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Characteristics of Turning Circle and Zig-Zag Manoeuvres of An Indonesian Ferry Ship In Shallow Water

A H Muhammad[1], D Paroka[2], S Rahman[2] M R Firmansyah[3] and T P Putra[4]

[1] Department of Marine Engineering, Faculty of Engineering, Hasanuddin University, Gowa, 50275 Indonesia
[2] Department of Ocean Engineering, Faculty of Engineering, Hasanuddin University, Gowa, 50275 Indonesia
[3] Department of Naval Architecture, Faculty of Engineering, Hasanuddin University, Gowa, 50275 Indonesia
[4] Research and Development Center for Sea, River, Lake and Ferry Transportation, Ministry of Transportation, Jakarta Pusat, 10110 Indonesia

Abstract. Ship manoeuvring performance is very important in navigation safety, especially when ships operate in shallow water. This paper describes the characteristics of turning circle and zig-zag manoeuvres of Indonesian ferry ships in shallow water. A time-domain simulation program was developed for this purpose. Several parameters such as ship speed and water depth levels have been considered in the simulation. The results shows a significant difference in the ship's trajectory and speed when the ship manoeuvring in different water depths. The ship manoeuvre trajectory diameter for shallow water (h/T=1.3) is greater than in deep water (h/T=4.0). Meanwhile, the speed of the ship during turns increases with the decreasing depth of the water (h). Likewise, the $20/20^0$ zig-zag manoeuvre of the ship shows that the heading angle in shallow waters has a smaller overshoot angle when compared to the ship manoeuvres in the deep waters.

1. Introduction

Ship Behaviour and performance in shallow water are strongly influenced by hydrodynamic interactions between the hull and the bottom channel. That is, the velocity of flow between the hull and the bottom increases, as the flow pressure decreases. A number of changes experienced by the ship when entering shallow water are expressed by changes in resistance, trim, steering, manoeuvrability and stopping [1]. Many researchers mention that the change in performance is not only influenced by the hydrodynamic interaction between the hull and the bottom channel, but the decrease in water depth also has an impact on the less efficient and not effective of the propeller and rudder action [2] and [3].

Many investigations have been carried out to shows the manoeuvring performance of ships in shallow water through changes in flow velocity or ship speed. Du, et al. [4] has examined ship's speed effect on shallow waters through a system-based method, where a nonlinear transient hydrodynamic and confinement model is implemented to account for the channel bottom effect. The turning manoeuvring model and the confinement model was validated using the experimental data. They concluded that with increasing speed it had increased the hydrodynamic interaction between the hull and the channel bottom. Similar results are also present by Skejic, et al. [5] in his research on water depth's effect on ship manoeuvring through numerical simulations and sea trials. They stated a significant difference in the ship's trajectory and manoeuvring speed when the ship was manoeuvring at different water depths. These were indicated by the increase in tactical diameter and speed of ship manoeuvring along with the decreasing water depth. According to the World Association for Water Transport Infrastructure [6] water depth level is defined as the ratio of water depth including $h/T>3$ (deep water), $1.5 < h/T < 3$ (medium water), $1.2 < h/T < 1.5$ (shallow water); and $h/T < 1.2$ (very shallow water).

Indonesian ferries ship is a type of ship crossing between islands (passengers and vehicles). This ship has unique characteristics compared to commercial ships in general. Some features of Indonesian ferries ship that can affect the manoeuvrability: i) The ship has a low draft (T); ii) The ship operates in confined water (deep and shallow water); iii) The ship has a superstructure with a relatively large wind catch area and; iv) The ship is equipped with a twin propulsion and rudder system (TRTP) with a relatively large ratio of distances between systems. Based on those characteristics, it is crucial view the Indonesian ferries manoeuver efficiency and navigation safety.

The limitation of the speed manoeuvring to the water's depth is an essential consideration in operating ships in confined waters. This paper aims to predict the manoeuvring capabilities (turning circle and zig-zag manoeuver) of Indonesian ferries in deep (*h/T*=4.0) and shallow water (*h/T*=1.3) from the point of view of manoeuver efficiency and navigation safety.

