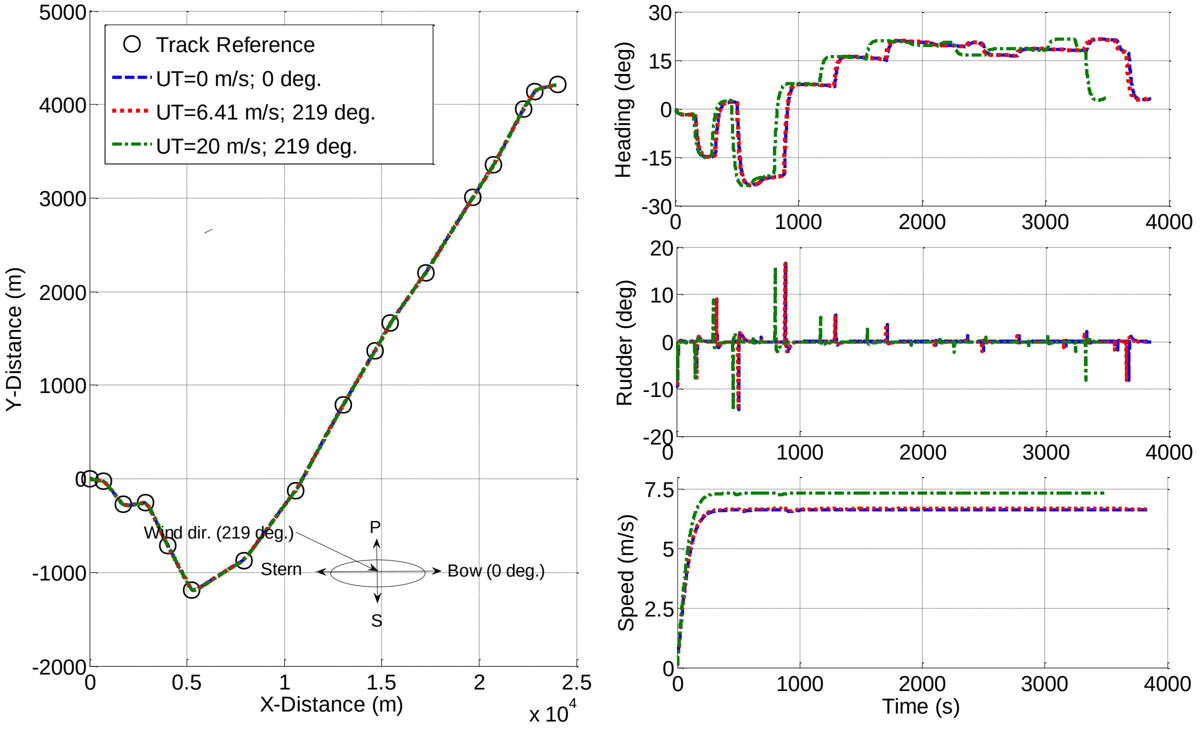

Figure 4 Ship trajectory with different wind speeds (U_T) at 219°

Figure 5 shows the historic results of the simulation for the course-keeping trajectory of the *KMP Bontoharu* with the wind blowing from the portside stern (268°) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed was 0.27% reduced compared to conditions without wind (U_T = 0 m/s), while the ship speed increased by 5.96% increases at a wind speed of 20 m/s. These changes in ship speed were caused by the ship's directional movements.

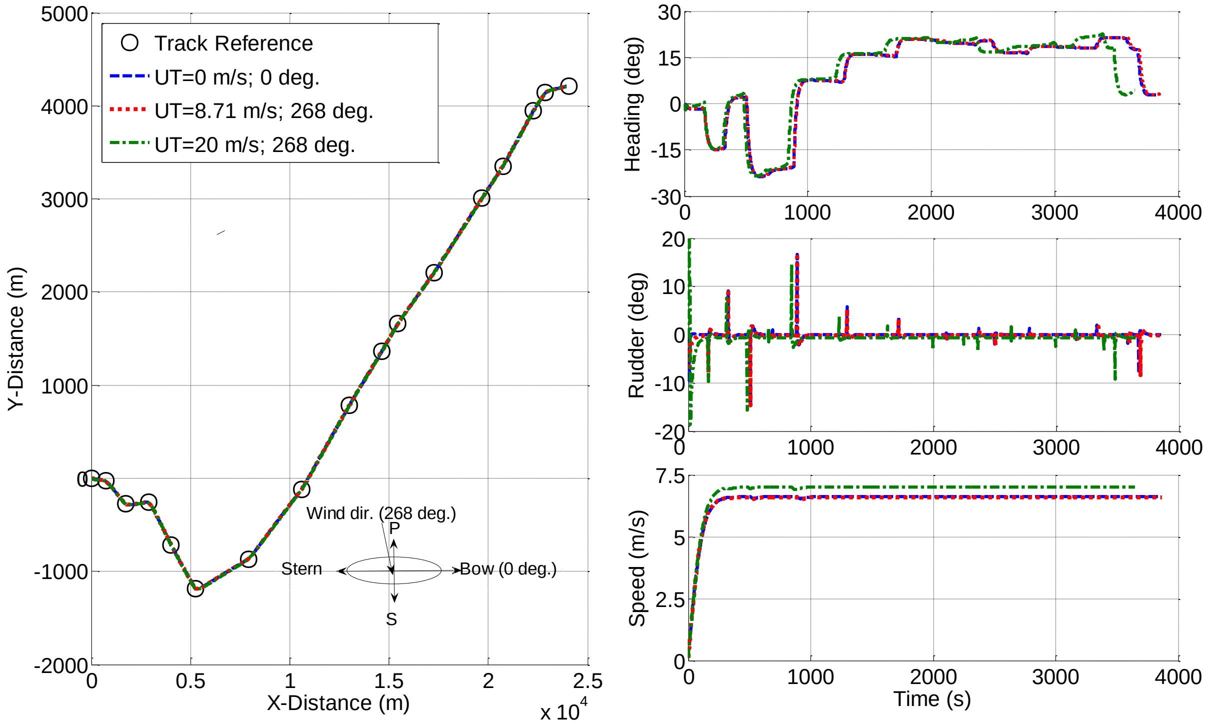

Figure 5 Ship trajectory with different wind speeds (U_T) at 268°

Figure 6 shows the sea-trial simulation results for the ship course-keeping trajectory with a 6.03 m/s wind velocity and a 254° wind direction at an initial ship speed of 3.98 m/s. We found that the traveling time under these conditions stood at 6,407 seconds. The simulation's traveling time was 11.84% higher than the sea-trial result. A possible reason for this difference is that the simulation excluded waves and currents.

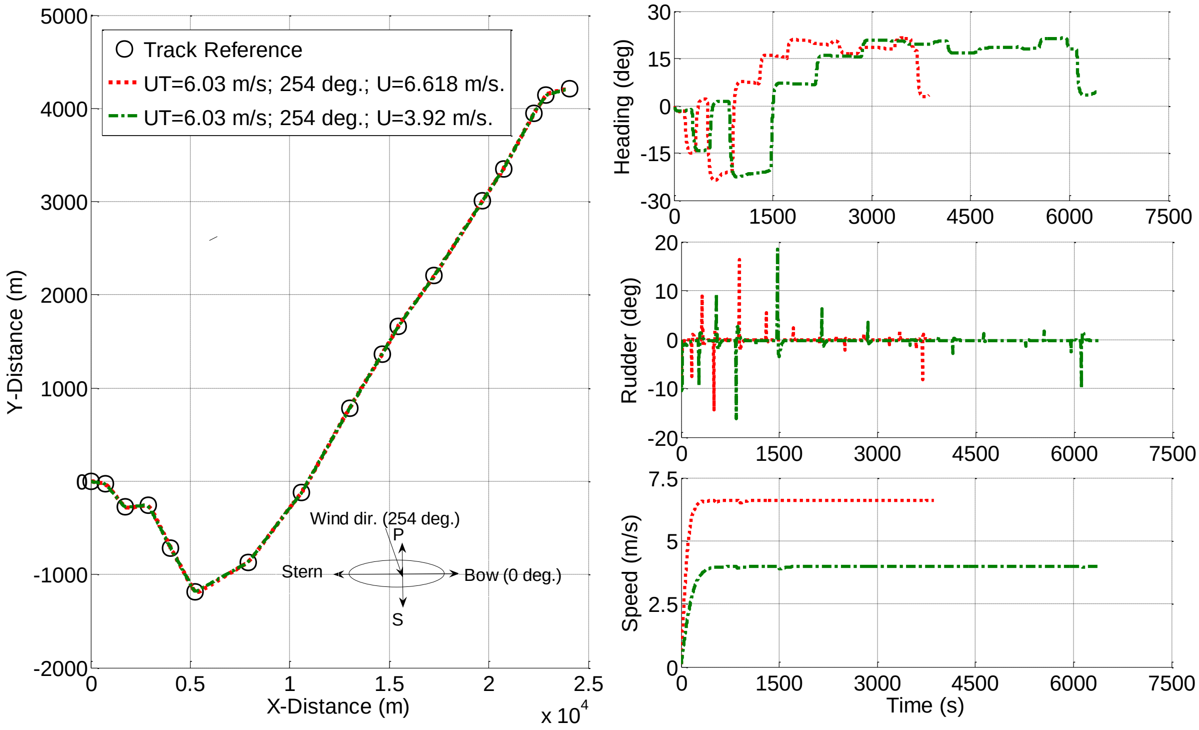

Figure 6 Sea-trial simulation result for ship trajectories with different initial ship speeds (U)

Figures 3, 4, and 5 also show the effects of winds velocity and direction on ship speed, with a course-keeping trajectory for an initial ship speed (U) of 6.618 m/s. We found that, when the wind blew from the starboard bow (88°) with a wind velocity of 20 m/s, the ship speed was 6.36% lower compared to conditions without wind ($U_T = 0$ m/s). Meanwhile, when the wind blew from the portside stern (219° and 268°), the ship speed was increased by 10.74% and 5.96%, respectively. The two latter speeds were beneficial because the track trajectory times were minimal.

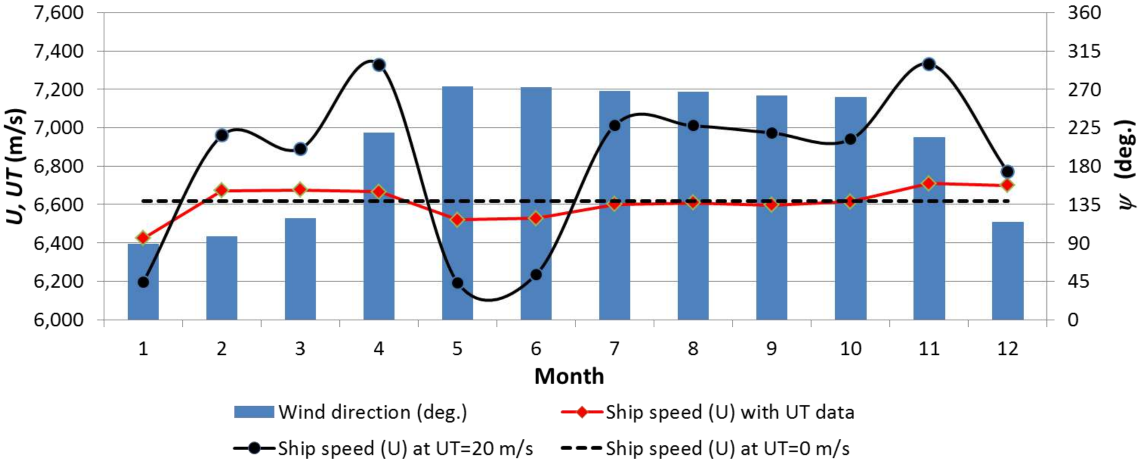

Figure 7 Tracking ship speed trajectories with different wind velocities and directions

In general, when the wind blew from the starboard and portside to the stern (98° to 268°), the ship's track trajectory time tended to benefit compared to conditions with the wind blows from the bow to the starboard and portside, as the simulation results in Figure 7. The ship's reduced speed when the wind blew from the bow to the starboard (less than 100°) was similar to the findings of Paroka et al. (2016) related to ship-speed changes caused by wind speeds and directions' influence on ferry maneuvering.

