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COMPARISON BETWEEN CONVENTIONAL AND AZIMUTHING PODDED PROPULSION ON MANEUVERING OF A FERRY UTILIZING MATLAB SIMULINK PROGRAM

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ABSTRACT

The aim of the paper is to describe the influences of conventional and azimuthing podded propulsion on passenger ferry maneuvering, particularly turning circle and zig-zag maneuvers. The MATLAB-simulink program was used to simulate the turning circle and the zig-zag maneuvers. The program was developed based on the mathematical model for ferry maneuvering. The model involved the setting-up of a 4-DOF in a modular of the Mathematical Modelling Group (MMG) of the hull, propellers-rudder or pod system. The simulation includes separating components of the hull equations, propeller-rudder or pod systems as well as the interaction between them. The results indicated that the azimuthing podded propulsion has an advantage for turning circle performance, meanwhile conventional propulsion is beneficial for zig-zag maneuvers. The 1st and 2nd overshoot times of conventional propulsion of the sea trial are higher than the simulation; but the turning cirles of the sea trial are lower.

Keywords: 4-DOF; Ferry; Maneuvering; Podded; Simulation

1. INTRODUCTION

As the largest archipelago in the world, Indonesia has more than 17,000 islands and a coastline of 95.181 km long, 2/3 of the area is sea, underscoring its important role in the national transportation system. Currently, 273 ships are sailing on 217 tracks (Kemenhub, 2013) and the number of ships will be increased in accordance with the plan to increase the number of tracks. However, due to the ship age factor, water conditions, and the lack of facilities and safety equipment on ship have caused accidents that have resulted in an increase in the number of casualties. From 2009–2013, 150 ship accidents were recorded in Indonesian waters; of which 56 accidents were due to ship grounding and collision (Kemenhub, 2013). In many cases, ship grounding and collision are caused by ships with low maneuvering quality (Viviani, 2003).

Kobayashi and Ishibashi (1993) explained the interaction between the hull, propeller and rudder for ships with twin-propeller and twin-rudder maneuverability. They concluded that the wake at propeller is affected by hull form, especially in ships with conventional propulsion. The conventional propulsion has an effect on the rudder characteristics and the rudder behind the hull in oblique motion. The characteristics of the unbalanced hydrodynamic force caused by the propeller create a partial vacuum in the region of the propeller. Therefore, ship maneuverability may become out of control. Other efforts for improving ship maneuvering have been done through computer simulation and experiments relating to propulsion types.

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Insel and Helvacioglu (1997) analyzed some alternative propulsion types (i.e. conventional propeller-rudder, propeller-high lift rudder, cycloidal propellers and Z-drives) on passenger ferries. They concluded that the cycloidal propeller has an advantage of keeping in position, meanwhile high lift rudder is beneficial for both thrust and side force to keep on track maneuvers. Toxopeus and Loeff (2002), and Stettler (2004) conducted intensive research on the application of podded propulsion from a maneuvering perspective by comparing specific ship designs with conventional and podded azhimuthing propulsion systems. The use of unconventional propulsors into ship design potentially increase the maneuvering performance of the ship.

Based on the aforementioned studies, this paper focuses on applying the concept of azhimuthing podded propulsion to Indonesian ferry maneuvering. By simulating the type of propulsion system, maneuverability of the ship is expected to be improved.

2. METHODOLOGY

2.1. Matematical Model

To assess ship maneuverability using computer simulation, mathematical models are the first ones to be developed, including the hydrodynamic derivation model. This model was based on an equation of motion (Equation 1), using the Ship Coordinate System shown in Figure 1.