2. Mathematical Model

In the prediction of ship manoeuvring in shallow water conditions through numerical simulations based on the mathematical model, it is important to use hydrodynamic coefficients on which shallow water effects. The models were based on the 3-DOF equations of manoeuvring motion (surge, sway and yaw) in Equation 1, using the coordinate system in Figure 1.

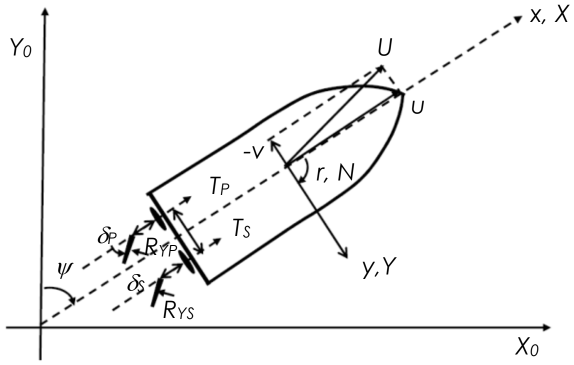

Figure 1. Coordinate system of ship.

$$
\begin{aligned}
&(m+m_x)\dot{u}-(m+m_y)rv = X_H + X_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + X_{R\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}\\
&(m+m_y)\dot{v}+(m+m_x)ru = Y_H + Y_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + Y_{R\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}\\
&(I_{zz}+J_{zz})\dot{r} = N_H + N_{P\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}} + N_{R\left\{\begin{smallmatrix}S\\P\end{smallmatrix}\right\}}
\end{aligned}
\qquad (1)
$$

The notations of m, m_x, and m_y are the mass of ship, and added mass inertia in *x*-and *y*-direction respectively; I_{zz} and J_{zz} are moments of inertia and added around *z*-axis respectively; *u*, *v* and *r* are velocity components at ship's centre of gravity (*G*). *X*, *Y*, and *N* represent the hydrodynamic forces and moment. The subscript *H*, *P*, and *R* refer to hull, propeller and rudder respectively according to the concept of MMG expression.

Force and moment acting on hull (X_H, Y_H, and N_H) are approximated by the polynomial function of β and r'. The equations are expressed by Kijima, et al. [7] in Equation 2.

$$
\begin{aligned}
X_H &= \frac{1}{2}\rho LdU^2(X'_{\beta r}r'\sin\beta + X'_{uu}\cos^2\beta)\\
Y_H &= \frac{1}{2}\rho LdU^2(Y'_\beta\beta + Y'_r r' + Y'_{\beta\beta}\beta|\beta| + Y'_{rr}r'|r'| + (Y'_{\beta\beta r}\beta + Y'_{\beta rr}r')\beta r')\\
N_H &= \frac{1}{2}\rho LdU^2 N'_\beta\beta + N'_r r' + N'_{\beta\beta}\beta|\beta| + N'_{rr}r'|r'| + (N'_{\beta\beta r}\beta + N'_{\beta rr}r')\beta r')
\end{aligned}
\qquad (2)
$$

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'_{uu}, $X'_{\beta r}$, Y'_{β}, Y'_{r}, $Y'_{\beta\beta}$, Y'_{rr}, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, N'_{β}, N'_{r}, $N'_{\beta\beta}$, N'_{rr}, $N'_{\beta\beta r}$, and $N'_{\beta rr}$ are called the hydodynamic derivatives.

The mathematical model of forces and moment induced by propeller and rudder (X_P, Y_P, N_P and X_R, Y_R, N_R) can be referred in Khanfir, et al. [8] and Dash, et al, [9].

3. Empirical Equation

3.1. Added Mass and Moment of Inertia

Added masses (m'_x and m'_y) and added moment of inertia (J'_Z) are predicted based on the equation developed by Sandakane, et al. [10]. The equation is obtained empirically from the simplified equation of ratio of the added mass and the moment of inertia in shallow water. The equation is represented as Equation 3.

$$\frac{m'_x}{m'_{x0}}, \frac{m'_y}{m'_{y0}}, \frac{J'_{zz}}{J'_{zz0}} = 1 + \alpha \left\{ \exp^{(\beta)*d/H)} - 1 \right\} \tag{3}$$

Where α and β are coefficient changes according to the ship motion mode and ship form coefficients such as draft-breadth ratio and the block coefficient.

