MANEUVERING PERFORMANCE OF A FERRY AFFECTED
BY RUDDER AREA AND SPEED

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SUMMARY

The aim of the study is to determine the effect of rudder area and speed on a ferry ship maneuvering performance, especially during the turning circle and zigzag maneuver. MATLAB-simulink was used to simulate turning circle and zigzag maneuver. The simulation utilized model based on the concept of Mathematical Modelling Group (MMG) includes testing/separating components of the hull equations, propeller and rudder as well as the interaction among them (hull, propeller and rudder). The result of simulation indicated that rudder dimension and ship speed affect both turning circle and zigzag maneuver of the ferry reasonably.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ</td>
<td>Roll angle</td>
</tr>
<tr>
<td>ρ</td>
<td>Density of water</td>
</tr>
<tr>
<td>β</td>
<td>Drift angle</td>
</tr>
<tr>
<td>δ</td>
<td>Rudder angle</td>
</tr>
<tr>
<td>ψ</td>
<td>Course angle or heading</td>
</tr>
<tr>
<td>Α</td>
<td>Rudder aspect ratio</td>
</tr>
<tr>
<td>ε</td>
<td>Phase angle</td>
</tr>
<tr>
<td>αH</td>
<td>Rudder to hull interaction coefficient</td>
</tr>
<tr>
<td>Adp</td>
<td>Advances diameter</td>
</tr>
<tr>
<td>Ar</td>
<td>Rudder area</td>
</tr>
<tr>
<td>B</td>
<td>Ship breadth</td>
</tr>
<tr>
<td>Bm</td>
<td>Added inertia of roll motion</td>
</tr>
<tr>
<td>Cp</td>
<td>Constants for open water propeller</td>
</tr>
<tr>
<td>CB (Cb)</td>
<td>Block coefficient</td>
</tr>
<tr>
<td>Dp</td>
<td>Propeller diameter</td>
</tr>
<tr>
<td>DT</td>
<td>Tactical diameter</td>
</tr>
<tr>
<td>fỵ</td>
<td>Gradient of the lift coefficient of rudder</td>
</tr>
<tr>
<td>Fg</td>
<td>Normal force acting on rudder</td>
</tr>
<tr>
<td>G</td>
<td>Center of gravity of vessel</td>
</tr>
<tr>
<td>lzz</td>
<td>Moment of inertia with respect to the z-axis</td>
</tr>
<tr>
<td>j</td>
<td>Advance coefficient</td>
</tr>
<tr>
<td>Jz</td>
<td>Added moment of inertia around z-axis</td>
</tr>
<tr>
<td>k</td>
<td>Moment with respect to the x-axis</td>
</tr>
<tr>
<td>kQ</td>
<td>Torque coefficient</td>
</tr>
<tr>
<td>kR</td>
<td>Moment of rudder</td>
</tr>
<tr>
<td>Kn</td>
<td>Thrust coefficient</td>
</tr>
<tr>
<td>Loa</td>
<td>Ship length overall</td>
</tr>
<tr>
<td>Lbp</td>
<td>Length of between perpendiculars</td>
</tr>
<tr>
<td>m</td>
<td>Mass of ship</td>
</tr>
<tr>
<td>n (rpm)</td>
<td>Propeller revolution</td>
</tr>
<tr>
<td>Vz</td>
<td>Advance velocity (m/s⁻¹)</td>
</tr>
<tr>
<td>P</td>
<td>Propeller pitch</td>
</tr>
<tr>
<td>P/dp</td>
<td>Propeller pitch ratio</td>
</tr>
<tr>
<td>tP</td>
<td>Thrust deduction factor</td>
</tr>
<tr>
<td>T</td>
<td>Draught of ship</td>
</tr>
<tr>
<td>r</td>
<td>Turning rate or angular velocity</td>
</tr>
<tr>
<td>r′</td>
<td>Non-dimensional turning rate</td>
</tr>
<tr>
<td>u</td>
<td>Velocity in x-direction (surge)</td>
</tr>
<tr>
<td>u</td>
<td>Acceleration in x-direction (surge)</td>
</tr>
</tbody>
</table>

1. INTRODUCTION

The number of ferry carrying trucks, bus, car, motor cycle, passenger etc., is increasing in Indonesia. The operation could improve national economic growth. In ferry building, from design to delivery, several tests must be conducted, particularly the operation ability.

Maneuvering characteristics are very important criteria to make sure that the ferry can operate in certain situation and location. Maneuverability is very critical aspect especially in harbour and offshore such as tow and tug to avoiding collision. Noor [1] suggested that maneuverability is an important characteristic that must be predicted during the early design of ship. The
Simulation of ship maneuvering has now progressed quite well and is very useful in designing the ship [2].