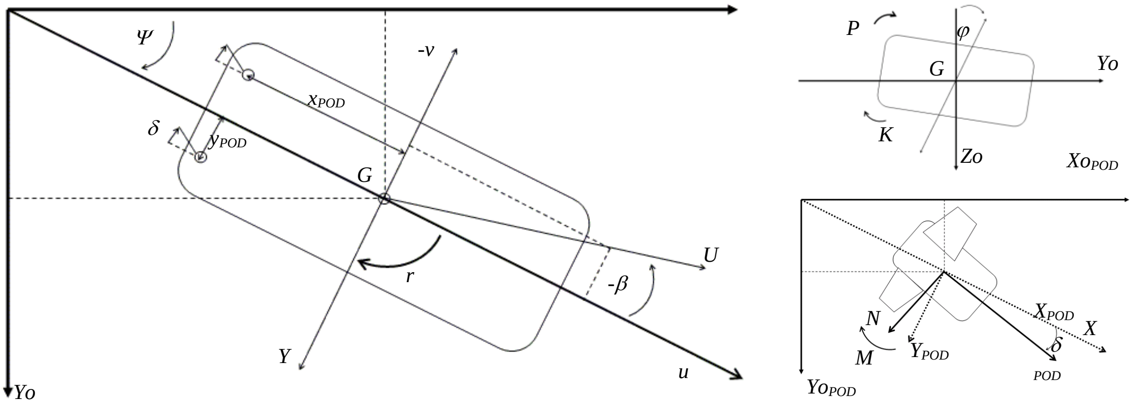


Figure 1 Ship coordinate system

$$
\begin{aligned}
X &= m(\dot{u} - rv) \\
Y &= m(\dot{v} - ru) \\
N &= I_{ZZ}\ddot{\psi} \\
K &= I_{XX}\,\dot{p}
\end{aligned}
\tag{1}
$$

The notation of *u*, *v* and *r* are velocity components at the center of gravity of the ship (G). *U* represents the resultant of ship speed; *m* is the mass of ship; I_{ZZ} and I_{XX} are respectively moments of inertia. *X*, *Y*, *N* and *K* represent the hydrodynamic forces and moments acting on the C.G. of the hull. Forces and moments can be defined separately as different elements of physical force and moment of the ship in accordance with the concept developed by Ogawa and Kansai (1997) as:

$$
\begin{aligned}
X &= X_H + X_R + X_P \\
Y &= Y_H + Y_R + Y_P \\
N &= N_H + N_R + N_P \\
K &= K_H + K_R + K_P
\end{aligned}
\tag{2}
$$

where, the subscripts *H*, *P* and *R* refer to hull, propeller and rudder, respectively. Force and moment induced by hull (X_H, Y_H, and N_H) in principle is an approximation of polynomial regression β and *r*'. Furthermore, the coefficients of these equations can be termed as derivatives of the hydrodynamic coefficients. 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 : $\beta = \tan^{-1}(v/u)$ and $r' = r(L/U)$ and heeling moment (K_H) equation expressed by Equation 4:

$$\begin{aligned} K_H &= -z_H Y_H - B_{44}\dot{\phi} - C_{44}\phi \\ B_{44} &= \frac{2a_0}{\pi}\sqrt{gm\overline{GM}}\,(I_{XX} + J_{XX}) \\ C_{44} &= gm\overline{GM} \end{aligned} \tag{4}$$

where z_H is the vertical distance between the center of gravity (G) and bouyancy (B), a_0 is the damping coefficient. B_{44} is the added inertia of roll motion; C_{44} is the moment inertia of roll motion; ϕ is the roll angle; *g* is the gravitational acceleration; *GM* is the metacentric height. J_{ZZ} is the added moment of inertia respect to z-axis.

According to Kijima and Yasuaki (2003), the force and moment equations induced by conventional propulsion (propeller - rudder) are expressed by Equation 5:

$$\begin{aligned} X_P &= (1 - t_P)\rho K_T D_P^4 n^2 \\ Y_P &= 0;\ N_P = 0;\ K_P = 0 \end{aligned} \tag{5}$$

where :

$$\begin{aligned} K_T(J_P) &= C_1 + C_2 J_P + C_3 J_P{}^2 \\ J_P &= U\cos\beta(1 - w_P)/(nD_P) \end{aligned}$$

Where t_P is the thrust deduction coefficient in straight forward moving; K_T is the thrust coefficient of a propeller force; *n* 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.