4. Conclusions

This study has analyzed a twin-rudder-system configuration's influence on a ship's course-keeping ability under various wind speeds and directions through the MATLAB-Simulink computer-simulation program. The results indicated that applying a twin-rudder system to ferry ships' to improve their course-keeping ability under windy conditions is very effective using a PID controller, reducing ship deviation and increasing ship speed by adjusting the ship's heading angle to the desired path. The track trajectory time in the ferry's course-keeping highly depends on wind velocity and direction. When the wind blows from the starboard and portside to the stern (98 to 268°), a ship's travel time tends to benefit compared to when the wind blows from the bow to the side. This research shows that the PID controller method can be applied to assist ships' movements due to other environmental influences, such as waves and currents. However, ships' course-keeping quality highly depends on the selected PID parameters.

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(ME-3829) Correction of equations of the manuscript

3 messages

Andi Haris <andi_haris@ft.unhas.ac.id> Sat, Apr 24, 2021 at 12:06 PM
To: ijtech@eng.ui.ac.id

Dear Editor in Chief,

Thank you very much for online publishing our paper entitled "Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions'' (Volume 12 issue 2 April 2021 **DOI:** https://doi.org/10.14716/ijtech.v12i2.3829). We would like to inform you that there is still an override character "&", especially in equations 1 and 10 on pages 434 and 436. It is likely that the error was due to difference equation MS-Word format. The proposed type correction of equations (Corrigendum) and final correction manuscript (docx /pdf file) are attached in this email.

We are very grateful to be able to communicate and collaborate with the friendly IJTech Editorial Team, hopefully this format error can be understood,

We hope that with the consideration from the editorial team, our manuscript can be revised.

Best regards.

Andi Haris Muhammad

081241793233 /andiharis.m@gmail.com

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4 attachments

Corrigendum_ME3829.docx
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We have re-uploaded the revised file, please check https://ijtech.eng.ui.ac.id/article/view/3829 to see the result,

Thank you for your cooperation,

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To: IJTech <ijtech@eng.ui.ac.id>

Sun, May 2, 2021 at 8:38 AM

Dear Editor in Chief,

Thank you very much for revising our manuscript entitled "Twin-Rudder-System Configurations’ Impact on Ferry Ships’ Course-Keeping Ability under Windy Conditions"

We are very grateful for the cooperation

Best regards.

Andi Haris Muhammad

[Quoted text hidden]

CORRIGENDUM TO:

Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions

Andi Haris Muhammad[1i], Daeng Paroka[2], Sabaruddin Rahman[2], Mohammad Rizal Firmansyah[3]

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In Equations 1 and 10 on pages 434 and 436, typed as:

$$\begin{aligned} m(u\&-rv) &= X_H + X_P + X_R + X_W \\ m(v\&-ru) &= Y_H + Y_P + Y_R + Y_W \\ I_{ZZ}\psi\& &= N_H + N_P + N_R + N_W \end{aligned} \qquad (1)$$

$$\delta = K_p(e) + K_d(e\&) + K_i\int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \qquad (10)$$

The equations 1 and 10 should be written as follow:

$$\begin{aligned} m(\dot{u} - rv) &= X_H + X_P + X_R + X_W \\ m(\dot{v} - ru) &= Y_H + Y_P + Y_R + Y_W \\ I_{ZZ}\dot{\psi} &= N_H + N_P + N_R + N_W \end{aligned} \qquad (1)$$

$$\delta = K_P(e) + K_d(\dot{e}) + K_i\int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \qquad (10)$$

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Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions

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Abstract. Ship course-keeping plays a vital role in navigation safety, especially when a ship is operating under windy conditions. A method to control ship movements through rudder-system configuration is necessary to stabilize a ship's course. This paper describes the twin-rudder-system configuration design's impact on a ship's course-keeping ability under windy conditions. A time-domain simulation using the MATLAB-Simulink program was developed for this purpose. A proportional integral derivative (PID) controller was used to adjust the ship's heading angle according to the desired path. Several parameters—such as relative wind velocity and directions—were accounted for in the simulation. The result shows that, at a wind direction of 88°, the ship's course-keeping speed decreased; however, increasing wind velocity caused a large deviation in the ship's heading angle. Meanwhile, the ship's course-keeping speed increased with rising windspeed directions of 219°. The ship's course-keeping time, at around 219° under the simulation's wind direction, was 11.84% lower than during a previous sea-trial. A possible reason for this difference is that the simulation excluded waves and currents.

Keywords: Course-keeping; Proportional integral derivative controller; Ship-tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigation due to time-saving and reduced fuel consumption (Prpic-Orsic et al., 2016). To achieve quality ship course-keeping and generate accurate heading angles, a controller that considers ship hydrodynamics—including both internal and external disturbance parameters—should be installed (Lee et al, 2009). Keeping a ferry ship on course differs from sea-going ships due to navigation environments and ship particulars (Prpic-Orsic et al., 2016). The navigation environment's complexity, and especially wind-load forces and moment, makes ferry ships with large superstructures more susceptible to marine accidents (Fujiwara and Ueno, 2006). Many studies have related wind effects to ship maneuvering; wind's load-force and moment have significantly affected transversal and lateral projections of windage areas due to ships' large superstructures, as well as wind velocities and directions relative to ships (Fujiwara and Ueno, 2006). Paroka et al. (2016) simulated wind's effect on ferry ships' maneuvering,

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explaining that ship-speed changes caused by wind highly depend on wind velocity and direction. When the wind blows from the bow direction and passes to the ship's starboard (0 to 100^o), ship speed tends to decrease. The corresponding decrease in ship speed is insignificant when the wind blows from a starboard direction and passes to the ship’s stern (100 to 180^o). Meanwhile, when the wind blows from the side of a ship (20 to 140^o), it tends to change the ship’s direction. A ship’s directional deviations due to wind vary by ship type, and a steering response is required. Ohtsu et al. (1996) reported that a wind blowing from starboard-bow quarters (45^o) made a ship’s steering becomes less sensitive, but steering became more sensitive when the wind came from the port-stern quarters (135^o). Increasing a ship’s speed as wind directions change is crucial (Ohtsu et al., 1996; Paroka et al., 2016). The information informing this behavior is essential to improve ships’ course-keeping quality—especially when ships must take appropriate action to handle wind disturbances. The improving quality of a ship’s course-keeping ability in windy conditions is strongly influenced by steering responses to wind-blowing loads through an appropriately configured rudder system design (Hasegawa et al., 2006). Steering control plays an essential role in responding to external forces to a ship’s yaw motion stability and course-keeping ability during maneuvers (Paroka, 2020).

Many efforts to improve ships’ maneuvering have been conducted using twin-rudder ship controllers. Yoshimura and Sakurai (1989) investigated the effect of a ship-fitted, twin-rudder, twin-propeller configuration on ships’ maneuvering. They found that a twin-rudder, twin-propeller configuration’s hydrodynamic characteristics did not differ significantly from the corresponding characteristics of a single-propeller, single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ships’ maneuvering when fitted with a twin-propeller, twin-rudder configuration. Furthermore, Khanfir et al. (2011) conducted captive model tests and free-running tests with a single-propeller, twin-rudder ship and a twin-propeller, twin-rudder ship. These tests aimed to evaluate drift angles’ effect on rudder forces and the peculiar phenomena concerning a normal rudder force for twin-rudder ships.

Other parameters that affect ships’ maneuvering performance include the distance of spacing between single rudders in twin-rudder ships. Gim (2013) conducted a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5–1.0 times the chord length of the rudder. He found that this spacing distance between rudders in twin-rudder configurations was also affected by interactions between rudders, and he also found that this critical distance should be less than 1.0 times the chord length of the rudder in order to decrease the turbulence flow and vortices. This result was similar to the findings of Chen et al. (2018), who used numerical simulation to confirming the excellent characteristics of twin-rudder ships compared to single-rudder ships. Chen et al. (2018) concluded that a ship fitted with a twin-rudder configuration would operate very well at 15^o rudder angles. Additionally, the twin rudders’ effective performance stopped at a lateral spacing equal to 1.3 times the chord length of the rudder.

These previous studies have shown that a rudder system’s configuration is the most crucial feature in achieving ship controllability goals. A rudder system must alter ship control to the desired heading angle, due to both internal and external disturbance parameters. The current paper focuses on applying the twin-rudder system to improve ferries’ course-keeping quality under windy conditions. By simulating fluctuating wind velocity and directions according to a ship’s operating route, quality course-keeping and accurate heading angles may be achieved, increasing the ship’s safety.

2. Methods

2.1. Mathematical Model

This study's ship maneuvering analysis used computer simulation to employ modular mathematical models, including a consideration of hydrodynamic derivatives. This study's models were based on surge, sway, and yaw motions (Equation 1) using the coordinate system shown in Figure 1.

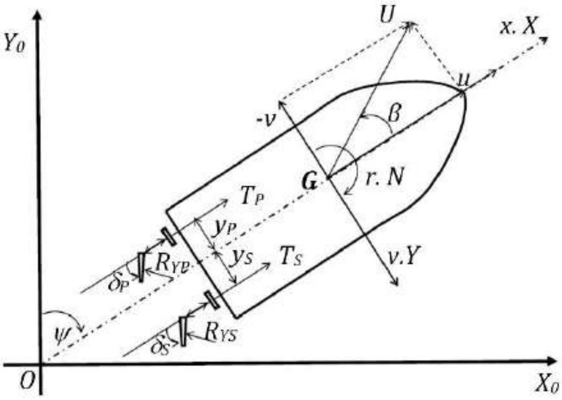

Figure 1 Coordinate ship system

$$\begin{aligned} m(\dot{u}-rv) &= X_H + X_P + X_R + X_W \\ m(\dot{v}-ru) &= Y_H + Y_P + Y_R + Y_W \\ I_{ZZ}\dot{\psi} &= N_H + N_P + N_R + N_W \end{aligned} \tag{1}$$

The notations u, v and r, are velocity components at the ship's center of gravity (G). m and I_{ZZ} represent the ship's mass and moments of inertia. X, Y, and N represent the hydrodynamic forces and moment. The subscript H, P, R, and W refer to the ship's hull, propeller, rudder, and wind. In principle, the force and moment induced by hull (X_H, Y_H, and N_H) approximate β and r' polynomial function. These equations were expressed by Yoshimura (2001) as Equation 2:

$$\begin{aligned} X_H &= \tfrac{1}{2}\rho L d U^2 (X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr} r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\ Y_H &= \tfrac{1}{2}\rho L d U^2 (Y'_\beta \beta + (Y'_r - m'_x) r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr} r'^3) \\ N_H &= \tfrac{1}{2}\rho L^2 d U^2 (N'_\beta \beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr} r'^3) \end{aligned} \tag{2}$$

where β is the drift angle at the midship position by $\tan^{-1}(v/u)$ and r' non-dimensionalized yaw rate by rL/U. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} is the hydrodynamic derivatives on the ship's maneuvering. The force and moment induced by twin-propeller configurations (X_P, Y_P, and N_P) were expressed by Khanfir et al. (2011) in Equation 3:

$$\begin{aligned} X_P &= \rho\Big((1-t_{P(S)}) n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}(J_{P(S)}) + (1-t_{P(P)}) n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}(J_{P(P)})\Big) \\ N_P &= \rho\Big((1-t_{P(S)}) y_{P(S)} n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}(J_{P(S)}) + (1-t_{P(P)}) y_{P(P)} n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}(J_{P(P)})\Big) \end{aligned} \tag{3}$$

where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}}) = k_0 + k_1 J_{P\substack{(S)\\(P)}} + k_2 J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\substack{(S)\\(P)}} = (u - y_{P\substack{(S)\\(P)}} r(1 - w_{P\substack{(S)\\(P)}}) / (n_{P\substack{(S)\\(P)}} D_{P\substack{(S)\\(P)}})$

where t_P is the thrust deduction coefficient in straightforward moving, K_T is the thrust coefficient of the propeller force, and n_P is the propeller revolution. D_P is the propeller

diameter, w_P is the effective wake fraction coefficient at the propeller's location, and J_P is the advance coefficient, while k_0, k_1, and k_2 are the constants for an open-water propeller. The sub-subscript *(S)* and *(P)* refer to starboard and portside.