3.2. Hydrodynamic Coefficient

The set of hydrodynamic coefficients is determined based on the equations developed by Kijima, et al. [7]. The equation is obtained semi empirically from a numerical calculation based on lifting surface theory and model tests in full load condition. In shallow water conditions, the coefficient can be obtained by multiplying a correction factor with a coefficient in deep water conditions. The equation is represented as Equation 4.

$$D_{shw} = f(h) D_{dep} \tag{4}$$

Where, D_{shw} is the derivatives in shallow water, D_{dep} is the derivatives in deep water, and $f(h)$ is the correcting factor, $h=d/H$ (d is draught, H is water deep). The correcting factor, $f(h)$ for hydrodynamic coefficient can be predicted by Equation 5 (for Y'_{β}, $Y'_{\beta\beta}$, $Y'_{\beta rr}$, N'_{β}, and N'_{r}) and Equation 6 (for $Y'_{r}-(m'+m'_{x})$, Y'_{rr}, $Y'_{\beta\beta r}$, $N'_{\beta\beta}$, N'_{rr}, $N'_{\beta\beta r}$, and $N'_{\beta rr}$,).

$$f(h) = \left[1/(1-h)^n)\right] - h \tag{5}$$

$$f(h) = 1 + a_1 h + a_2 h^2 + a_3 h^3 \tag{6}$$

Where, n, a_1, a_2, and a_3 are the coefficient of the correcting factor. The resistance and propulsion parameters for simulation are predicted by Holtrop Method [11] and [12]. In shallow water conditions, the resistance coefficient of shallow water $(R'_0)_{shallow}$ is predicted by Equation 7[13].

$$\frac{(R'_0)_{shw}}{(R'_0)_{dep}} = 0.388(T/H)^2 + 1 \tag{7}$$

Where, (R'_0) *deep* is the resistance coefficients in deep water, T is draught and H is water deep.

4. Simulation Program

4.1. Time Domain Simulation

The prediction of ship manoeuvrability can be analysed through the swept paths [14]. The analysis has been carried out using the time domain simulation program of MATLAB-Simulink [15] and [16]. The swept paths of the ship can be obtained by double integrating the acceleration of manoeuvring ship motion mathematical models including hydrodynamic derivatives as the integration process of the 3-DOF equation of motion (surge sway and yaw) in Equation 8, 9 and 10.

$$(m+m_x)\dot{u}-(m+m_y)rv = X_H + X_P\begin{Bmatrix}S\\P\end{Bmatrix} + X_R\begin{Bmatrix}S\\P\end{Bmatrix}$$

$$\dot{u} = X_H + X_P\begin{Bmatrix}S\\P\end{Bmatrix} + X_R\begin{Bmatrix}S\\P\end{Bmatrix} + (m+m_y)rv/(m+m_x) \tag{8}$$

$$u = \int \dot{u}\ dt; x = \int u\ dt$$

$$(m+m_y)\dot{v}+(m+m_x)ru = X_H + X_P\begin{Bmatrix}S\\P\end{Bmatrix} + X_R\begin{Bmatrix}S\\P\end{Bmatrix}$$

$$\dot{v} = X_H + X_P\begin{Bmatrix}S\\P\end{Bmatrix} + X_R\begin{Bmatrix}S\\P\end{Bmatrix} + (m+m_y)ru/(m+m_x) \tag{9}$$

$$v = \int \dot{v}\ dt; y = \int \dot{v}\ dt$$

$$(I_{zz}+J_{zz})\dot{r} = X_H + X_P\begin{Bmatrix}S\\P\end{Bmatrix} + X_R\begin{Bmatrix}S\\P\end{Bmatrix}$$

$$\dot{r} = (X_H + X_P\begin{Bmatrix}S\\P\end{Bmatrix} + X_R\begin{Bmatrix}S\\P\end{Bmatrix})/(I_{zz}+J_{zz}) \tag{10}$$

$$r = \int \dot{r}\ dt; \psi = \int r\ dt$$

4.2. Simulation Data

The object of the study is the ferry ship of KMP Bontoharu, owned by PT. (Persero) ASDP Indonesia Ferry. Ship with a capacity of 1050 GT with a length of 54.00 m (*LOA*) is operated at the Bira-Pamatata crossing in South Sulawesi Province. The ship particulars are presented in Table 1.

Table 1. Ship particulars.