Ship maneuverability is also directly related to navigation safety and economy. In some restricted waters, marine accidents can occur if the ability to maneuver the ship is not adequate. On the other hand, the dynamic stability of ships with poor course could only maintain its position by using a control device as often as possible. The consequences for a ship like this is not just a voyage being longer than planned, but also more energy is consumed by the control device [3].

Many accidents are caused by a ship with low maneuvering quality [4].

Ship designer need to consider the existing rules, both nationally and internationally. In 2002, the International Maritime Organization (IMO) [5] issued a Resolution MSC.137 (76) "Standards for Ship Maneuverability", to develop safety standards and to ensure the safety of cruise ship operating at sea.

In principle, maneuverability is greatly influenced by hull design, propulsion, rudder and steering system. A number of these elements are in a direct significantly influence the hydrodynamic force and moment when ship maneuvers [6].

2. METHODOLOGY
2.1 Mathematical Model

In analyzing the ship maneuvering through computer simulation, mathematical model is important to be developed including hydrodynamic coefficients derived here. In this study, a mathematical model based on the equations of motion, Eq. 1 of ship developed (4-degrees of freedom) the surge, sway, yaw and roll motions.

The mathematical model for maneuvering motion can be described by Eq. 1 using the ship coordinate system, Fig.1.

\[
\begin{align*}
X &= m(u - v) \\
Y &= m(\dot{v} - ru) \\
N &= I_{zz}\dot{\psi} \\
K &= I_{xx}\ddot{p}
\end{align*}
\]

The notation of \(u\), \(v\) and \(r\) are velocity components at centre of gravity of ship (C.G). \(U\) represents resultant of the ship speed. \(X\), \(Y\), \(N\) and \(K\) represent the hydrodynamic forces and moment acting on the C.G. of the hull. These forces and moments can be defined separately into the different elements of physical force and moment of the ship in accordance with the concept developed by Ogawa and Kansai [7] as follows:

\[
\begin{align*}
X &= X_H + X_p + X_R \\
Y &= Y_H + Y_p + Y_R \\
N &= N_H + N_p + N_R \\
K &= K_H + K_p + K_R
\end{align*}
\]

Where, the subscript \(H\), \(P\) and \(R\) refer to hull, propeller and rudder respectively. Force and moment induced by hull \((X_H, Y_H, N_H)\) in principle is an approximation of polynomial regression \(\beta\) and \(r\). Furthermore the coefficients of these equation can be termed as derivative of the hydrodynamic coefficients. The equation can be expressed by Eq 3:

\[
\begin{align*}
X_H &= \frac{1}{\rho}\rho dU (X'_H + \rho g \beta' + (X'_{m_H} - m'_H)\beta + X''_H \beta^2) \\
Y_H &= \frac{1}{\rho}D_{f}\rho dU (Y'_H + (Y'_m - m'_H)\beta' + Y''_H \beta^2 + Y''_{s_H} \beta^2) \\
N_H &= \frac{1}{\rho}D_{f}\rho dU (N'_H + (N'_m - m'_H)\beta' + N''_H \beta^2 + N''_{s_H} \beta^2) \\
K_H &= \frac{1}{\rho}D_{f}\rho dU (K'_H + (K'_m - m'_H)\beta' + K''_H \beta^2 + K''_{s_H} \beta^2)
\end{align*}
\]

where:
\[
\beta = \tan^{-1}(v/u) \quad \text{and} \quad r' = r(U/L)
\]

and heeling moment equation expressed by Eq 4:

\[
K_H = -z_{hi}Y_H - B_{hi}\phi - C_{hi}\phi
\]

where:
\[
z_{hi} = OG - h \\
C_{hi} = \frac{gM}{M}
\]

\[
B_{hi} = \frac{2}{\pi} \sqrt{gM}(I_{xx} + J_{xx})
\]

According to Kijima [8], equation force and moment induced by propeller and rudder can be expressed by the eq. 5:

\[
\begin{align*}
X_p &= (1 - t_p)\rho K_p \psi \cdot n^2 \\
Y_p &= 0; \quad N_p = 0; \quad K_p = 0
\end{align*}
\]

where:
Force and moment on rudder area \((X_R, Y_R, N_R\text{ and } K_R)\) can be expressed by Eq. 6:

\[
X_R = -2(l - t_R)F_n \sin \delta
\]

\[
Y_R = -2(1 + a_{hi})F_n \cos \delta
\]

\[
N_R = -(x_R + a_{h}y_R)F_n \cos \delta
\]

\[
K_R = -\gamma_R Y_R
\]

where:

\[
F_n = \frac{1}{2} \rho A_n f_n U^2 \sin \alpha_R
\]

\[
f_n = 6.13 \Lambda (2.25 + \Lambda)
\]

\[
U_x = \sqrt{u_x^2 + v_x^2}
\]

\[
\alpha_x = \delta - \tan^{-1}\left(\frac{v_x}{u_x}\right)
\]

\[
u_x = \varepsilon (1 - w) u
\]

\[
\times \sqrt{\frac{1 + K_x (1 + (8 K_x / \pi J^2) - 1)) + (1 - \eta)}{1}}
\]

\[
\gamma_R = \gamma_R (v - r l_R)
\]