Force and moment coefficients on rudder area (X_R, Y_R, N_R and K_R) can be expressed by Equation 6:

$$\begin{aligned} X_R &= -2(1 - t_R)F_N \sin\delta \\ Y_R &= -2(1 + a_H)F_N \cos\delta \\ N_R &= -(x_R + a_H x_H)F_N \cos\delta \\ K_R &= -z_R Y_R \end{aligned} \tag{6}$$

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 dimension of rudder force is defined as follows:

$$F_N = \tfrac{1}{2} \rho A_R f_\alpha U_R^2 \sin \alpha_R$$

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 (Λ):

$$\begin{aligned}
& f_\alpha = 6{,}13\Lambda/(2{,}25+\Lambda) \\
& U_R = \sqrt{u_R^2 + v_R^2} \\
& \alpha_R = \delta - \tan^{-1}\left(\frac{-v_R}{u_R}\right) \\
& u_R = \varepsilon(1-w)u \times \sqrt{\mu \left\{1+\kappa\left(\sqrt{1+(8K_T/\pi J^2)}-1\right)\right\}^2 + (1-\eta)} \\
& v_R = \gamma_R (v - r\, l_R)
\end{aligned}$$

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.

For the case of a ship equipped with podded propulsion, force and moment is calculated as developed by Ayaz et al. (2005) in Equation 7:

$$\begin{aligned}
& X_{POD} = (1-t_{POD})\rho K_{T-POD}\, D_P^4 n^2 \\
& Y_{POD} = -(1+a_{HPOD}) S\, Cos\,\delta + X_{POD}\, Sin\,\delta \\
& K_{POD} = z_{POD}\, Y_{POD} \\
& N_P = (1+a_{HPOD} \frac{x_{HPOD}}{y_p}) x_{POD} S\, Cos\,\delta - x_{POD} X_{POD}\, Sin\,\delta
\end{aligned} \qquad (7)$$

The corrections for scale effect on K_T for pod drivers ($K_{T\text{-}POD}$) is modified according to the Funeno method in Molland et al. (2011) in Equation 8.

$$K_{T-POD} = K_{T-PROP-POD} + K_{R-POD} \qquad (8)$$

where the subscript *POD* refers to pod drivers; t_{POD} is the suction coefficient of the propeller; a_{HPOD} is the coefficient of the pod-induced side force; $x_{HPOD} = (0.05067J_{POD}-0.04696)$ is the longitudinal coordinate of the point of action of the pod–hull side force; $K_{T\text{-}PROP\text{-}POD} = (0.2491+1.0326)K_{T\text{-}OPEN}$ is the propeller thrust; $K_{R\text{-}POD} = (-0.1125J-0.0625)K_{T\text{-}PROP\text{-}POD}$ is the pod resistance; x_{POD} and z_{POD} are longitudinal and vertical coordinates, respectively, of the pod's center pressure.

2.2. Computer Simulation

According to IMO standards for ship maneuverability (2002), the assessment of ship maneuvering should be analysed based on the swept path. There are two methods for this purpose. The first method is a free running test, and the second one is a computer simulation, using mathematical models. Here, maneuvering performance investigations have been carried out using the time domain computer simulation program of MATLAB-Simulink. The swept path of ship can be obtained by double integrating the acceleration of the ship in the surge, sway, yaw and roll of mathematical models that include the hydrodynamic derivatives (Muhammad et al., 2008; Maimun et al., 2011). The equations of motion in this time domain simulation are then solved by the numerical integration in the Dormand–Prince method (Maimun et al., 2011). The step integration for surge force can be expressed by Equation 9.

Then, by the same method, the motion integration process for sway, yaw and roll were performed. The next simulations were developed and analyzed through computer simulations with the MATLAB-Simulink software.

$$X = m(\dot{u} - rv);\ \dot{u} = (X/m) + rv;\ u = \int \dot{u}\, dt;\ x = \int u\, dt \tag{9}$$

2.3. Ship Data

The main particulars of a simulated passenger ferry are presented in Table 1. The ship was equipped with two conventional propellers (FPP) and two conventional rudders, mounted behind the ship. Tables 2 and 3 show the propulsion parameters and hydrodynamic derivatives, respectively used in the simulation. The resistance and propulsion parameters for simulation were predicted using the Holtrop Method (Holtrop & Mennen, 1982; Holtrop, 1984), for a ship with podded propulsion, the parameters were predicted by Ayaz et al. (2005) and Funeno in Molland et al. (2011). Hydrodynamic derivatives were predicted using the derived regression equation developed by Yoshimura and Ning (2003), and Yoshimura (2010).

