Improvement of Turning Performance by Cyclic Control of Motor-driven Waterjet Propulsion System

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This study was aimed at improving the turning performance of an electric ship with a waterjet propulsion system under low load operation by applying cyclic control of motor output. The required patterns of the cyclic control, including duty ratio and waterjet frequency, for the improvement of the turning performance were estimated by predicting the thrust power of the waterjet during cyclic control. The effectiveness of the cyclic control was also evaluated through turning performance tests using an electric boat “Raicho-S”. By analyzing the average thrust power of the waterjet, based on predicted motor revolution during cyclic control, it was confirmed that the contribution of cyclic control was more enhanced at waterjet frequencies ranging from 0.8 to 2.0 s⁻¹ and at duty ratios ranging from 0.33 to 0.6. These estimated patterns of cyclic control were included in the turning performance test conditions of “Raicho-S”. Improvement of the turning performance, including an increase in turning speed and a decrease in turning radius, was confirmed. The increasing and decreasing tendencies of turning speed in relation to the jet frequency and the duty ratio were in qualitative agreement with those of thrust power predicted in the preliminary analysis. The turning performance during cyclic control was confirmed to be optimized at the condition in which the jet frequency and the duty ratio were respectively 1 s⁻¹ and 0.33 in the present test conditions.

1. Introduction

Waterjet propulsion system has lower risk of cavitation compared to propeller propulsion and is suitable for sailing at high speed. [1] Therefore, the small size waterjet propulsion units generally use gasoline engines, and large waterjet propulsion units use gas turbine engines and high-speed diesel engines as its power source. Waterjet propulsion is adopted in water motorcycles for leisure, high-speed vessels and patrol boats. However, for both waterjet propulsion and general propeller propulsion, thrust maneuverability significantly decreases under the condition of low-speed navigation. [2] Also, when low-speed navigating with the current internal combustion engine driving of the waterjet propulsion system, it is inefficient to suppress forward thrust by changing the vertical direction of injection jets while maintaining the minimum rotational speed of the internal combustion engine. On the other hand, development, construction and research of the electric propulsion vessels [3] [4] have been based on quiescence and low vibration of the ship, and improvement of the propulsive efficiency. The current electric propulsion ship is generated by the generator driven diesel engines and drives the traction motor.

Propeller speed control of the electric propulsion boats (i.e. motor speed control) is usually controlled by the inverter with a high control accuracy. It has three advantages: high follow ability for rapid acceleration/deceleration instruction, stable control and reliability of the operating system from the over speed control and smooth boat speed control.

The authors’ research group conducted research and development aimed at practical application of battery-powered boat to a power source of the rapid charge corresponding type secondary battery.

In 2011, they developed the motor-driven waterjet battery-powered boat "Raicho-S" [5] [6]. The battery-powered boat is different from the electric propulsion vessels and are equipped with a secondary battery instead of a power generation equipment on board. "Raicho-S" is mainly developed for application by the fishing industry. It is a small vessel, 8m long with a capacity of 8 people, permanent magnet synchronous with a rated output of 45kW motor and 26.6kW/h lithium-ion battery. Battery-powered boats have high load following capability, high precision and degree-of-freedom control, rather than the current power supplied electric propulsion vessels. The authors have carried out various studies concerning the improvement of the maneuvering performance utilizing sophisticated speed controls of the electric boat [7], in which, they have confirmed that steering response of the low-speed cruising increases when giving a cyclic torque command to the motor inverter instantaneously to increase the jet speed. [8]
The purpose of this paper is to evaluate the cyclic control pattern for the motor cyclic control waterjet propulsion system intended for improving the maneuverability at low-speed navigation due to the cyclic control of the waterjet installed on the "Raicho-S". In addition, the authors quantitatively evaluates the effectiveness of the motor cyclic controlled by the turning performance test of the actual ship.

