Abstract

The complexity operating conditions of marine propulsion system significantly determines the total performance of a vessel. Chebyshev polynomial which possesses the ability to early identify hydrodynamic properties of marine propeller satisfies the precision need to model the propeller characteristic across four quadrants hence useful for dynamical modeling of ship manoeuvring in all-round operations. Determination of propeller thrust and torque coefficients of propeller B-4.58 across four quadrants is performed using the scheme and is compared with the result from experimental tank test. Investigation which reveals that the result generated is valid for first quadrant deduced that the scheme is practically applicable. The coefficients were then used in a thrust and torque estimation scheme and further applied in a ship manoeuvring simulation model. Simulation for crash stopping condition which fully utilised four quadrants of propeller operations was performed and the results were analysed.

1. Introduction

Ship manoeuvring performance in narrow waterways near canal regions has been thoroughly observed for ages [1,2,3]. Notable problem identified includes the effect of the depth and lateral restrictions around the regions. Particularly, large vessels travel in shallow water in proximity of canal bank experience ship-bank effect

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significantly due to lateral forces and turning moments by asymmetric flow around the ship hull. Recent study by [4] emphasized the criticalness of the phenomenon in controlling the ship to manoeuvre along its intended courses which possibly causes grounding or collision to happen. Fitting of two pairs of fins in combination with the existing ship rudder have been proposed to resolve the problem. A MATLAB Simulink manoeuvring model has been developed to simulate and investigate the potential remedial actions of the configuration proposed.

Generally, a ship manoeuvring simulation model solves the surge, sway and yaw motions through the ship gravity centre. The model composed of ship motion parameters and the hydrodynamics of the ship hull, propeller, rudder and the disturbances [5] derived from the environmental conditions. The propeller force model in linear direction which represents the properties of propeller thrust $K_t$ is expressed as the function of advance speed ratio $J$. The values are obtained from the propeller characteristics generated from open water test which commonly given in a performance curve.

Emphasis given by [6] stating that despite the curve form of open water propeller test is immediate and obvious, the model is inconvenient to be applied in mathematical analysis and computer programming. Ordinary polynomial fitting is often adopted to solve the issue. However, some difficulties arose since the fitting result is not commonly used, hard to keep higher fitting accuracy and requires many sets of coefficients for different requirements. A Chebyshev polynomial fitting which possesses the following features has been proposed to address such problems. Firstly, the polynomial coefficients are independent for n-th order assigned. Secondly, the fitting error is small where the n-th fitting with the minimum mean square error would be the best approximation. Lastly, the expression is changeable into ordinary polynomial as highlighted by [7].

The propellers which are basically designed to produce forward force to propel the ships moving ahead, periodically they functioned oppositely. In steady state operation, the advance ratio $J$ varies in a small range of $J \in [0.6, 0.8]$ [8]. However, the ships sometimes inevitably have to slowing down, braking or moving astern, especially during harbor operations. In such dynamic conditions, the advance speed ratio $J$ may significantly changes to even negative values. When the propeller speed $n = 0$, the value of $K_t$, $K_q$ and $J$ would be infinity ($\infty$). This condition is troublesome for program design and simulation modeling [9].

The expression of Chebyshev polynomial which has been widely used in many fields especially as function approximation in numerical calculation satisfies the precision need to model the dynamics of the propeller across four quadrants [7]. Hence the troublesome in simulating the complex operating condition of the propeller can be solved by applying the analysis of the all-round dynamics properties of the propeller. The application of such fitting in the field of simulated modeling can be found in previous works by [7, 8, 9, 10]. Recently, [11] proposed to utilise the scheme in ship manoeuvring simulation modeling.

This paper presents the development of thrust and torque estimation scheme based on Chebyshev polynomial which detailed out in [11]. The thrust and torque coefficients obtained from the Chebyshev fitting were compared with the result from experimental test. Further, the figures were exerted in the thrust estimation scheme which will be accordingly integrated in a ship manoeuvring simulation model.

2. Propeller properties: Chebyshev polynomial and experimental test

Fig. 1 plotted the comparison result of torque and thrust coefficients generated from Chebyshev polynomial and experimental test in the domain of the first quadrant. It is clearly shown that the coefficients decrease simultaneously with respect to the increase of advance ratio $J$ values.