Force and moment due to twin-rudder configurations (X_R, Y_R, and N_R) can be expressed by Equations 4–8 (Khanfir et al., 2011).

$$\begin{aligned}
X_R &= -(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} - (1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)} \\
Y_R &= -(1+a_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{R(YS)}\cos\delta_{(P)}\right) \\
N_R &= -(x_R + a_H x_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{RY(P)}\cos\delta_{(P)}\right) + f\left(x_R\right) \\
f\left(x_R\right) &= y_{P(S)}(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)}
\end{aligned} \tag{4}$$

where δ is the rudder angle, x_R is the rudder's location, and t_R, a_H, and x_H are the interactive force coefficients for the hull, propeller, and rudder as functions of the propeller's advance constant. The rudder's normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

$$F_{RY^{(S)}_{(P)}} = \tfrac{1}{2}\rho A_R U_{R^{(S)}_{(P)}}{}^2 f_\alpha \sin\alpha_{R^{(S)}_{(P)}} \tag{5}$$

where A_R is the rudder area, and f_α is the gradient of the rudder's lift coefficient, which can be approximated by the function of the rudder's aspect ratio (f_α = $6.13\Lambda/(2.25)$. The effective inflow velocity to the rudder (U_R) and the effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6:

$$U_{R^{(S)}_{(P)}} = \sqrt{u_{R^{(S)}_{(P)}}{}^2 + v_{R^{(S)}_{(P)}}{}^2} \qquad \text{and} \qquad \alpha_{R^{(S)}_{(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R^{(S)}_{(P)}}\left(\beta_{R^{(S)}_{(P)}}\right) \tag{6}$$

The effective inflow velocity (u_R) to the rudder in the surge direction can be expressed by Equation 7:

$$u_{R^{(S)}_{(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P^{(S)}_{(P)}} \times \sqrt{\eta_{P^{(S)}_{(P)}}\left\{1+\kappa\left(\sqrt{1+8K_{T^{(S)}_{(P)}}\Big/\pi J_{P^{(S)}_{(P)}}{}^2} - 1\right)\right\}^2 + (1-\eta_{P^{(S)}_{(P)}})} \tag{7}$$

where: $\varepsilon_{\substack{(S)\\(P)}} = 1 - w_{R^{(S)}_{(P)}}\Big/1 - w_{P^{(S)}_{(P)}}$; $\kappa = kx\Big/\varepsilon_{\substack{(S)\\(P)}}$; $\eta_{P^{(S)}_{(P)}} = D_{P^{(S)}_{(P)}}\Big/H_{R^{(S)}_{(P)}}$; $u_{P^{(S)}_{(P)}} = \left(1 - w_{P^{(S)}_{(P)}}\right)\left(u - y_{P^{(S)}_{(P)}} r\right)$

Here, ε, κ, γ_R, and l_R are the parameters describing the rudder inflow velocity angle, while ($1\text{-}w_R$) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H_R) is the ratio of the propeller diameter to the rudder height.

The effective inflow velocity (v_R) to the rudder in the sway direction can be expressed by Equation 8:

$$v_{R^{(S)}_{(P)}} = u_{R^{(S)}_{(P)}} \tan\left(\delta_{R^{(S)}_{(P)}}\right) \tag{8}$$

where: $\delta_{R^{(S)}_{(P)}} = \gamma_{R^{(S)}_{(P)}}\beta_{R^{(S)}_{(P)}} + \tan^{-1}\left(y_{R^{(S)}_{(P)}}\Big/x_{R^{(S)}_{(P)}}\right)$ and $\beta_{R^{(S)}_{(P)}} = \beta - L_{R^{(S)}_{(P)}} r$

Here, δ_R is the rudder angle, β_R is the effective drift angle at the rudder, and L_R is the flow-straightening coefficient of the yaw rate. For the case of a ship operating under windy conditions, the force and moment (X_W, Y_W, and N_W) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A)q_A A_F; \quad Y_W = C_{AY}(\psi_A)q_A A_L; \quad N_W = C_{AN}(\psi_A)q_A A_L L_{OA} \tag{9}$$

where $\psi_A = \tan^{-1}\left[U_T\cos\psi + U\cos\beta / U_T\sin\psi - U\cos\beta\right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi+\beta)$

C_{AX}, C_{AY}, and C_{AN} are the wind load forces and moments' coefficients, respectively, as a function of the wind direction relative to a ship (ψ_A). U_T and ψ are wind velocity and direction angles with reference to the coordinate system, q_A is wind pressure, q_T is wind pressure due to the elevation of the center of a windage area, and q_S is the wind pressure induced by wind velocity, without an elevation effect. A_F and A_L are the transversal and lateral projections of the windage area, respectively.

2.2. *Autopilot Ship Steering*

The rudder is the most critical feature in achieving controllability goals (Lee et al., 2009). The control system must alter the control surfaces to the desired heading angle. The schematic equation of the PID control system that a ship tracks can be expressed by Equation 10 (Lee et al., 2009).

$$\delta = K_P(e) + K_d(\dot{e}) + K_i\int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \tag{10}$$

where δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain, and integral gain respectively; and e is an error between the heading target (ψ_T) and the actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference heading angles. The reference heading angle equation and target zone correction can be expressed by Equation 11:

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t)/x_k - x(t)) \text{ and } (x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \tag{11}$$

where x_k and y_k are the track-point coordinates, $x(t)$ and $y(t)$ are the ship's coordinates position, and R_0 is the target zone's radius.

2.3. *Simulation Program*

According to IMO (2002) criteria for ship maneuvering, a swept path should be used to analyze a ship's course-keeping prediction. A ship's swept path can be obtained by double-integrating the ship motion mathematical model's acceleration, including hydrodynamic derivatives. A numerical integration of the Dormand–Prince method (Maimun et al., 2013; Muhammad et al., 2015) then solved the equations of motion in this time-domain simulation using the MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for the acting hull force and moment in Equation 2—and the interaction force coefficient among the hull, propeller, and rudder—were predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). This regression equation is among the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circles and zigzag maneuvering for ships with twin-rudder and twin-propeller systems, as well as validation through model testing or free-running tests. In many cases, the regression equation has been used to predict ferry ships' maneuvering under active wind and wave conditions (Paroka et al., 2015, 2016, 2017b). A ship's resistance coefficients for simulation were predicted using the Holtrop method (Holtrop and Mennen, 1982; Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\, J_P - 0.1178\, J_P{}^2$) was predicted using polynomial regression, based on the open water test's statistical data for the B-series propeller (Carlton, 2007). The coefficient of the wind load force and moment in Equation 9 was predicted using the methodology proposed by Fujiwara and Ueno (2006). The control method used in the simulation was a proportional integrated derivative (PID) controller. The designed rudder angle (δ=±35 deg.) was

calculated using Equation 10 with a PID gain (K_p = 2.208; K_i = 0.027 and K_d = 45.372), and it was selected using the pole placement method with the second-order linear Nomoto model of the ship (Nomoto et al., 1957). The methods used by Paroka et al. (2017a) in developing an automatic control system to predict and avoid ferry-ship collisions were compared using a free-running experiment.

2.4. *Ship and Sea-Trial Data*

The study's object was the *KMP Bontoharu* ferry ship (1053 gross tonnage), owned by PT. ASDP Indonesia Ferry. The ship has twin propellers and twin rudders, and the distance between the rudders and propellers is 2.3 m. The ship's particulars are presented in Table 1. The ship's sea trial on the Selayar-to-Bulukumba route was 15.385 nautical miles long, involving a 7,268-second traveling time, around a 6.03 m/s wind velocity, and a 254^o wind direction. The trial data were taken on September 20, 2015.

Table 1 Ship particulars

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m^2	182.87	*Z*	2×4
Lbp,m	47.45	A_F, m^2	129.20	*D, m*	1.450
B, m	14	A_{OD}, m	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_C, m	2.70	*n*	8.784
V, m/s^2	6.618	H_L, m	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, m	10.48	*Chord, m*	0.900
				A_R, m^2	2×1.395
				BHP, HP	2×1000
				RPMME	1850

2.5. *Wind Data*

Monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years, from 2006 to 2018, at six-hour intervals. The model provided wind speed data with a resolution of 0.25 × 0.25 degrees. This model was validated by Dee et al. (2011). Furthermore, it was validated locally by Lina et al. (2015) using data from eight buoys deployed in the Yellow Sea and the East China Sea. This study's coordinate for its observation data was at 5.75^oS and 120.5^oE.

3. Results and Discussion

The wind speed trend peaked in January, with a maximum of 10.06 m/s (88^o), as Figure 2 shows. Meanwhile, April's monthly wind speed trend decreased, with a minimum of 6.41 m/s (219^o). The monthly wind speed movements varied, depending on the month occurring during the west or east monsoon seasons.

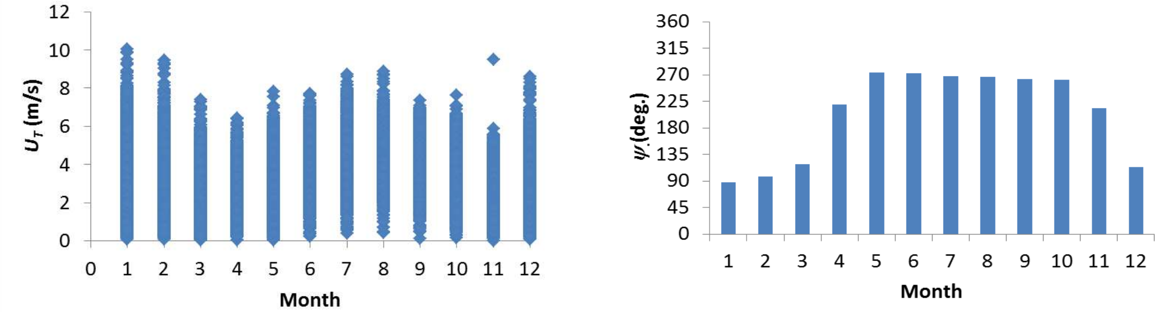

Figure 2 Significant wind velocity and direction on the Selayar–Bulukumba route

Based on the wind data characteristics in Figure 2, the *KMP Bontoharu*'s course-keeping was simulated for three conditions of wind direction parameters—the starboard bow (88º) and the portside stern of the ship (219º and 268º)—using the time domain simulation program of MATLAB-Simulink. This information is essential to ship navigation due to time-savings and reduced fuel consumption by controlling a twin-rudder configuration design. Figure 3 shows the historic result of the simulation for the course-keeping trajectory of the *KMP Bontoharu* (Selayar to Bulukumba) under wind velocities' effect.