2. Prediction of Thrust by the Motor Cyclic Control

This study is intended to improve the maneuverability of the thrust at low-speed by providing a cyclic torque instruction to the inverter-motor for driving the waterjet propulsion units. Thrust $F$ of the waterjet are represented by the law of momentum as in the following formula.

$$F = \rho Q_j v_j = \rho A_j v_j^2$$  \hspace{1cm} (1)

Respectively, $\rho$, $Q_j$, $v_j$ and $A_j$ are fluid density, injection flow, and injection flow rate and injection port area. Injection flow rate is proportional with the motor rotational speed, thus thrust $F$ is the proportional to the square of the impeller rotational speed $N$ ($F \propto N^2$). Therefore, when torque command value $T_m$ are the same, it is possible to obtain high thrust compared to the continuous output even at the time of low-speed cruising when maintaining a high instantaneous jetting speed. The inverter mounted on "Raicho-S" is operated by the torque control. Figure 1 above illustrates a torque command signal to the inverter with the cyclic control. Respectively, $\Delta t$, $t_C$, $T_S$ and $T_m$ shown in Fig.1 are torque command time in the cyclic control, torque command value and the average torque command value when the torque command cyclic torque is rated 100%.

In this study, duty ratio $D = \Delta t / t_C$ is represented by a ratio of $\Delta t$ and $t_C$ and evaluates the turning performance at the time of changing the waterjet of the jetting frequency $f_J = 1 / t_C$.

Torque command value is expressed as $T_S = T_m / D$. Therefore, if the average torque command value $T_m$ are equal, $T_S$ can be set high by subtracting $D$. The bottom graph of Fig.1 shows the time variation of the motor rotational speed for the cyclic control at the time of the torque command value (above). As shown, the torque command that is inputted as a rectangular ON-OFF signal to the inverter has motor rotational speed $N_{on}(t)$ of the ($t_0$ to $t_1$) while the ON signal being inputted has delayed responses when reaching a steady rotational speed $N_S$ of the set torque. On the other hand, the motor rotational speed $N_{off}(t)$ of the ($t_1 \rightarrow t_2$) gradually reduces trend over time by the inertia of the motor. Thus, the change in the motor rotational speed with respect to the torque command of the ON-OFF does not become rectangular and has a delayed response. The cyclic control that

![Fig. 1 Torque command and motor revolution](image)
contributes to the thrust is dependent on the setting of $D$ and $f_j$. For this study, the battery system, motor inverter system and waterjet propulsion system of the "Raicho-S" are used to predict the thrust from the motor rotation speed at the time of cyclic control and to evaluate the cyclic control's effective range $D$ and $f_j$. The time variation of the motor rotation speed for the ON-OFF command torque are respectively shown as follows.

$$N_{ON}(t) \cong (N_S - N_{t0}) \left[ 1 - \exp\{C_{R,ON}(t - t_0)\} \right] + N_{t0}$$

$$N_{OFF}(t) \cong N_S \exp\{C_{R,OFF}(t - t_1)\} - (N_S - N_{t1})$$

$C_{R,ON}$ and $C_{R,OFF}$ is a coefficient that is determined based on the measurement of the values of motor rotational speed in the real seawater operational test of "Raicho-S". For this study, torque command to the motor rotational speed that goes up to steady-state rotational speed $N_S$ from a stopped state and measured value of the motor rotational speed after given an OFF torque command from a steady state was used to obtain the following equations from $C_{R,ON}$ and $C_{R,OFF}$ of the least square method.

$$C_{R,ON} = -2.96 \times 10^{-4} N_S^{1.22}$$

$$C_{R,OFF} = -0.163 N_S^{0.310}$$

The relationship of the constant rotational speed $N_S$ in respect to the torque command value $T_S$ of the "Raicho-S" is given by the following equation.

$$N_S = 480 \times T_S^{0.5}$$

Figure 2 is the comparison between the measured value of the motor rotational speed at the time of cyclic control and predicted values from formula (2) and (3). The predicted values are almost identical to the measured values. The average relative error of both the duty ratio of 0.33 - 1 and injection frequency 0.66 - 2.5 s$^{-1}$ was 8.2%. Then, the thrust of the waterjet from the motor rotation speed was predicted. As described above, the thrust $F$ of the waterjet is approximated by the following equation since it is proportional to the square of the motor rotation speed $N$.