Table 1 Main particulars of ship

Parameter	Value
Loa, m	36.40
Lbp,m	31.50
Lwl, m	35.73
B, m	8.70
H, m	2.65
T,m	1.65
V, m/s^2	10.50
Cb	0.63
Δ, Ton	321.80

Table 2 Propulsion and rudder parameters

Parameters	Conventional	Podded
Dp,m	1.1	1.1
Z	4	4
A_E/A_O	0.40	0.40
Rps, rev/s	8.578	8.578
w	0.219	0.219
t	0.142	0.142
$J_P=J_{POD}$	0.499	0.499
K_T	0.230	0.259
$A_{R,}\ m^2$	2.078	-

Table 3 Hydrodynamic derivative coefficients

Coeficient	Value	Coeficient	Value
X'o	-0.00743	*Y'β*	0.4629
X'ββ	-0.1477	*Y'r-m'x*	0.0348
X'βr-m'y	0.06604	*Y'βββ*	1.2
X'rr	0.03	*Y'ββr*	-0.5
X'βββ	1.183	*Y'βrr*	0.34
		Y'rrr	-0.04
N'β	0.1397	*1-tr*	0.856
N'r	-0.05592	*αh*	0.8478
N'βββ	0.3	*ε*	1.0306
N'ββr	-0.33	*K*	0.3986
N'βrr	0.01	*l'R*	0.9042
N'rrr	0	*γr*	0.4884

3. RESULTS AND DISCUSSION

Figure 2 shows the results of the simulation conducted for turning circle maneuvers. It was found that the tactical diameter (D_T) of the ship equipped with conventional propulsion at ship speed (U) of 10.5 knots (5.397 m/s) with a full draught of 1.65 m is 75.94 m or 2.41 times the ship length of 31.5 m. This tactical diameter meets the IMO criterion of less than five times ship length. The advance (A_D) is 66.27 m or 2.4 times ship length. This value is also within the

IMO criterion of 4.5 times ship length. Figure 2 also shows the results of the turning circle of the ship with both conventional and podded propulsion.