Parameter	Value
Length over all (*LOA*), m	54.00
Length between perpendiculars (*Lbp*),m	47.45
Breadth (*B*), m	14
Depth (*D*), m	3.4
Draft (*T*),m	2.45
Ship speed (*V*), m/s^2	6.618
Displacement (*Δ*), Ton	1148
Propeller blade number (*Z*)	2 x 4
Propeller diameter (D_P), m	1.422
Pitch-diameter ratio (*P/D*), m	1.066
Propeller number of revolutions per second(*n*), rps	8.784
Span of rudder, m	1.550
Chord of rudder, m	0.900
Blade area of rudder (A_R), m^2	2 x 1.395
Power of main engine(*BHP*), HP	2 x 1000
Main Engine number of revolutions per minute (*RPM*)	1850

5. Results and Discussion

This study focuses on the manoeuvring prediction of a ferry ship in deep and shallow water conditions. A time domain simulation program by MATLAB Simulink was developed for this purpose. Several parameters such as the initial speed of the ship and water depth level have been considered in the simulation. The information is critical in ship navigation safety, particularly when ship operating in shallow water. Figure 2 shows the simulation results for the 35^0 starboard turn manoeuvring of a KMP Bontoharu in shallow water (*h/T*=1.3), medium shallow water (*h/T*=2.0) and deep water (*h/T*=4.0) at the initial speed of the ship (*U*) 6,618 m/s. It was found that the tactical diameter (D_T) of the ferry ship for shallow water was 10.9 % and 53.1 % larger than that for medium shallow water and deep water respectively. Figure 2 also shows the effect of depths water conditions (h/T=1.3) on the increase in the forward speed of the ship (u) and the turning speed (deg/s) during the ship turning manoeuvring. This trend is similar to the findings of Skejic, et al. [5] Which confirming the characteristics of ship manoeuvring in shallow and deep water.

Figure 3 shows the simulation results of the $20^0/20^0$ zig-zag manoeuvring of a KMP Bontoharu at three different water depth conditions (shallow, medium shallow and deep waters). The horizontal and vertical axes express time and heading angle (ψ) respectively. It shows that the ship manoeuvres' heading angle in shallow water has a smaller overshoot angle compared to the ship manoeuvres in medium shallow and deep water. A ship zigzag manoeuvres in shallow water (h/T=1.3), took 65.7 seconds for the 1st overshoot with the heading angles of 3.35^0. These result were faster in 4.0 and 7.9 seconds and heading angles of 6.84^0 and 8.24^0 than in medium shallow and deep water respectively. This result is similar to the findings of Maimun et al. [15], which confirms the characteristics of pusher barge manoeuvring in shallow and deep water. Table 2 and 3 indicates the summary of simulation results of ship turning circle and zigzag manoeuvres in two different water depths.

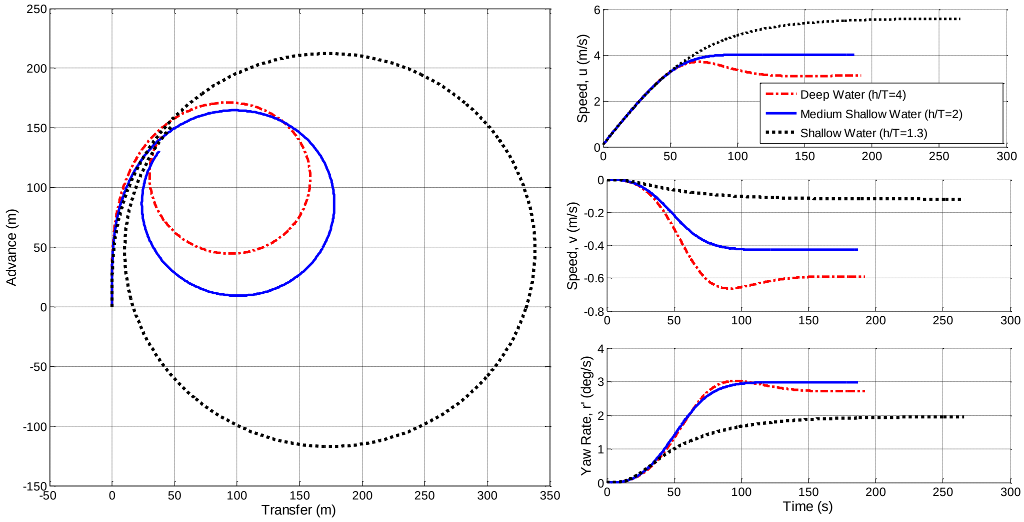

Figure 2. Turning circles in shallow and deep water at initial speed (U) 6.618 m/s.