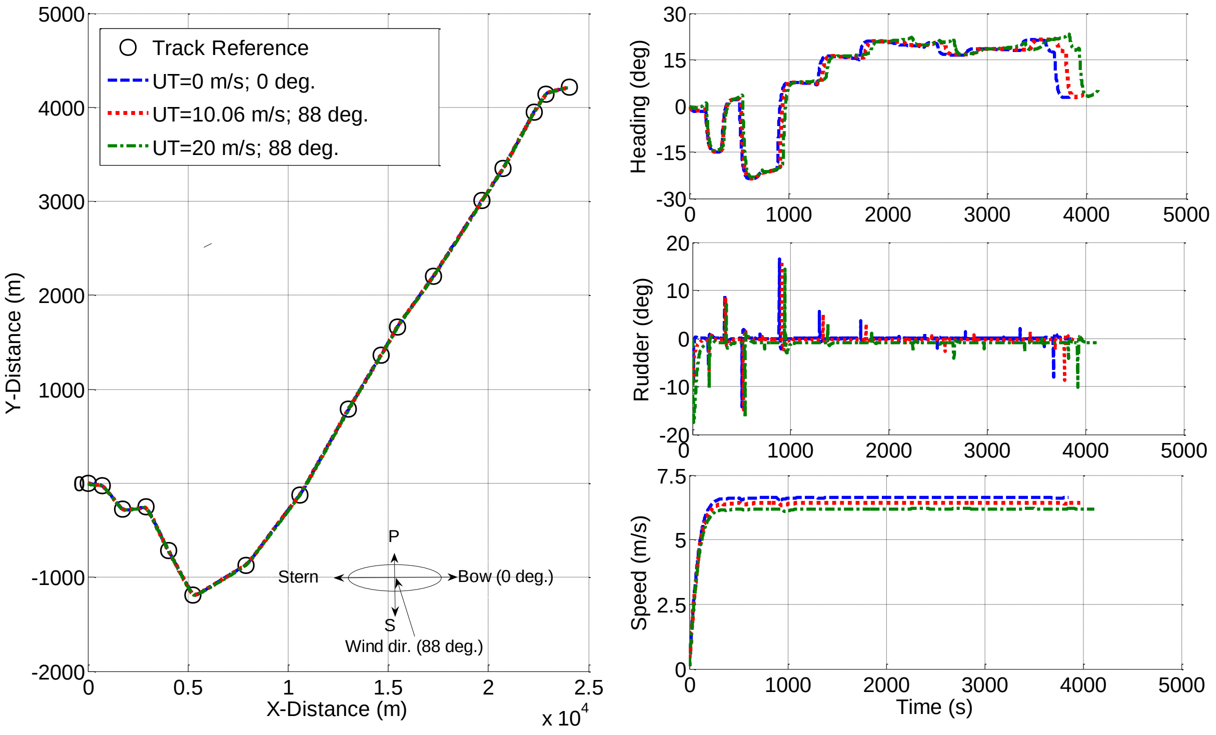

Figure 3 Ship trajectory with different wind speeds (U_T) at 88º

The horizontal axis expresses the time, while the vertical axis expresses the heading angle (ψ), rudder angle (δ), and ship speed (u), respectively. The wind blew from the starboard bow (88º) at wind velocities of 10.06 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory slowly deviated from the initial track with a low heading with significant course-keeping time compared to conditions without winds ($U_T =$ 0 m/s). Meanwhile, the ship's course-keeping trajectory with increased wind velocities caused more deviations and low ship speeds.

Figure 4 shows the simulation results for the *KMP Bontoharu*'s course-keeping with the wind blowing from the portside stern (219º) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory quickly deviated from the initial track with a high heading and short course-keeping time at each blown wind velocity, compared to conditions without winds (U_T = 0 m/s). These characteristics differed when the wind blew from the starboard side (88º). The wind direction angle caused these differences, as Ohtsu et al. (1996) found, relating to changes in a ship's heading and rudder angle as a result of wind velocity and ship direction in course-keeping.

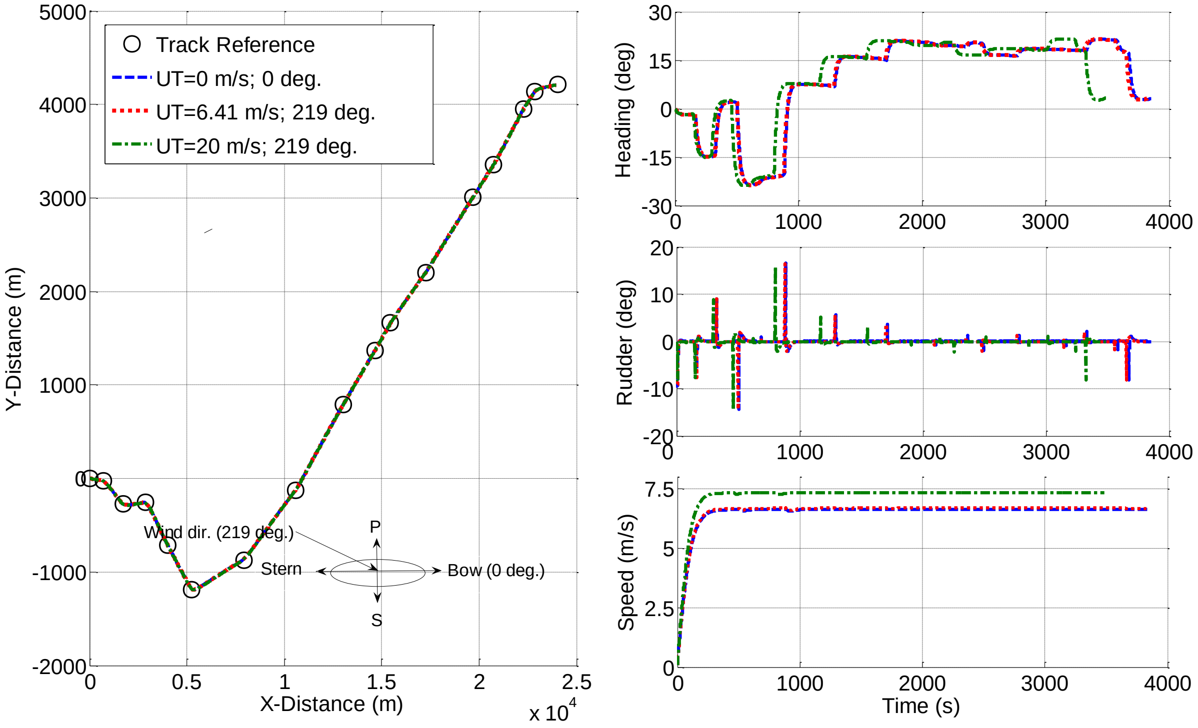

Figure 4 Ship trajectory with different wind speeds (U_T) at 219°

Figure 5 shows the historic results of the simulation for the course-keeping trajectory of the *KMP Bontoharu* with the wind blowing from the portside stern (268°) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed was 0.27% reduced compared to conditions without wind (U_T = 0 m/s), while the ship speed increased by 5.96% increases at a wind speed of 20 m/s. These changes in ship speed were caused by the ship's directional movements.

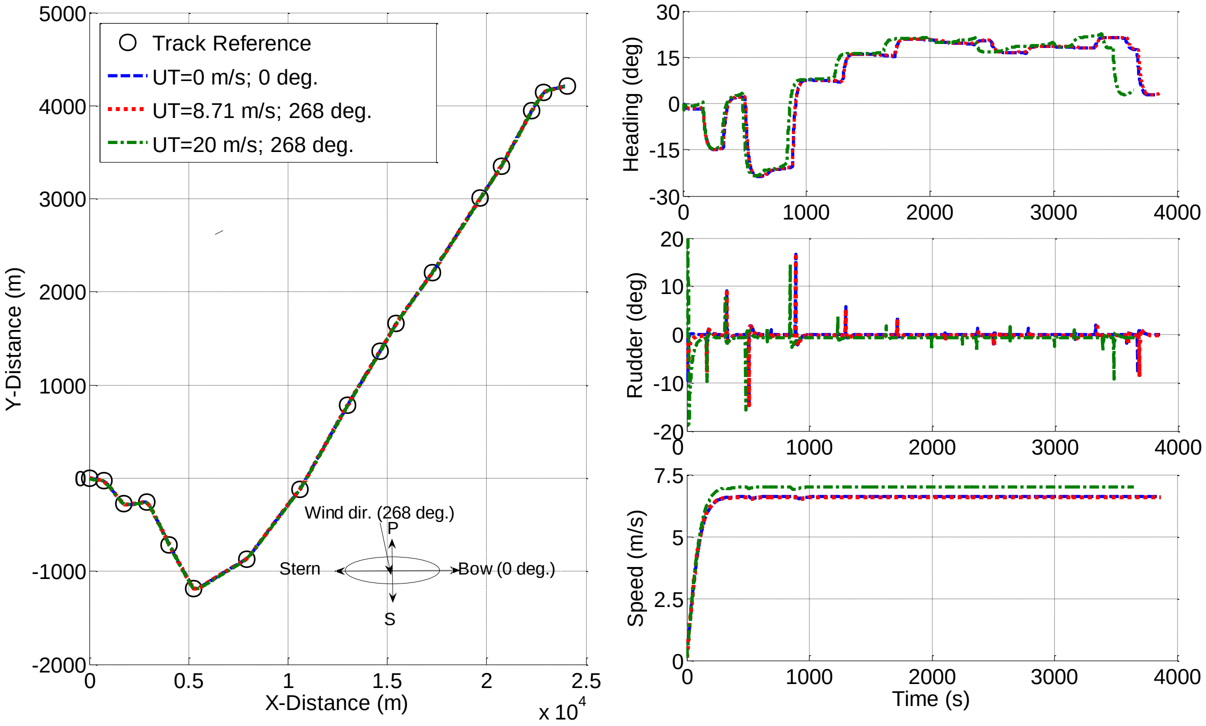

Figure 5 Ship trajectory with different wind speeds (U_T) at 268°

Figure 6 shows the sea-trial simulation results for the ship course-keeping trajectory with a 6.03 m/s wind velocity and a 254° wind direction at an initial ship speed of 3.98 m/s. We found that the traveling time under these conditions stood at 6,407 seconds. The simulation's traveling time was 11.84% higher than the sea-trial result. A possible reason for this difference is that the simulation excluded waves and currents.