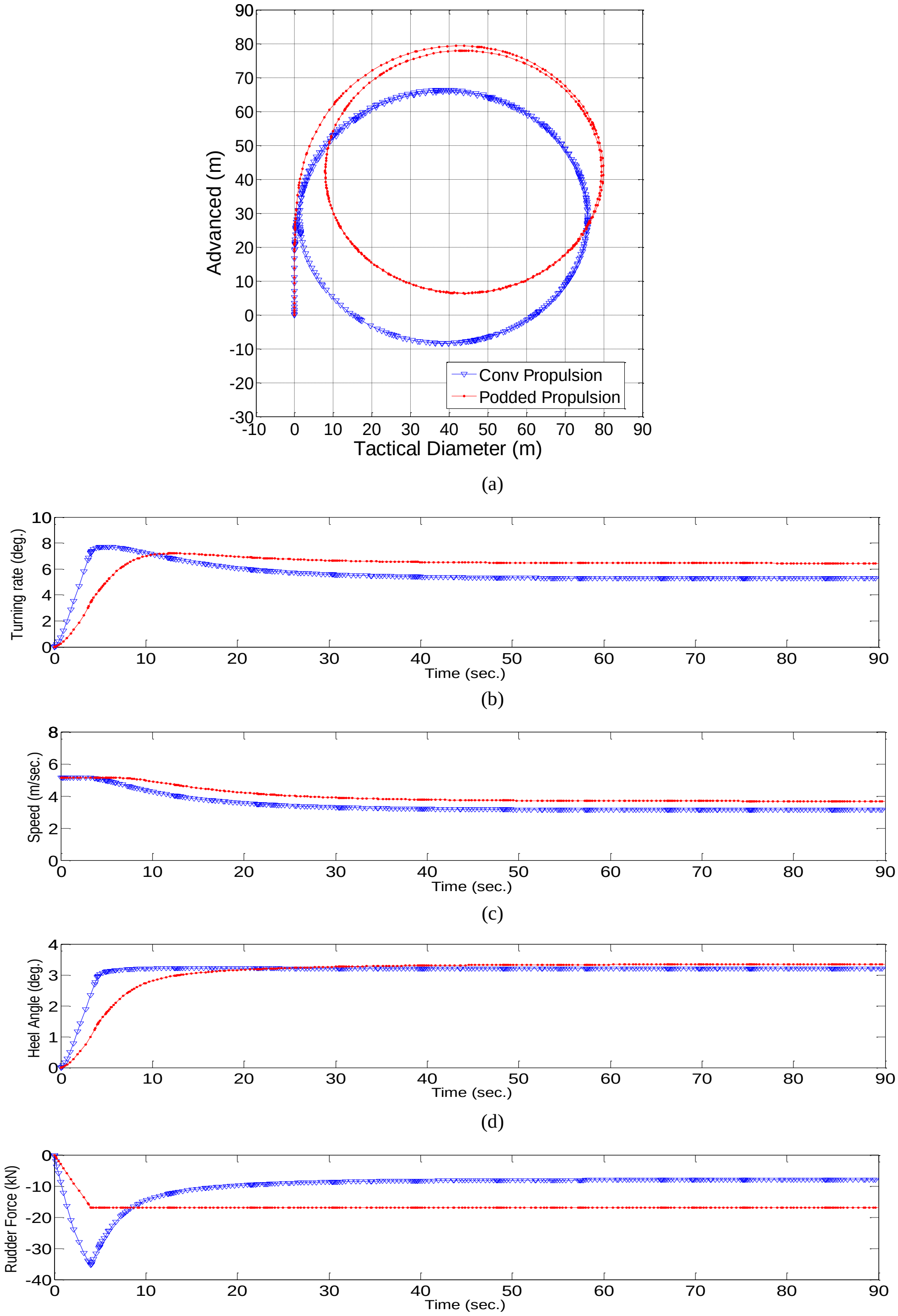
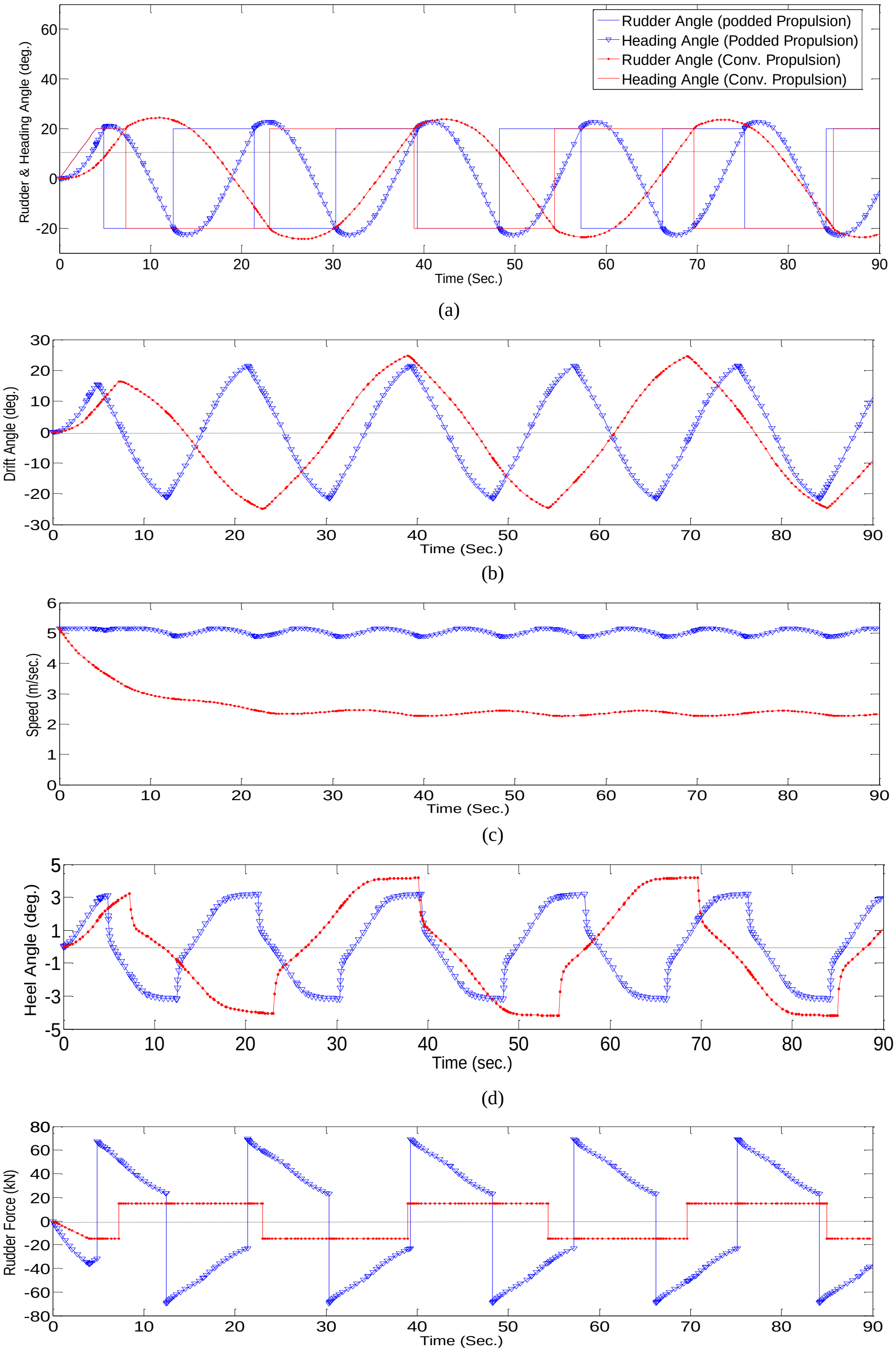