$$F \cong \kappa N^2$$

$\kappa$ is the coefficient given based on the measured values of the motor speed and thrust. Connecting the steel rods that has rated capacity of 5000N (accuracy 0.04%) and general purpose load cell (A&D Company, Ltd. LC1122-K500) between the "Raicho-S" and the quay to organize the motor speed and the thrust relationship in the steady state.(Fig.3). Coefficient $\kappa$ of the least square method is estimated to $1.89 \times 10^{-4}$. The average relative error of the predicted and measured values of the thrust was 7.6% of the control range of "Raicho-S" by equation (7).
Time variation of the thrust at torque command OFF using the coefficient $\kappa$ described above is approximately described by the following equation.

$$F_{\text{ON}}(t) \cong \kappa N_{\text{ON}}^2(t) \quad (8)$$

$$F_{\text{OFF}}(t) \cong \kappa N_{\text{OFF}}^2(t) \quad (9)$$

From one cyclic of motor rotation speed of equation (2), (3) and motor speed and thrust relationship represented by (9), the integral average value $F_{\text{Cyc}}$ of expected average thrust of the time period control is represented by the following equation.

$$F_{\text{Cyc}} \cong \frac{\int_{t_0}^{t_1} \kappa N_{\text{ON}}^2(t)dt + \int_{t_1}^{t_2} \kappa N_{\text{OFF}}^2(t)dt}{\int_{t_0}^{t_2} dt}$$

$$= \kappa \frac{N_S^2 (t_1 - t_0) + \frac{2N_S(N_S - N_{t_0})}{C_{\text{RON}}} [1 - \exp\{C_{\text{RON}}(t_1 - t_0)\}] - (N_S - N_{t_0})^2 [1 - \exp\{2C_{\text{RON}}(t_1 - t_0)\}] + \frac{N_S^2}{2C_{\text{RON}}} [\exp\{2C_{\text{RON}}(t_2 - t_1)\} - 1] - 2N_S(N_S - N_{t_1}) C_{\text{RON}} [\exp\{C_{\text{RON}}(t_2 - t_1)\} - 1] + (N_S - N_{t_1})^2 (t_2 - t_1)}{t_2 - t_0}$$

(10)

It is predicted that the thrust upon changing the duty ratio and the injection frequency by using this equation. Figure 4 and 5 are an organized result of the predicted value $F_{\text{C}}$ of average thrust at the time of continuous output $D=1$ and the ratio of the predicted value of $F_{\text{Cyc}}$ average thrust of the time period control, respectively. The torque command value $T_S$ of "Raicho-S" are set within 90% from the point of view of the motor inverter protection. Thus, duty ratio $D$ and torque command value $T_m$ restrict each other according to the relationship of $T_m = T_{in}/D$. The values shown in the figure are calculated under the condition of $T_{in}=30\%$, $D \geq 0.33(=0.5/1.5)$. From Fig. 4, the thrust ratio has the maximum value at $f_j = 0.8 - 2 \text{ s}^{-1}$ range. At the lower peak positions of the jetting frequency domain, thrust ratio increases at a large slope with respect to order jetting frequency low duty ratio, whereas, the high frequency range shows a tendency to continue to slowly decrease at a lower gradient in descending order of duty ratio. When thrust ratio in the low frequency range is reduced, OFF torque command time $\Delta t$ increases and the average number of revolution on the motor decreases. Furthermore, the thrust ratio of high frequency
decreases because average rotational speed reduces when torque command signal input of rotational speed \( N_{\text{on}}(t) \) does not sufficiently reach the \( N_s \).