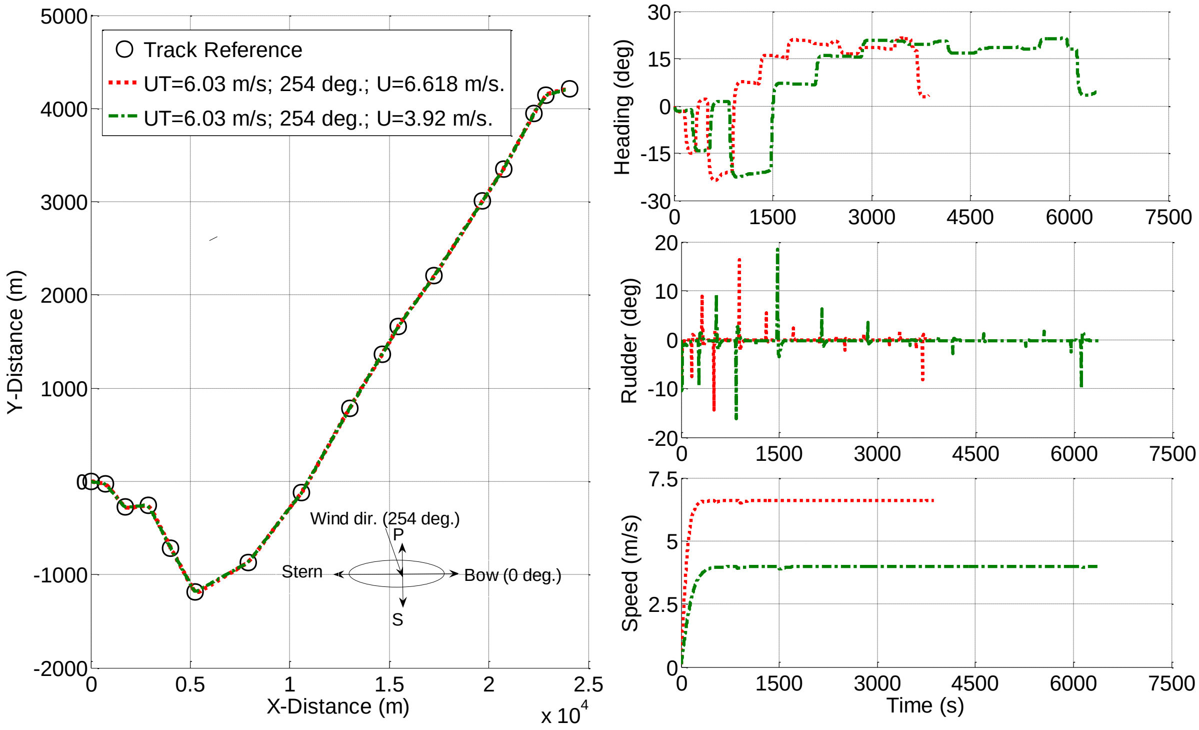

Figure 6 Sea-trial simulation result for ship trajectories with different initial ship speeds (U)

Figures 3, 4, and 5 also show the effects of winds velocity and direction on ship speed, with a course-keeping trajectory for an initial ship speed (U) of 6.618 m/s. We found that, when the wind blew from the starboard bow (88°) with a wind velocity of 20 m/s, the ship speed was 6.36% lower compared to conditions without wind ($U_T = 0$ m/s). Meanwhile, when the wind blew from the portside stern (219° and 268°), the ship speed was increased by 10.74% and 5.96%, respectively. The two latter speeds were beneficial because the track trajectory times were minimal.

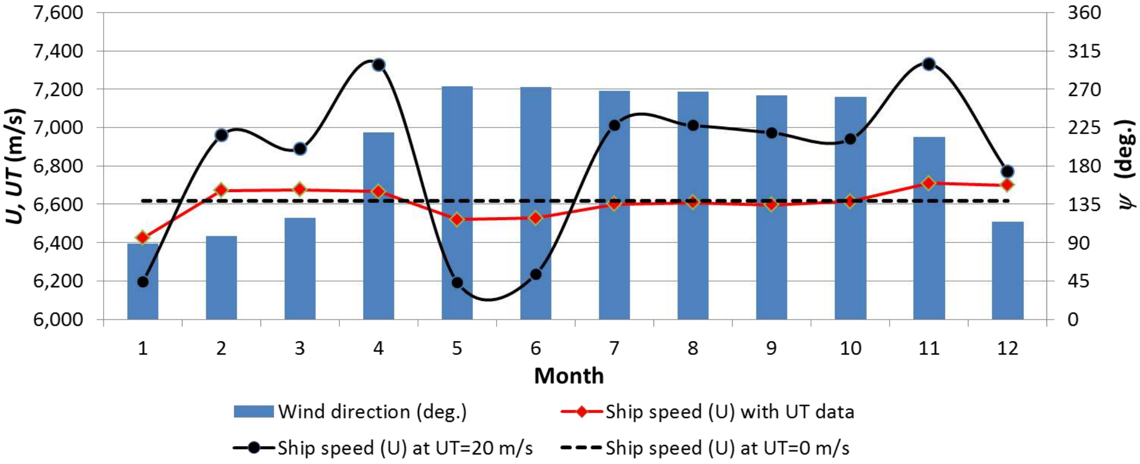

Figure 7 Tracking ship speed trajectories with different wind velocities and directions

In general, when the wind blew from the starboard and portside to the stern (98° to 268°), the ship's track trajectory time tended to benefit compared to conditions with the wind blows from the bow to the starboard and portside, as the simulation results in Figure 7. The ship's reduced speed when the wind blew from the bow to the starboard (less than 100°) was similar to the findings of Paroka et al. (2016) related to ship-speed changes caused by wind speeds and directions' influence on ferry maneuvering.

4. Conclusions

This study has analyzed a twin-rudder-system configuration's influence on a ship's course-keeping ability under various wind speeds and directions through the MATLAB-Simulink computer-simulation program. The results indicated that applying a twin-rudder system to ferry ships' to improve their course-keeping ability under windy conditions is very effective using a PID controller, reducing ship deviation and increasing ship speed by adjusting the ship's heading angle to the desired path. The track trajectory time in the ferry's course-keeping highly depends on wind velocity and direction. When the wind blows from the starboard and portside to the stern (98 to 268°), a ship's travel time tends to benefit compared to when the wind blows from the bow to the side. This research shows that the PID controller method can be applied to assist ships' movements due to other environmental influences, such as waves and currents. However, ships' course-keeping quality highly depends on the selected PID parameters.

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CORRIGENDUM TO:

Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions

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In Equations 1 and 10 on pages 434 and 436, typed as:

$$\begin{aligned} m(u\& - rv) &= X_H + X_P + X_R + X_W \\ m(v\& - ru) &= Y_H + Y_P + Y_R + Y_W \\ I_{ZZ}\psi\&\& &= N_H + N_P + N_R + N_W \end{aligned} \tag{1}$$

$$\delta = K_p(e) + K_d(e\& + K_i\int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \tag{10}$$

The equations 1 and 10 should be written as follow:

$$\begin{aligned} m(\dot{u} - rv) &= X_H + X_P + X_R + X_W \\ m(\dot{v} - ru) &= Y_H + Y_P + Y_R + Y_W \\ I_{ZZ}\dot{\psi} &= N_H + N_P + N_R + N_W \end{aligned} \tag{1}$$

$$\delta = K_P(e) + K_d(\dot{e}) + K_i\int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \tag{10}$$

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Twin-Rudder-System Configurations' Impact on Ferry Ships' Course-Keeping Ability under Windy Conditions

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Abstract. Ship course-keeping plays a vital role in navigation safety, especially when a ship is operating under windy conditions. A method to control ship movements through rudder-system configuration is necessary to stabilize a ship's course. This paper describes the twin-rudder-system configuration design's impact on a ship's course-keeping ability under windy conditions. A time-domain simulation using the MATLAB-Simulink program was developed for this purpose. A proportional integral derivative (PID) controller was used to adjust the ship's heading angle according to the desired path. Several parameters—such as relative wind velocity and directions—were accounted for in the simulation. The result shows that, at a wind direction of 88°, the ship's course-keeping speed decreased; however, increasing wind velocity caused a large deviation in the ship's heading angle. Meanwhile, the ship's course-keeping speed increased with rising windspeed directions of 219°. The ship's course-keeping time, at around 219° under the simulation's wind direction, was 11.84% lower than during a previous sea-trial. A possible reason for this difference is that the simulation excluded waves and currents.

Keywords: Course-keeping; Proportional integral derivative controller; Ship-tracking; Simulation

1. Introduction

Course-keeping quality is significant in ship navigation due to time-saving and reduced fuel consumption (Prpic-Orsic et al., 2016). To achieve quality ship course-keeping and generate accurate heading angles, a controller that considers ship hydrodynamics—including both internal and external disturbance parameters—should be installed (Lee et al, 2009). Keeping a ferry ship on course differs from sea-going ships due to navigation environments and ship particulars (Prpic-Orsic et al., 2016). The navigation environment's complexity, and especially wind-load forces and moment, makes ferry ships with large superstructures more susceptible to marine accidents (Fujiwara and Ueno, 2006). Many studies have related wind effects to ship maneuvering; wind's load-force and moment have significantly affected transversal and lateral projections of windage areas due to ships' large superstructures, as well as wind velocities and directions relative to ships (Fujiwara and Ueno, 2006). Paroka et al. (2016) simulated wind's effect on ferry ships' maneuvering,

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explaining that ship-speed changes caused by wind highly depend on wind velocity and direction. When the wind blows from the bow direction and passes to the ship's starboard (0 to 100°), ship speed tends to decrease. The corresponding decrease in ship speed is insignificant when the wind blows from a starboard direction and passes to the ship's stern (100 to 180°). Meanwhile, when the wind blows from the side of a ship (20 to 140°), it tends to change the ship's direction. A ship's directional deviations due to wind vary by ship type, and a steering response is required. Ohtsu et al. (1996) reported that a wind blowing from starboard-bow quarters (45°) made a ship's steering becomes less sensitive, but steering became more sensitive when the wind came from the port-stern quarters (135°). Increasing a ship's speed as wind directions change is crucial (Ohtsu et al., 1996; Paroka et al., 2016). The information informing this behavior is essential to improve ships' course-keeping quality—especially when ships must take appropriate action to handle wind disturbances. The improving quality of a ship's course-keeping ability in windy conditions is strongly influenced by steering responses to wind-blowing loads through an appropriately configured rudder system design (Hasegawa et al., 2006). Steering control plays an essential role in responding to external forces to a ship's yaw motion stability and course-keeping ability during maneuvers (Paroka, 2020).

Many efforts to improve ships' maneuvering have been conducted using twin-rudder ship controllers. Yoshimura and Sakurai (1989) investigated the effect of a ship-fitted, twin-rudder, twin-propeller configuration on ships' maneuvering. They found that a twin-rudder, twin-propeller configuration's hydrodynamic characteristics did not differ significantly from the corresponding characteristics of a single-propeller, single-rudder ship. Khanfir et al. (2008) proposed predicting a mathematical model coefficient on ships' maneuvering when fitted with a twin-propeller, twin-rudder configuration. Furthermore, Khanfir et al. (2011) conducted captive model tests and free-running tests with a single-propeller, twin-rudder ship and a twin-propeller, twin-rudder ship. These tests aimed to evaluate drift angles' effect on rudder forces and the peculiar phenomena concerning a normal rudder force for twin-rudder ships.

Other parameters that affect ships' maneuvering performance include the distance of spacing between single rudders in twin-rudder ships. Gim (2013) conducted a twin-rudder performance test in a circulating water channel using particle image velocimetry (PIV). He set the distance between two single rudders to 0.5–1.0 times the chord length of the rudder. He found that this spacing distance between rudders in twin-rudder configurations was also affected by interactions between rudders, and he also found that this critical distance should be less than 1.0 times the chord length of the rudder in order to decrease the turbulence flow and vortices. This result was similar to the findings of Chen et al. (2018), who used numerical simulation to confirming the excellent characteristics of twin-rudder ships compared to single-rudder ships. Chen et al. (2018) concluded that a ship fitted with a twin-rudder configuration would operate very well at 15° rudder angles. Additionally, the twin rudders' effective performance stopped at a lateral spacing equal to 1.3 times the chord length of the rudder.

These previous studies have shown that a rudder system's configuration is the most crucial feature in achieving ship controllability goals. A rudder system must alter ship control to the desired heading angle, due to both internal and external disturbance parameters. The current paper focuses on applying the twin-rudder system to improve ferries' course-keeping quality under windy conditions. By simulating fluctuating wind velocity and directions according to a ship's operating route, quality course-keeping and accurate heading angles may be achieved, increasing the ship's safety.