Figure 2 Turning circles difference in propulsion types: a) Turning trajectory; b) Turning rate of ship history; c) Speed of ship history; d) Heel angle history; e) Rudder force history

A ship equipped with conventional propulsion has a 6.38% tactical diameter larger than the podded propulsion. However, a ship with podded propulsion has a 4.05% bigger heel angle and 15.51% lower speed than the ship with the conventional propulsion. It was also found that the type of propulsion equipment was affected by the hull, especially for a ship with podded propulsion. The type of podded propulsion has a 52.30% bigger side force than the ship with a conventional rudder, despite during the ship's first movement, the side force of the podded propeller is lower. This result is similar to the findings of Ayaz et al. (2005), confirming the excellent characteristics of podded propulsion vessels compared with those of conventional vessel propulsion. Betancourt (2005) suggested that a ship with podded propulsion will operate very well both at lower speeds and pod angles.



(a)

(b)

(c)

(d)

Figure 3 Zig-zag manuvers difference propulsion types: a) Rudder /podded & heading angle history; b) Drift angle of ship history; c) Speed of ship history; d) Heel angle history; e) Rudder force history

Figure 3 shows the results of the simulation for a zig-zag maneuver $20^o/20^o$ of the ship. The horizontal and vertical axes express time and heading angle (ψ), respectively. It shows that the heading angle of the ship with conventional propulsion has a smaller overshoot angle when compared to the ship with podded propulsion. A ship with conventional propulsion, took 5.45 seconds for the 1^{st} overshoot and it was 14 seconds faster for the 2^{nd} overshoot with the heading angles of 1.19^o and 2.62^o, respectively. The overshoot times of a ship with podded propulsion were higher in the 1^{st} and 2^{nd} overshoot times and the heading angles than a ship equipped with conventional propulsion. The same situation occurs in the turning trajectory results, a ship with podded propulsion performance on zig-zag maneuver (1^{st} overshoot) has 23% bigger heel angles and 36% lower speeds than a ship with conventional propulsion. The reason is the effect of the side forces of the propeller is lower, especially at the ship's first moving. This is similar to the findings of Insel and Helvacioglu (1997), that the propeller-high lift rudders were beneficial for both the thrust and side force movements for keeping the maneuvering on track.