Fig. 1. Comparison result: (a) thrust coefficients; (b) torque coefficients.
At the point of $J=0.50$, the trust coefficients from both result are approaching each other with an error of 0.01039. Accordingly, at the point of $J=0.55$, the torque coefficients show similar characteristic with an error of 0.00195. It can be deduced that the thrust and torque coefficients generated from Chebyshev expression for the inside domain revealed a promising result hence practically applicable. Table 1 provides the error analysis of all result.

<table>
<thead>
<tr>
<th>$J$</th>
<th>$K_t$ Chebyshev</th>
<th>$K_t$ Experiment</th>
<th>Error</th>
<th>$10K_q$ Chebyshev</th>
<th>$10K_q$ Experiment</th>
<th>Error</th>
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<tr>
<td>0.00</td>
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<td>0.01701</td>
<td>0.49854</td>
<td>0.44245</td>
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<td>0.30305</td>
<td>0.34053</td>
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<tr>
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3. Thrust and torque estimation scheme

The presence of knowledge on propeller properties is fundamental to estimate the required propeller thrust and hence to design the best system performance. While it is difficult to address such problem using conventional approach and experiments, as well as time and cost consuming [8], a simulation-based approach is considered to be the effective way to solve the problem. The previous works of [8,9,10] on the thrust estimation and propeller modeling based on the Chebyshev polynomial have proved that the result is satisfactorily practicable.

Fig. 2 depicted the system model built in MATLAB Simulink platform. The model basically consists of four components; propeller, ship hull, ship speed and advance speed. The input is the propeller speed $n$ and the output are propeller torque $Q$, propeller thrust $T$ and ship speed $Vs$. Each element is detailed out as follows.

Block [1] calculates propeller thrust $T$ and propeller torque $Q$ where inputs are propeller speed $n$ and advance speed $Va$. The thrust coefficient $K_t$ and torque coefficient $K_q$ are to be obtained from the Chebyshev calculation. Block [2] calculates ship hull resistance $Rt$ where input is ship speed $Vs$. Block [3] calculates ship speed $Vs$ where input is propeller thrust $T$ and ship hull resistance $Rt$. Blok [4] calculates advance speed $Va$ where input is the ship speed.

The values of thrust deduction factor $t$ and wake fraction number $w$ are determined as follows.
where $n$ and $n_e$ are the propeller and engine speed, $V_s$ and $V_{se}$ are ship and ship rated speed respectively. The parameters of the vessel and propeller used are given in Table 2.

Table 2. Parameter of the ship and propeller model.

<table>
<thead>
<tr>
<th>Ship</th>
<th>Propeller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (L) (m)</td>
<td>Breadth (B) (m)</td>
</tr>
<tr>
<td>3.325</td>
<td>0.520</td>
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</table>

4. Application in the ship manoeuvring simulation

The mathematical model of ship manoeuvring can be described by the Eqs. (3) – (5), using the coordinate system in Fig. 3.

$$X = m(\dot{u} - rv) = X_H + X_P + X_R + X_{disturbance}$$  \hspace{1cm} (3)

$$Y = m(\dot{\psi} + ru) = Y_H + Y_P + Y_R + Y_{disturbance}$$  \hspace{1cm} (4)

$$N = I_{xz}\ddot{\psi} = N_H + N_P + N_R + N_{disturbance}$$  \hspace{1cm} (5)

Particularly, while the lateral force and moment of propeller are small at ahead direction, the propeller advance force is dominant. The mathematical model is expressed as follows.

$$X_p = (1 - t_p)pKtD_p^4n^2$$  \hspace{1cm} (6)

$$Y_p = 0$$  \hspace{1cm} (7)

$$N_p = 0$$  \hspace{1cm} (8)

Integrating the Chebyshev polynomial into the model, the value of the thrust property $Kt$ will be obtained from the scheme in place of the traditional way which is determined from the result of open water test.
The following Fig. 4 displays the simulation result of crash stopping condition using the scheme developed.

Fig. 4. Time series of propeller and ship characteristics.

At first, the propeller speed accelerates to reach 90rpm and being constant until 275s before reaccelerates to zero. Afterwards, the propeller rotates in reverse direction until a maximum speed of 30rpm at 600s and maintains at such speed to the end of the simulation. The result clearly shows that the ship reaches the furthest distance at 900s while at the same time managed to stop completely.

5. Conclusion

The propeller properties generated from the Chebyshev polynomial has proven to be practicable in place of open water result. The properties obtained have also been utilised in the thrust and torque estimation scheme. The properties and the scheme developed were integrated into an all-round dynamics of ship manoeuvring simulation. The result records that the propeller indicates a successful performance during stopping condition.

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References