2. Methods

2.1. *Mathematical Model*

This study's ship maneuvering analysis used computer simulation to employ modular mathematical models, including a consideration of hydrodynamic derivatives. This study's models were based on surge, sway, and yaw motions (Equation 1) using the coordinate system shown in Figure 1.

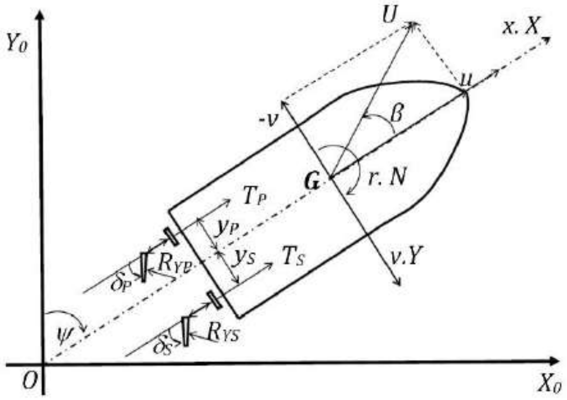

Figure 1 Coordinate ship system

$$
\begin{aligned}
m(\dot{u}-rv) &= X_H + X_P + X_R + X_W \\
m(\dot{v}-ru) &= Y_H + Y_P + Y_R + Y_W \\
I_{ZZ}\dot{\psi} &= N_H + N_P + N_R + N_W
\end{aligned}
\tag{1}
$$

The notations *u*, *v* and *r*, are velocity components at the ship's center of gravity (*G*). *m* and I_{ZZ} represent the ship's mass and moments of inertia. *X*, *Y*, and *N* represent the hydrodynamic forces and moment. The subscript *H*, *P*, *R*, and *W* refer to the ship's hull, propeller, rudder, and wind. In principle, the force and moment induced by hull (X_H, Y_H, and N_H) approximate β and *r'* polynomial function. These equations were expressed by Yoshimura (2001) as Equation 2:

$$
\begin{aligned}
X_H &= \tfrac{1}{2}\rho LdU^2(X'_0 + X'_{\beta\beta}\beta^2 + (X'_{\beta r} - m'_y)\beta r' + X'_{rr}r'^2 + X'_{\beta\beta\beta\beta}\beta^4) \\
Y_H &= \tfrac{1}{2}\rho LdU^2(Y'_\beta\beta + (Y'_r - m'_x)r' + Y'_{\beta\beta\beta}\beta^3 + Y'_{\beta\beta r}\beta^2 r' + Y'_{\beta rr}\beta r'^2 + Y'_{rrr}r'^3) \\
N_H &= \tfrac{1}{2}\rho L^2dU^2(N'_\beta\beta + N'_r r' + N'_{\beta\beta\beta}\beta^3 + N'_{\beta\beta r}\beta^2 r' + N'_{\beta rr}\beta r'^2 + N'_{rrr}r'^3)
\end{aligned}
\tag{2}
$$

where β is the drift angle at the midship position by $\tan^{-1}(v/u)$ and *r'* non-dimensionalized yaw rate by *rL/U*. X'_0, $X'_{\beta\beta}$, $X'_{\beta r}$, X'_{rr}, $X'_{\beta\beta\beta\beta}$, Y'_β, Y'_r, $Y'_{\beta\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, Y'_{rrr}, N'_β, N'_r, $N'_{\beta\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$ and N'_{rrr} is the hydrodynamic derivatives on the ship's maneuvering. The force and moment induced by twin-propeller configurations (X_P, Y_P, and N_P) were expressed by Khanfir et al. (2011) in Equation 3:

$$
\begin{aligned}
X_P &= \rho\Big((1-t_{P(S)})n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}(J_{P(S)}) + (1-t_{P(P)})n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}(J_{P(P)})\Big) \\
N_P &= \rho\Big((1-t_{P(S)})y_{P(S)}n_{P(S)}{}^2 D_{P(S)}{}^4 K_{T(S)}(J_{P(S)}) + (1-t_{P(P)})y_{P(P)}n_{P(P)}{}^2 D_{P(P)}{}^4 K_{T(P)}(J_{P(P)})\Big)
\end{aligned}
\tag{3}
$$

where $K_{T\substack{(S)\\(P)}}(J_{P\substack{(S)\\(P)}}) = k_0 + k_1 J_{P\substack{(S)\\(P)}} + k_2 J_{P\substack{(S)\\(P)}}{}^2$ and $J_{P\substack{(S)\\(P)}} = (u - y_{P\substack{(S)\\(P)}}r(1-w_{P\substack{(S)\\(P)}}))/(n_{P\substack{(S)\\(P)}}D_{P\substack{(S)\\(P)}})$

where t_P is the thrust deduction coefficient in straightforward moving, K_T is the thrust coefficient of the propeller force, and n_P is the propeller revolution. D_P is the propeller diameter, w_P is the effective wake fraction coefficient at the propeller's location, and J_P is the advance coefficient, while k_0, k_1, and k_2 are the constants for an open-water propeller. The sub-subscript *(S)* and *(P)* refer to starboard and portside.

Force and moment due to twin-rudder configurations (X_R, Y_R, and N_R) can be expressed by Equations 4–8 (Khanfir et al., 2011).

$$\begin{aligned}
X_R &= -(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} - (1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)} \\
Y_R &= -(1+a_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{R(YS)}\cos\delta_{(P)}\right) \\
N_R &= -(x_R + a_H x_H)\left(F_{RY(S)}\cos\delta_{(S)} + F_{RY(P)}\cos\delta_{(P)}\right) + f(x_R) \\
f(x_R) &= y_{P(S)}(1-t_{R(S)})F_{RY(S)}\sin\delta_{(S)} + y_{P(P)}(1-t_{R(P)})F_{RY(P)}\sin\delta_{(P)}
\end{aligned} \tag{4}$$

where δ is the rudder angle, x_R is the rudder's location, and t_R, a_H, and x_H are the interactive force coefficients for the hull, propeller, and rudder as functions of the propeller's advance constant. The rudder's normal (F_{RY}) acting on the rudder stock can be expressed by Equation 5:

$$F_{RY\substack{(S)\\(P)}} = \tfrac{1}{2}\rho A_R U_{R\substack{(S)\\(P)}}^{\,2} f_\alpha \sin\alpha_{R\substack{(S)\\(P)}} \tag{5}$$

where A_R is the rudder area, and f_α is the gradient of the rudder's lift coefficient, which can be approximated by the function of the rudder's aspect ratio (f_α = 6.13Λ/(2.25). The effective inflow velocity to the rudder (U_R) and the effective angle of attack of the inflow velocity to the rudder (α_R) can be expressed by Equation 6:

$$U_{R\substack{(S)\\(P)}} = \sqrt{u_{R\substack{(S)\\(P)}}^{\,2} + v_{R\substack{(S)\\(P)}}^{\,2}} \qquad \text{and} \qquad \alpha_{R\substack{(S)\\(P)}} = \delta_{\substack{(S)\\(P)}} - \delta_{R\substack{(S)\\(P)}}\left(\beta_{R\substack{(S)\\(P)}}\right) \tag{6}$$

The effective inflow velocity (u_R) to the rudder in the surge direction can be expressed by Equation 7:

$$u_{R\substack{(S)\\(P)}} = \varepsilon_{\substack{(S)\\(P)}} u_{P\substack{(S)\\(P)}} \times \sqrt{\eta_{P\substack{(S)\\(P)}}\left\{1+\kappa\left(\sqrt{1+8K_{T\substack{(S)\\(P)}}\Big/\pi J_{P\substack{(S)\\(P)}}^{\,2}}-1\right)\right\}^2 + (1-\eta_{P\substack{(S)\\(P)}})} \tag{7}$$

where: $\varepsilon_{\substack{(S)\\(P)}} = 1 - w_{R\substack{(S)\\(P)}}\Big/1 - w_{P\substack{(S)\\(P)}}$; $\kappa = kx\Big/\varepsilon_{\substack{(S)\\(P)}}$; $\eta_{P\substack{(S)\\(P)}} = D_{P\substack{(S)\\(P)}}\Big/H_{R\substack{(S)\\(P)}}$; $u_{P\substack{(S)\\(P)}} = \left(1 - w_{P\substack{(S)\\(P)}}\right)\left(u - y_{P\substack{(S)\\(P)}} r\right)$

Here, ε, κ, γ_R, and l_R are the parameters describing the rudder inflow velocity angle, while (1-w_R) and η are the propeller wake fraction and effective efficiency, respectively. (D_P/H_R) is the ratio of the propeller diameter to the rudder height.

The effective inflow velocity (v_R) to the rudder in the sway direction can be expressed by Equation 8:

$$v_{R\substack{(S)\\(P)}} = u_{R\substack{(S)\\(P)}} \tan\left(\delta_{R\substack{(S)\\(P)}}\right) \tag{8}$$

where: $\delta_{R\substack{(S)\\(P)}} = \gamma_{R\substack{(S)\\(P)}}\beta_{R\substack{(S)\\(P)}} + \tan^{-1}\left(y_{R\substack{(S)\\(P)}}\Big/x_{R\substack{(S)\\(P)}}\right)$ and $\beta_{R\substack{(S)\\(P)}} = \beta - L_{R\substack{(S)\\(P)}} r$

Here, δ_R is the rudder angle, β_R is the effective drift angle at the rudder, and L_R is the flow-straightening coefficient of the yaw rate. For the case of a ship operating under windy conditions, the force and moment (X_W, Y_W, and N_W) acting on the ship were expressed by Equation 9 (Fujiwara and Ueno, 2006):

$$X_W = C_{AX}(\psi_A) q_A A_F ; \quad Y_W = C_{AY}(\psi_A) q_A A_L ; \quad N_W = C_{AN}(\psi_A) q_A A_L L_{OA} \tag{9}$$

where $\psi_A = \tan^{-1}\left[U_T \cos\psi + U\cos\beta / U_T \sin\psi - U\cos\beta\right]$ and $q_A = q_T + q_S + 2\sqrt{q_T q_S}\cos(\psi+\beta)$

C_{AX}, C_{AY}, and C_{AN} are the wind load forces and moments' coefficients, respectively, as a function of the wind direction relative to a ship (ψ_A). U_T and ψ are wind velocity and direction angles with reference to the coordinate system, q_A is wind pressure, q_T is wind pressure due to the elevation of the center of a windage area, and q_S is the wind pressure induced by wind velocity, without an elevation effect. A_F and A_L are the transversal and lateral projections of the windage area, respectively.

2.2. *Autopilot Ship Steering*

The rudder is the most critical feature in achieving controllability goals (Lee et al., 2009). The control system must alter the control surfaces to the desired heading angle. The schematic equation of the PID control system that a ship tracks can be expressed by Equation 10 (Lee et al., 2009).

$$\delta = K_P(e) + K_d(\dot{e}) + K_i \int_0^T e(t)dt \text{ and } e = (\psi_T - \psi_P) \tag{10}$$

where δ is designed rudder angle; K_p, K_d, and K_i are proportional gain, derivative gain, and integral gain respectively; and e is an error between the heading target (ψ_T) and the actual heading angle (ψ_P). Furthermore, the line-of-sight (LOS) method (Fossen, 2002) helps control ships reach target headings through reference heading angles. The reference heading angle equation and target zone correction can be expressed by Equation 11:

$$\psi_{ref}(t) = \tan^{-1}(y_k - y(t) / x_k - x(t)) \text{ and } (x_k - x(t))^2 + (y_k - y(t))^2 \le R_0^2 \tag{11}$$

where x_k and y_k are the track-point coordinates, $x(t)$ and $y(t)$ are the ship's coordinates position, and R_0 is the target zone's radius.