The field measurement of the ship sea trial by *PT IKI (Industri Kapal Indonesia)* shipyard was carried out on 27th, July 2006 on the KMP Sultan Murhum owned by PT. ASDP Indonesia Ferry. Table. 4 shows the sea trial results for the turning circle of the ship. It was determined that the tactical diameter of the ship for the rudder area of 2.078 m^2 at a speed of 10.5 knots (5.397 m/s) with a full draught of 1.65 m results in 49.7 m (to port), consequently, indicating 1.58 times the vessel length of 31.5 m. This tactical diameter meets the required IMO criterion of less than five times the ship length and a 24% smaller tactical diameter compared with the simulation results. The reason, may be the effect of the environmental conditions, (i.e. wind speed and waves) during the sea trial. The turning circle time and the heading angle at V= 5.397 m/s are 105 seconds for the port turning circle with a heading angle of 8^o. The tactical diameter time of the sea trial is 46% higher than the simulation results, while the simulation result is 60% smaller for the heel angle. For the zig-zag maneuver of $20^o/20^o$ for the rudder area of 2.078 m^2 at a speed of 5.397 m/s with a full draught of 1.65 m, the horizontal and vertical axes express time. It shows that the overshoot time is 16 seconds for the 1^{st} overshoot and 48 seconds faster for the 2^{nd} overshoot, indicating that overshoot times of the sea trial test were 65% and 71% higher, respectively, than simulation results.

Table 4 indicates the summary of simulation and sea trial results for conventional and podded propulsion systems.

Table 4 Turning circle and zigzag characteristics of two different propulsion types

Parameter	IMO Criteria	Sim Conv.	Sim Podded	S Trial Conv.
D_T, m	< 5 L	75.94	71.09	49.7
A_D, m	< 4.5 L	66.27	79.34	-
S, second		67	60	105
r, turning rate (rad/sec)		7.7	6.9	-
Speed on turning (m/sec.)		3.13	3.705	-
Ø, rad	$<10^0$	3.197	3.332	8
1^{st} Overshoot, ψ, deg.	< 25°	1.19	4.34	-
1^{st} Overshoot, *s*, second		5.45	10.99	16
2^{nd} Overshoot , ψ, deg.	< 40°	2.62	4.38	-
2^{nd} Overshoot, *s*, second		14.01	26.61	48
r, turning rate (rad/sec)		8.0	5.0	-
Speed on zigzag (m/sec.)		4.85-5.14	2.26-2.44	-
Ø, rad	$<10^0$	3.161	4.182	-

Generally, the use of azimuthing podded propulsion for a ferry produces a stable motion response at the turning circle with a constant angle of 20 degrees as indicated by Figures 2b, 2c, 2d, and 2e for turning rate history, speed, heel angle, and pod force, respectively, when compared with conventional propulsion. Another advantage is in maneuvering through narrow waters, including the port area with a relatively small tactical diameter. On the other hand, conventional propulsion (propeller-rudder) has the advantage of a resulting high force, particularly during the first movement (less than 20 seconds). High rudder force, Figure 3e, shows that conventional propulsion has an advantage of zig-zag maneuvering or ship position adjustment with a relatively fast motion response.

4. CONCLUSION

A maneuvering study was conducted, including a simulation by the MATLAB Simulink of both conventional and azimuthing podded propulsion for a passenger ferry. Comparison of the results of using conventional propulsion simulation with the results of the ferry sea trial was also covered. Time domain simulation program developed by MATLAB Simulink has shown that the influences of propulsion type on ship maneuvering is significant. Selecting the propulsion system device on the ferry can result in a reduction in the tactical diameter during the turning circle or overshoot time of zig-zag maneuver and possible increase in safety of the ship. Podded propulsion has an advantage for turning circle performance; meanwhile conventional propulsion is beneficial for zig-zag maneuvers. In case of conventional propulsion the 1st and 2nd overshoot times of the sea trial are higher than the simulation; meanwhile the turning circles of the sea trial are lower.

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