2.2 Programming and Simulation

According to IMO standard, the assessment of the ship maneuvering is analyzed based on swept path. There are two methods for this purpose. Firstly, free running model test. Secondly, computer simulation using mathematical model. Here, the investigation has been carry out using time domain simulation program based on MATLAB-Simulink. The swept path of ship can be obtained by double integrating the acceleration of the ship in surge, sway, yaw and roll axis of mathematical model that include the hydrodynamic derivatives [6]. The step integration can be expressed:

\[
\text{Surge : } X = m(\ddot{u} - rv)
\]

\[
\text{ Acceleration : } \dot{u} = (X + m) + rv
\]

\[
\text{Velocity : } u = \int \dot{u} dt
\]

\[
\text{Position : } x = \int u dt
\]

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

2.3 Ship Operation Scenario

To determine the effect of rudder area and speed variations on a ferry ship maneuvering performance, the scenario role in the operation of ships are: 1) The vessel is operated with variation in rudder area \((A_R = 1.632 \text{ m}^2, A_R = 1.819 \text{ m}^2 \text{ and } A_R = 2.078 \text{ m}^2)\). 2) The vessel is operated with variation of speed \((V = 2 \text{ knots, 6 knots and } V = 10.5 \text{ knots})\).

Tables 1, 2 and 3 show the ship particulars, parameters of the propeller and rudder, hydrodynamic derivatives coefficient of KMP Sultan Murhum respectively. In support maneuver, ship was equipped with two conventional propulsors (FPP) and 2 conventional rudders, mounted behind the ship. A number of parameters in the prediction of propulsion using Holtrop method [9][10]. Rudder area parameters obtained from field data, \(A_R = 2.078 \text{ m}^2 \) (original) and \(A_R = 1.632 \text{ and } 1.819 \text{ m}^2 \) (modified). Further hydrodynamic coefficients predicted by the derived regression equation developed by Yoshimura and Ning [11] and Yoshimura [12].
3. RESULT AND DISCUSSION

3.1 Effect of Rudder Area Variations.

Fig 2 shows the result of the simulation for turning circle on ship operated. The tactical diameters ($D_T$) and advances ($A_D$) maneuver of the ship were calculated. It is found that the tactical diameter of the vessel for rudder area of $2.078 \, m^2$ at a speed of 10.5 knot with a full draught 1.65 m is 73 m, 2.42 times the vessel length, of 31.5 m. This tactical diameter meets the required IMO criterion of not more than five times the ship length. The advance is 65.7 m or 2.1 times the vessel length. This value is also within the IMO criterion of 4.5 times ship length.

Fig. 2 shows the comparison of the turning circle of the two rudder area modified ($A_R = 1.819 \, m^2$ and $1.632 \, m^2$). It shows that the tactical diameter increased are 2.09% for $A_R = 1.819 \, m^2$ dan 3.66 % for $A_R = 1.632 \, m^2$ compared with original rudder area ($A_R = 2.078 \, m^2$). Fig. 3 shows the history of the heel angle during turning circle maneuvering. It is shows that the heel angle reduced diminishes as rudder area reduces. At the rudder area of $2.078 \, m^2$, which heel angle is $3.21^\circ$ while $3.15^\circ$ and $3.10^\circ$ at rudder area of $A_R = 1.819 \, m^2$ and $1.632 \, m^2$ respectively. This value is also within the IMO criterion ($<10^\circ$). It is found that the rudder area dimension has effect on the maneuvering performances of a ferry ship.

Fig. 4 show the result of the simulation for the zigzag maneuver 20/20 of the ship was simulated. The horizontal and vertical axes respectively express time and heading angle ($\psi$). It shows that the heading angle of original of rudder area dimension ($A_R = 2.078 \, m^2$) has the bigger overshoot angle as compared to the modified rudder area ($A_R = 1.819 \, m^2$ and $1.632 \, m^2$). At rudder area $2.078 \, m^2$, which takes time 5.5 second for $1^{st}$ overshoot and 14 seconds fasten for $2^{nd}$ overshoot with the heading angle of $1.5^\circ$ and $3.5^\circ$ respectively. It shows that the time used and heading angle reduced diminishes as rudder area reduces. Results can be seen in Table 4.