2.3. *Simulation Program*

According to IMO (2002) criteria for ship maneuvering, a swept path should be used to analyze a ship's course-keeping prediction. A ship's swept path can be obtained by double-integrating the ship motion mathematical model's acceleration, including hydrodynamic derivatives. A numerical integration of the Dormand–Prince method (Maimun et al., 2013; Muhammad et al., 2015) then solved the equations of motion in this time-domain simulation using the MATLAB-Simulink program. The coefficient of hydrodynamic derivatives for the acting hull force and moment in Equation 2—and the interaction force coefficient among the hull, propeller, and rudder—were predicted using the derived regression equation developed by Yoshimura and Masumoto (2012). This regression equation is among the models used by Sukas et al. (2019) in developing the SINMAN Program to predict turning circles and zigzag maneuvering for ships with twin-rudder and twin-propeller systems, as well as validation through model testing or free-running tests. In many cases, the regression equation has been used to predict ferry ships' maneuvering under active wind and wave conditions (Paroka et al., 2015, 2016, 2017b). A ship's resistance coefficients for simulation were predicted using the Holtrop method (Holtrop and Mennen, 1982; Holtrop, 1984). The propeller thrust coefficient ($K_T(J_P) = 0.4061 - 0.3034\, J_P - 0.1178\, J_P^{\,2}$) was predicted using polynomial regression, based on the open water test's statistical data for the B-series propeller (Carlton, 2007). The coefficient of the wind load force and moment in Equation 9 was predicted using the methodology proposed by Fujiwara and Ueno (2006). The control method used in the simulation was a proportional integrated derivative (PID) controller. The designed rudder angle (δ=±35 deg.) was

calculated using Equation 10 with a PID gain ($K_p = 2.208$; $K_i = 0.027$ and $K_d = 45.372$), and it was selected using the pole placement method with the second-order linear Nomoto model of the ship (Nomoto et al., 1957). The methods used by Paroka et al. (2017a) in developing an automatic control system to predict and avoid ferry-ship collisions were compared using a free-running experiment.

2.4. *Ship and Sea-Trial Data*

The study's object was the *KMP Bontoharu* ferry ship (1053 gross tonnage), owned by PT. ASDP Indonesia Ferry. The ship has twin propellers and twin rudders, and the distance between the rudders and propellers is 2.3 m. The ship's particulars are presented in Table 1. The ship's sea trial on the Selayar-to-Bulukumba route was 15.385 nautical miles long, involving a 7,268-second traveling time, around a 6.03 m/s wind velocity, and a 254° wind direction. The trial data were taken on September 20, 2015.

Table 1 Ship particulars

Hull	Value	Super structure	Value	Propeller and rudder	Value
Loa, m	54.00	A_L, m²	182.87	*Z*	2×4
Lbp,m	47.45	A_F, m²	129.20	*D, m*	1.450
B, m	14	A_{OD}, m	218.23	*Ae/Ao*	0.645
H, m	3.4	*C*	-0.44	*Pitch, m*	1.320
T,m	2.45	H_C, m	2.70	*n*	8.784
V, m/s²	6.618	H_L, m	3.38	*Span, m*	1.550
Δ, Ton	1148	H_{BR}, m	10.48	*Chord, m*	0.900
				A_R, m²	2×1.395
				BHP, HP	2×1000
				RPMME	1850

2.5. *Wind Data*

Monthly wind velocity data were obtained from ERA-Interim reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for 10 years, from 2006 to 2018, at six-hour intervals. The model provided wind speed data with a resolution of 0.25 × 0.25 degrees. This model was validated by Dee et al. (2011). Furthermore, it was validated locally by Lina et al. (2015) using data from eight buoys deployed in the Yellow Sea and the East China Sea. This study's coordinate for its observation data was at 5.75°S and 120.5°E.

3. Results and Discussion

The wind speed trend peaked in January, with a maximum of 10.06 m/s (88°), as Figure 2 shows. Meanwhile, April's monthly wind speed trend decreased, with a minimum of 6.41 m/s (219°). The monthly wind speed movements varied, depending on the month occurring during the west or east monsoon seasons.

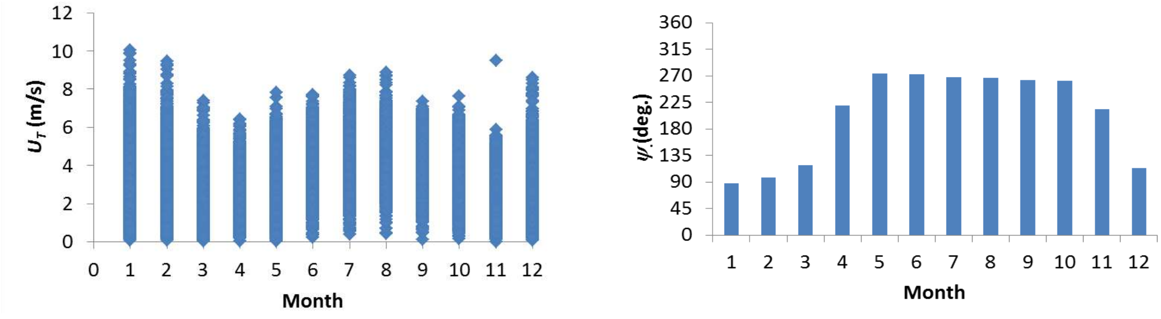

Figure 2 Significant wind velocity and direction on the Selayar–Bulukumba route

Based on the wind data characteristics in Figure 2, the *KMP Bontoharu*'s course-keeping was simulated for three conditions of wind direction parameters—the starboard bow (88°) and the portside stern of the ship (219° and 268°)—using the time domain simulation program of MATLAB-Simulink. This information is essential to ship navigation due to time-savings and reduced fuel consumption by controlling a twin-rudder configuration design. Figure 3 shows the historic result of the simulation for the course-keeping trajectory of the *KMP Bontoharu* (Selayar to Bulukumba) under wind velocities' effect.

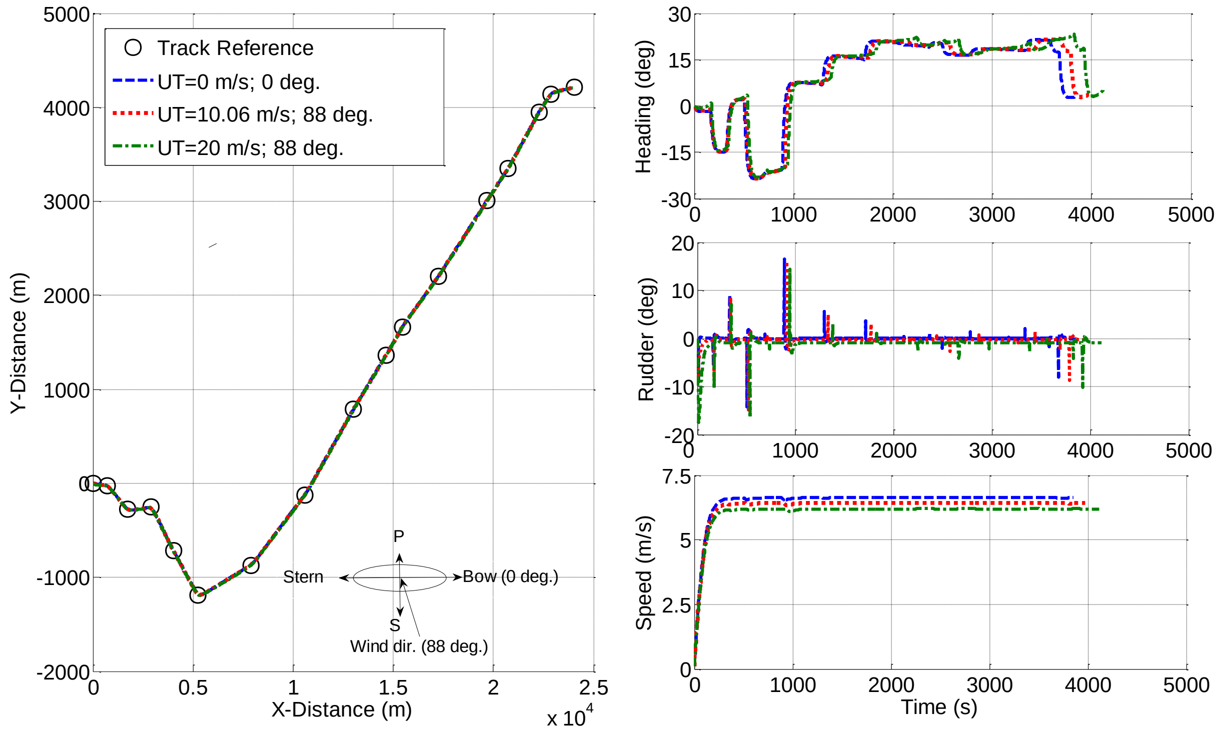

Figure 3 Ship trajectory with different wind speeds (U_T) at 88°

The horizontal axis expresses the time, while the vertical axis expresses the heading angle (ψ), rudder angle (δ), and ship speed (u), respectively. The wind blew from the starboard bow (88°) at wind velocities of 10.06 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory slowly deviated from the initial track with a low heading with significant course-keeping time compared to conditions without winds ($U_T =$ 0 m/s). Meanwhile, the ship's course-keeping trajectory with increased wind velocities caused more deviations and low ship speeds.

Figure 4 shows the simulation results for the *KMP Bontoharu*'s course-keeping with the wind blowing from the portside stern (219°) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. We found that the course-keeping trajectory quickly deviated from the initial track with a high heading and short course-keeping time at each blown wind velocity, compared to conditions without winds (U_T = 0 m/s). These characteristics differed when the wind blew from the starboard side (88°). The wind direction angle caused these differences, as Ohtsu et al. (1996) found, relating to changes in a ship's heading and rudder angle as a result of wind velocity and ship direction in course-keeping.