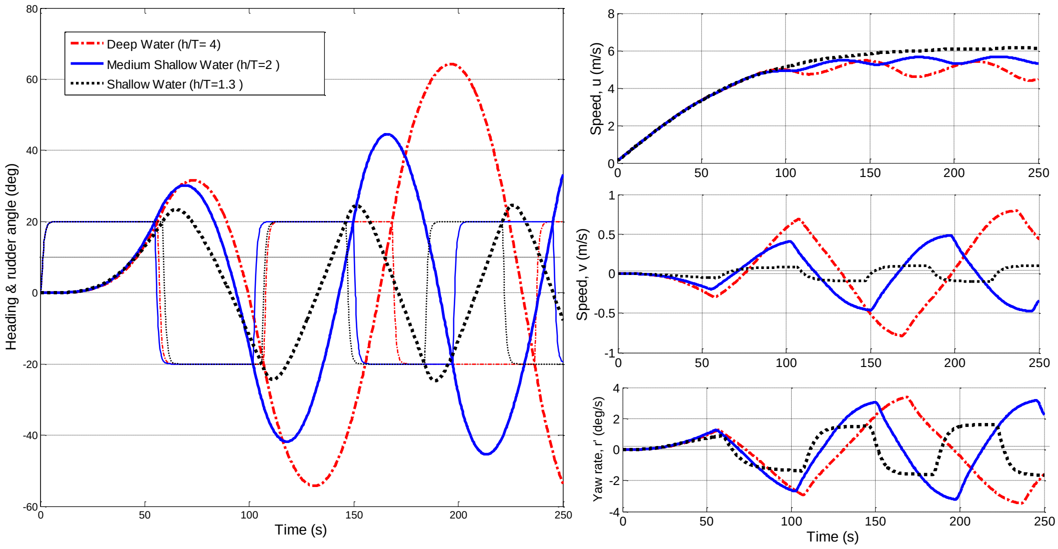

Figure 3. Zig-zag $20^0/20^0$ manoeuvres in shallow and deep water at initial speed (U) 6.618 m/s.

Table 2. Turning circle characteristics in shallow and deep water.

No.	Simulation type	δ (deg.)	Vs (m/s)	D_T (m)	A_D (m)	u (m/s)	v (m/s)	r (deg./s)
1	Turning circle (h/T = 4.0)	35	6.618	158.4	171.2	3.10	-0.59	2.72
2	Turning circle (h/T = 2.0)	35	6.618	177.8	164.6	4.00	-0.43	2.98
3	Turning circle (h/T = 1.3)	35	6.618	338.3	212.3	5.88	-0.12	1.95

Table 3. Zig-zag manoeuvres characteristics in shallow and deep water.

No.	Simulation type	δ (deg.)	Vs (m/s)	1st (deg.)	Time (s)	2nd (deg.)	Time (s)	u (m/s)
1	Zig-zag manoeuvre (h/T = 4.0)	20/20	6.618	11.59	73.6	-34.2	131.5	5.41
2	Zig-zag manoeuvre (h/T =2.0)	20/20	6.618	10.19	69.7	-21.8	118.3	5.68
3	Zig-zag manoeuvre (h/T =1.3)	20/20	6.618	3.35	65.7	-4.34	111.6	6.13

6. Conclusions

Prediction of ferry ship Indonesian manoeuvring in shallow water through a time domain simulation program has been analyzed. The numerical simulation results show that the tactical diameter (D_T) of the ferry in shallow waters was 53.1% greater than the tactical diameter in deep water, while the forward speed (U) and turning rate (deg./s) of the ship have increased when the ship is manoeuvring in shallow water. On the other hand, in a zigzag maneuver of 20/20 degrees, the ship heading angle in shallow water has a smaller overshoot angle than ship maneuvering in deep water. So that through reducing the initial speed of the ship when entering shallow water it can improve ship safety,

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