Table 4. Summary of simulation result of turning circle and zigzag maneuver with rudder area. The large the rudder area the greather the steering force produced, in line with smaller tactical and advance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IMO Criteria</th>
<th>Rudder Area ($A_R$), $m^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_T$, m</td>
<td>$&lt; 5 , L$</td>
<td>76.3 77.9 79.1</td>
</tr>
<tr>
<td>$A_D$, m</td>
<td>$&lt; 4.5 , L$</td>
<td>70.5 67.5 65.5</td>
</tr>
<tr>
<td>$\theta$, rad</td>
<td>$&lt;10^\circ$</td>
<td>0.7 1.1 1.4 1.1 1.4 1.4 1.2</td>
</tr>
<tr>
<td>1$^{st}$ overshoot, $\psi$, deg.</td>
<td>$&lt; 25^\circ$</td>
<td>1.5 1.4 1.2</td>
</tr>
<tr>
<td>1$^{st}$ overshoot, s, second</td>
<td>5.5 5.9 6.3</td>
<td></td>
</tr>
<tr>
<td>2$^{nd}$ overshoot, $\psi$, deg.</td>
<td>$&lt; 40^\circ$</td>
<td>3.5 3.6 2.6</td>
</tr>
<tr>
<td>2$^{nd}$ overshoot, s, second</td>
<td>14 15.7 16.5</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Effect of Speed Variations.

Fig 5 shows the comparison result of the simulation for turning circle with speed variations, namely $V = 2$ knots, $V = 6$ knots, and $V = 10.5$ knots respectively with draught of 1.65 m and rudder area of $2.078 \, m^2$. It shows that the tactical diameter and advanced reduced diminishes as speed reduces. Tactical diameter and advanced increased are 7.3 and 19.98% at $V=2$ knots dan 1.96 and 7.77% at $V = 6$ knots compared with full speed ($V = 10.5$ knots). Fig. 6 shows the history of the heel angle during turning circle maneuvering. It shows that the heel angle reduced diminishes as speed reduces. At $V= 10.5$ knots, heel angle is $3.21^\circ$ while $3.15^\circ$ and $3.10^\circ$ at $V = 6$ and 2 knots respectively. This value is also fulfill the IMO criterion ($<10^\circ$). It is found that the ship speed has effect on the
maneuvering performances of the ferry, proportionally.

Fig. 7 shows that the comparison results of the simulation for the zigzag maneuver 20/20 with speed of ship. The horizontal and vertical axes respectively express time and heading angle ($\psi$). It shows that the heading angle of full speed ($V=10.5$ knots) has the bigger overshoot angle compared with the other speeds ($V=6$ and $V=2$ knots). At $V= 10.5$ knots, it takes 5.5 second for 1st overshoot and 14 seconds faster for 2nd overshoot with the heading angle of 1.5$^\circ$ and 3.5$^\circ$. It shows that the time used and heading angle find reduced diminishes as rudder area reduces. Results can be seen in Table 5. The higher the speed the greater the force by propeller. This is in line with bigger tactical diameter and advance.

Table 5. Summary of simulation result of turning circle and zigzag maneuver at three different speeds.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IMO Criteria</th>
<th>Speed (knot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_T$, m</td>
<td>$&lt; 5, L$</td>
<td>10.5, 6, 2</td>
</tr>
<tr>
<td>$A_D$, m</td>
<td>$&lt; 4.5, L$</td>
<td>76.3, 74.8, 70.7</td>
</tr>
<tr>
<td>$\Theta$, rad</td>
<td>$&lt;10^\circ$</td>
<td>3.2, 3.2, 1.1</td>
</tr>
<tr>
<td>1st Overshoot, $\psi$, deg.</td>
<td>$&lt; 25^\circ$</td>
<td>1.2, 1.2, 1.0</td>
</tr>
<tr>
<td>1st Overshoot, s, second</td>
<td>5.5, 7.4, 14</td>
<td></td>
</tr>
<tr>
<td>2nd Overshoot, $\psi$, deg.</td>
<td>$&lt; 40^\circ$</td>
<td>2.6, 2.3, 1.6</td>
</tr>
<tr>
<td>2nd Overshoot, s, second</td>
<td>14, 19.8, 45.1</td>
<td></td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

Based on the analysis, during turning circle and zigzag maneuver the following conclusions have been made:

1. The larger the rudder area the greater the steering force produced.
2. The faster the ship the greater the force induced by propeller.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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