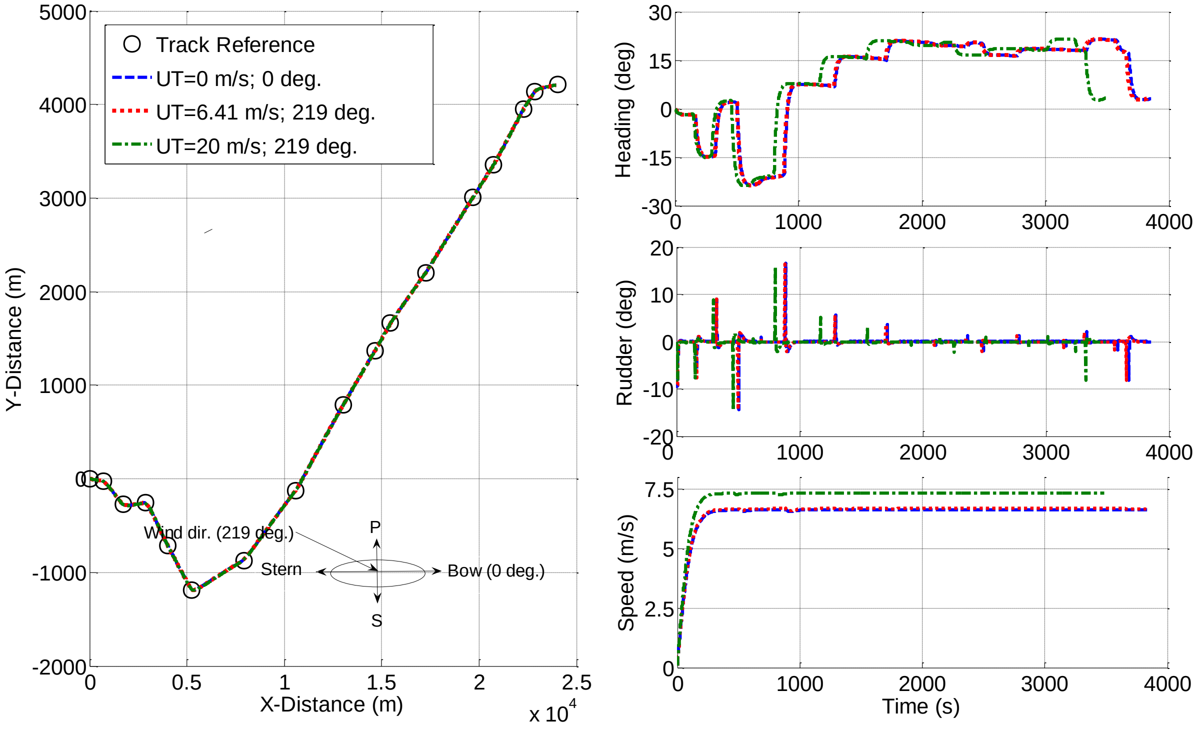

Figure 4 Ship trajectory with different wind speeds (U_T) at 219°

Figure 5 shows the historic results of the simulation for the course-keeping trajectory of the *KMP Bontoharu* with the wind blowing from the portside stern (268°) at a wind velocity range of 0–20 m/s for the initial ship speed (U) of 6.618 m/s. At a wind velocity of 8.71 m/s, the ship's speed was 0.27% reduced compared to conditions without wind (U_T = 0 m/s), while the ship speed increased by 5.96% increases at a wind speed of 20 m/s. These changes in ship speed were caused by the ship's directional movements.

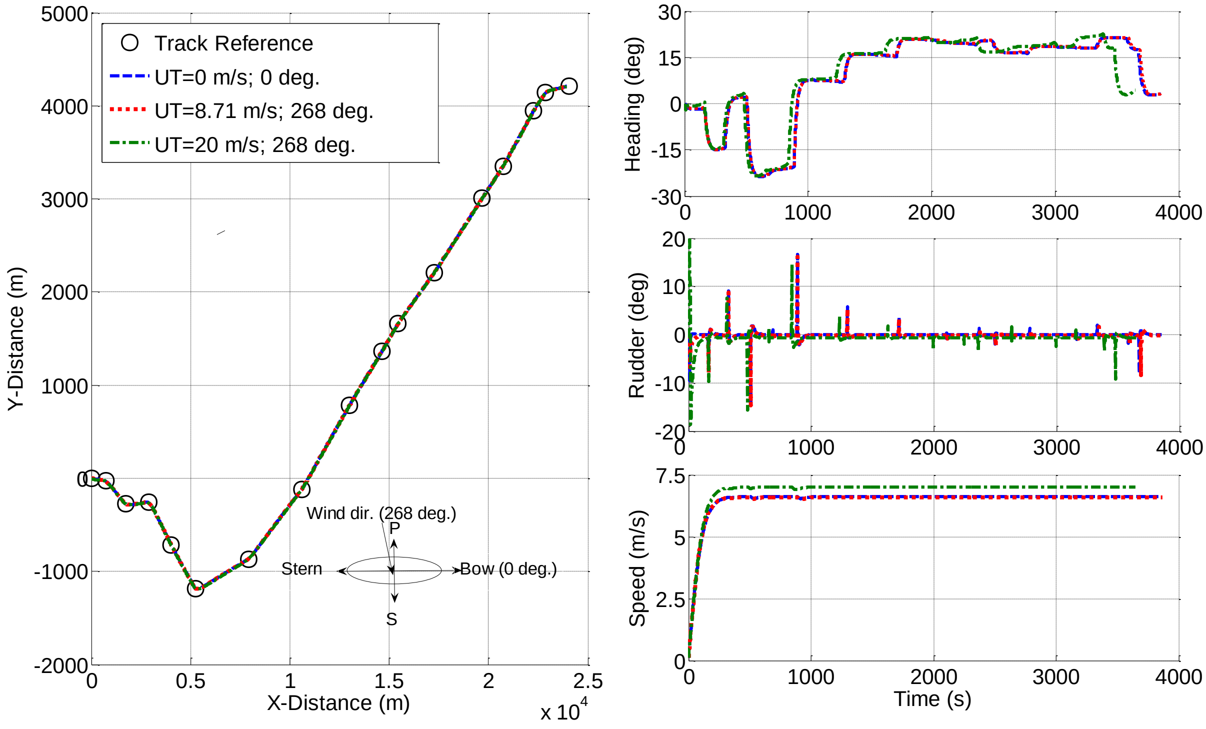

Figure 5 Ship trajectory with different wind speeds (U_T) at 268°

Figure 6 shows the sea-trial simulation results for the ship course-keeping trajectory with a 6.03 m/s wind velocity and a 254° wind direction at an initial ship speed of 3.98 m/s. We found that the traveling time under these conditions stood at 6,407 seconds. The simulation's traveling time was 11.84% higher than the sea-trial result. A possible reason for this difference is that the simulation excluded waves and currents.

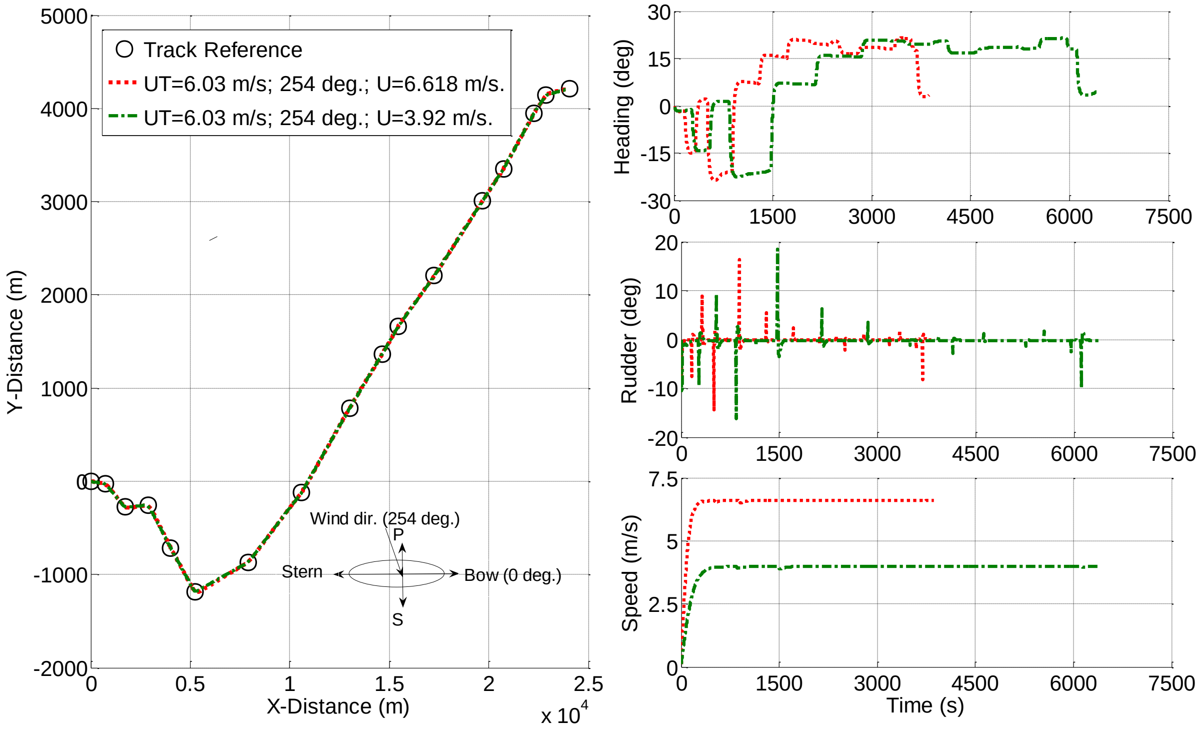

Figure 6 Sea-trial simulation result for ship trajectories with different initial ship speeds (*U*)

Figures 3, 4, and 5 also show the effects of winds velocity and direction on ship speed, with a course-keeping trajectory for an initial ship speed (U) of 6.618 m/s. We found that, when the wind blew from the starboard bow (88°) with a wind velocity of 20 m/s, the ship speed was 6.36% lower compared to conditions without wind (U_T = 0 m/s). Meanwhile, when the wind blew from the portside stern (219° and 268°), the ship speed was increased by 10.74% and 5.96%, respectively. The two latter speeds were beneficial because the track trajectory times were minimal.

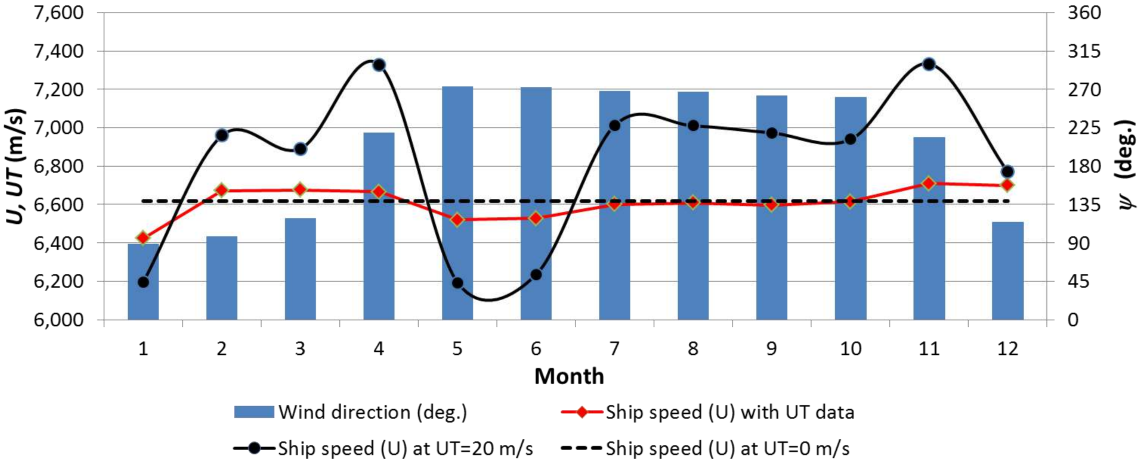

Figure 7 Tracking ship speed trajectories with different wind velocities and directions

In general, when the wind blew from the starboard and portside to the stern (98° to 268°), the ship's track trajectory time tended to benefit compared to conditions with the wind blows from the bow to the starboard and portside, as the simulation results in Figure 7. The ship's reduced speed when the wind blew from the bow to the starboard (less than 100°) was similar to the findings of Paroka et al. (2016) related to ship-speed changes caused by wind speeds and directions' influence on ferry maneuvering.

4. Conclusions

This study has analyzed a twin-rudder-system configuration's influence on a ship's course-keeping ability under various wind speeds and directions through the MATLAB-Simulink computer-simulation program. The results indicated that applying a twin-rudder system to ferry ships' to improve their course-keeping ability under windy conditions is very effective using a PID controller, reducing ship deviation and increasing ship speed by adjusting the ship's heading angle to the desired path. The track trajectory time in the ferry's course-keeping highly depends on wind velocity and direction. When the wind blows from the starboard and portside to the stern (98 to 268°), a ship's travel time tends to benefit compared to when the wind blows from the bow to the side. This research shows that the PID controller method can be applied to assist ships' movements due to other environmental influences, such as waves and currents. However, ships' course-keeping quality highly depends on the selected PID parameters.

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