Focusing on the influence of duty ratio on thrust ratio (Fig.5), the low jetting frequency condition of \( f_j \leq 1.5 \text{ s}^{-1} \) and the thrust ratio is maximum at \( D = 0.33 \), which decreases with the increasing duty. The \( f_j \geq 2.0 \text{ s}^{-1} \) has the maximum value of the thrust ratio at the \( D = 0.4 - 0.6 \) region and the peak position moves to a higher duty ratio side while reducing the thrust ratio.

From the predicted result of the thrust shown above, in the range of duty ratio \( D = 0.33 - 0.6 \) and injection frequency \( f_j = 0.8 - 2.0 \text{ s}^{-1} \), the cyclic control contributes to the improvement of the thrust. It can be expected to improve the turning performance.

3. Turning Performance Test

3.1 Experimental Method

Conducting the turning performance test of the "Raicho-S" based on the duty ratio and the injection frequency pattern to evaluate the effectiveness of the cyclic control in the improvement of the maneuvering motor-driven waterjet propulsion boat. The turning performance tests are conducted under a continuous output condition \((D=1)\) and duty ratio \( D \), the average torque command value \( T_m \) and period control of changing the jetting frequency \( f_j \). Each condition is compared to the turning radius \( R \) as well as the turning angular velocity \( \omega \). After having reached a steady boat speed in a waterjet injection angle 0 deg. of straight state, the injection angle is changed to 10 deg. The following equations are obtained from the turning radius and the turning angular velocity in the steady turning state of the second lap.

\[
\omega = \frac{dH}{dt} \tag{11}
\]

\[
R = \frac{v}{\omega} \tag{12}
\]

\( H \) and \( v \) are respectively the bow angle and the average speed during turning. These values are within the speed measurement error of 0.028 m/s, blow angle measurement error 0.1° and are measured by the sampling frequency 10 s\(^{-1}\) of GPS (Recelogic Inc. VBSS10). To reduce the error of measurement caused by the weather oceanographic conditions, the turning tests are conducted at a time of less low and high tide with wind speed of 2m or less. In addition, it is arranged so that the average values differ by 90° in four directions.
In the previous chapter, it was estimated that the contribution of cyclic control was more enhanced at waterjet frequencies ranging from 0.8 to 2.0 s\(^{-1}\) and at duty ratios ranging from 0.33 to 0.6. Based on this result, the turning performance test conditions were determined as shown in Table 1. The average torque command value \(T_m\) are the same for condition of A, B and C. The average ranges of the torque command and the duty ratio are respectively \(D = 0.33 - 1.0\) and \(T_m = 20 - 30\%\). In addition, in order to evaluate the effect of injection frequency on the turning performance, \(T_m = 30\%\) and \(D = 0.33\) of the injection frequency was changed to \(f_J = 0.67 - 2.5\) s\(^{-1}\) (A1, A4 ~ A9).

### Table 1 Test matrix

<table>
<thead>
<tr>
<th>Run #</th>
<th>Average Torque, (T_m) [%]</th>
<th>Command Torque, (T_s) [%]</th>
<th>Duty Ratio, (D) [-]</th>
<th>Jet Frequency, (f_J) [s(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>90</td>
<td>0.33</td>
<td></td>
<td>0.67</td>
</tr>
<tr>
<td>A2</td>
<td>60</td>
<td>0.50</td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>A3</td>
<td>30</td>
<td>1.00</td>
<td></td>
<td>0.83</td>
</tr>
<tr>
<td>A4</td>
<td>30</td>
<td>0.33</td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>A5</td>
<td>30</td>
<td>0.33</td>
<td></td>
<td>1.50</td>
</tr>
<tr>
<td>A6</td>
<td>30</td>
<td>0.33</td>
<td></td>
<td>2.00</td>
</tr>
<tr>
<td>A7</td>
<td>30</td>
<td>0.33</td>
<td></td>
<td>2.50</td>
</tr>
<tr>
<td>A8</td>
<td>25</td>
<td>75</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>A9</td>
<td>25</td>
<td>50</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>B1</td>
<td>25</td>
<td>25</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>B2</td>
<td>25</td>
<td>40</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>B3</td>
<td>25</td>
<td>20</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>C1</td>
<td>20</td>
<td>60</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>C2</td>
<td>20</td>
<td>40</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>C3</td>
<td>20</td>
<td>20</td>
<td>0.33</td>
<td>0.67</td>
</tr>
</tbody>
</table>

3.2 Experimental Result

Figure 6 shows the average torque command value \(T_m = 30\%\), duty ratio \(D = 0.33\), and \(f_J = 0.67\) s\(^{-1}\) injection frequency of bow angle \(H\) after the start of turning. The gradient of the bow angle can be approximated by a straight line, thus it can be seen that pivoting is carried out at a substantially constant angular velocity.

Figure 7 shows the results obtained by organizing the turning radius \(R\) with respect to the pivot in the boat speed \(v\). Plots in the figure represents the results of the duty ratio. Turning radius increases along with the increase of the turning of the boat speed. Turning radius at the time of cyclic control is smaller than the continuous output condition \((D=1)\) and the reducing effect appears more pronounced in low duty ratio. This result shows that the same average torque command value and cyclic control in ship speed area improves its turning ability.

![Fig. 6 Heading change under turning test](image1)

![Fig. 7 Turning radius](image2)
Figure 8 shows the ratio of the turning angular velocity \( \omega \) of the time period control \( \omega / \omega_0 \) at the time of continuous output for turning angular velocity \( \omega_0 \).

Plots in the figure are the result of the acquired \( f_J = 0.67 \text{ s}^{-1} \). From the figure, turn angular velocity ratio increases with decreasing duty ratio and is qualitatively consistent with the prediction result of the thrust ratio shown in Fig.5. In addition, turning angular velocity at the time of cyclic control \( D=0.33 \) can be seen that it has improved 5 to 10 percent relative to the time of continuous output.

Figure 9 shows the influence of the injection frequency on the turn angular velocity ratio. Plots in the figure are the result acquired from both \( D=0.33 \) and \( T_m=30\% \). As you can see from the graph, it has the maximum value of the slewing angular velocity ratio near the injection frequency of \( f_J = 1.0 \text{ s}^{-1} \), and it can be seen that the slewing angular velocity with respect to the continuous output is improved by 10% or more. At the lower frequency band, than this position, the turn angular velocity is increased at a relatively large gradient and tends to decrease gradually at the high frequency range. Tendency to increase and decrease at the turning angular velocity for these injection frequencies show the prediction results and qualitative match of Fig.4 of the indicated thrust ratio. Thus, it can be said that the improvement of the average thrust by the cyclic control contributed to the improvement of the cornering performance.

Cyclic control of the motor drive waterjet evaluates the control pattern that effectively improves the thrust. In addition, by implementing the performance test in real seawater for the "Raicho-S", it quantitatively showed the improvement of the turning performance of the cyclic control.

4. Conclusion

The purpose of this paper was to improve the maneuverability at low speed navigation of the cyclic control of the waterjet. The cyclic control pattern necessary for the maneuverability improvement of the predicted thrust at the time of motor cyclic control was evaluated. In addition, the efficacy of the motor cyclic controlled by the turning performance test of the actual ship evaluated. Motor cyclic control was analytically shown to effectively contribute to the improvement of the average thrust in the range of ejection frequency \( f_J = 0.8 - 2.0 \text{ s}^{-1} \) and duty ratio \( D = 0.33 - 0.6 \) that was predicted from the average thrust of the motor rotation speed at the time of the cyclic control.

Result of the turning performance tests during motor cyclic control, including those of the cyclic control patterns, was confirmed that the slewing angular velocity increased at continuous output and the turning radius decreased. The duty ratio and injection frequency tendency of the turning angular velocity to increase and decrease showed the results that it matched the predicted thrust ratio of the motor rotation speed. Turning performance by motor cyclic control was its highest under the...
condition of duty ratio $D=0.33$ and injection frequency $f_J = 1 \text{ s}^{-1}$. Turning angular velocity was improved more than 10% compared to continuous output.

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Reference