An Overall Ship Propulsion Model for Fuel Efficiency Study

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Abstract

An overall ship propulsion plant involving marine engine, propeller and ship dynamic model was presented in this work. The cycle mean value model was utilized to describe the operation process in engine dynamic, intake/exhaust and turbocharger system. The ship shafting system was modelled using the power balance and its efficiency. The predicted results of fuel consumption, engine delivered power and vessel speeds were tested with measured data under different engine response. The whole ship voyage model will be used to predict fuel consumption and exhaust emissions under different sailing conditions in further study.

1. Introduction

In order to meet the recent requirement of energy saving and CO2 emission reduction, many researches have been drawn to develop simulation model to estimate real performance of ships in the actual sea condition. The ship behavior in actual sailing condition is one of the major concerns for designers and ship owners. Ship weather-routing is defined as a procedure to determine an optimal route based on the weather forecasts and ship hydrodynamics motion \cite{1, 2}. For the propulsion power source, the propeller trust or engine power is set to be constant during the voyage. However, from vessel maneuvering to full cruise, the engine load changes from 10\% to 80\%. When the ship encounters storm or heavy sea, and the propeller works in a very hostile environment, the engine speed should be slow down to reduce non-useful output work and fuel consumption and ensuring the sailing safety. The propeller and engine compose a strongly coupled system to determine vessel speed. Therefore the engine response in waves should not be ignored when we need to evaluate fuel consumption and emissions in the actual voyage.
In the present study, a marine propulsion model was built including two-stroke marine engine and fixed pitch propeller system. Coupled with vessel voyage model, a container ship could be actuated under different engine response along the desired trajectory. Then the fuel consumption during different sailing conditions could be predicted. It provides new perspective to study optimal sailing route.

1. Marine engine model

Fuel consumption is directly related to marine engine operation conditions. Normally, the larger container ships are equipped with two-stroke marine engine with speed lower than 130rpm \(^{[3]}\) as the main engine, delivering power to propeller. And a four-stroke marine engine is used as auxiliary engine responsible for all onboard power or off-loading equipment. In this study, the marine engine is modeled using a cycle mean value model approach in conjunction with differential equations for the fast transient power plant performance calculation of the engine crankshaft speed and delivered power. The thermodynamic and flow dynamic process in engine operation are taken into consideration. The main components of the engine are shown in Figure 1.

![Schematic of engine main components](image)

Fig.1 Schematic of engine main components

For a direct injection marine diesel engine, the degree of fuel/air mixture homogeneity is very important to determine the thermal efficiency and fuel consumption. For this cycle mean value model, the indicated thermal efficiency \(\eta_{in}\) is expressed as a function of excess air ratio based on the measured data from MAN Diesel & Turbo Corporation \(^{[4]}\). The fuel mass flow rate is calculated by the variation of the mass of injected fuel per cylinder and per cycle controlled by fuel pump rack position. Thus the fuel and air mass flow rate are calculated:

\[
m_f = m_f N_{cyl} n_e (60 \text{rev}_{cy})
\]

\[
m_a = \eta_v p_{inl} v_{cyl} N_{cyl} n_e (60 \text{rev}_{cy} T_{inl})
\]

Where \(m_f\) is the fuel mass injected into the cylinder; \(N_{cyl}\) is the number of cylinders; \(n_e\) is the engine rotational speed; \(\text{rev}_{cy}\) is the revolutions per cycle; \(p_{inl}\) and \(T_{inl}\) are inlet pressure and temperature, respectively; \(\eta_v\) is the volumetric efficiency; \(v_{cyl}\) is the volume per cylinder, and \(R\) is the gas constant number.

The engine output torque \(Q_i\) is derived using engine indicated thermal efficiency, fuel mass flow rate and rotational speed:

\[
Q_i = 30 \eta_{i} H_u m_f / (\pi n_e)
\]

Where \(H_u\) is the low calorific value of the fuel.
In this study, the friction loss torque $Q_f$ due to piston reciprocating motion etc. could be expressed as a function of friction force and engine speed. Therefore, the engine shaft rotation speed $n_e$ could be calculated by applying the angular momentum conservation in propulsion plant system:

$$\frac{dn_e}{dt} = 30 \frac{[Q_i(t-\tau_i)-Q_f-Q_p]}{(\pi I_e)}$$

(4)

Where $\tau_i$ means the ignition delay; $Q_i$ is the propeller torque, and $I_e$ is inertia moment of the engine.

The variance of flow mass, temperature and pressure through intake and exhaust manifold are expressed based on volume dynamic as follows:

$$\frac{dT_{out}}{dt} = \frac{(m_{in}kT_{in}-m_{out}kT_{out}-T_{out}dm_{g}/dt)}{m_g}$$

(5)

$$\frac{dm_{g}}{dt} = m_{in}-m_{out}$$

(6)

$$\frac{dp_{out}}{dt} = kR(m_{in}T_{in}-m_{out}T_{out})/V_g$$

(7)

Where the subscript $in$ and $out$ indicate the variables at the inlet and outlet of the manifold respectively.

After the exhaust manifold, the exhaust gas is expanded in the turbine and then drives the compressor. Operation working map of turbocharger is necessary to get information on mass flow rate and efficiency.

2. **Engine speed governor model**

Incremental PID engine governor model is utilized to control the fuel injector rack position, according to the deviation of target engine speed and feedback calculated value. It highlights with little effect by faulty action. When the propeller load is changed suddenly due to the wave fluctuation or mechanical accident, the self-tuning of fuel supply could be achieved, maintaining the same engine speed in order to protect the engine integrity during fast transients.

3. **Propeller model**

If there is no gearbox between the two-stroke marine engine and propeller, the propeller rotation speed equals to the engine speed. When the engine delivered power and operation speed are known, the propeller torque $Q_p$ and thrust $T_p$ can be calculated using the dimensionless coefficients:

$$Q_p = K_Q \rho n_p^2 D_p^5$$

(8)

$$T_p = K_T \rho n_p^2 D_p^4$$

(9)

Where $K_Q$ is the non-dimensional torque coefficient; $K_T$ is the non-dimensional thrust coefficient. $\rho$ is the density of sea water; $n_p$ is the propeller rotation speed and $D_p$ is the diameter of the propeller.

The mathematical modeling of the ship propulsion plant was implemented in the Marine System Simulator toolbox in Matlab/Simulink environment, as shown in Figure 2. The vessel movement is actuated by the propeller thrust.

4. **Ship hydrodynamics modelling**

The accuracy of describing ship’s hydrodynamic behavior under different sailing conditions also influences the prediction of marine fuel consumption. In this study, vessel moving includes six degrees of freedom (DOF) to determine the translational and rotational movement. The first three coordinates related to position and translational motions are surge, sway and heave, corresponding with roll, pitch and yaw in orientation and rotational motion for the last three coordinates, as shown in Figure 3.
The vessel speed is given by the motion equation with fluid memory effects:

\[ M\nu' + C_{RB}\nu + C_A\nu_r + B\nu_r + G\eta = \tau + \tau_H \]  

(10)

Where \( M \in \mathbb{R}^{5 \times 6} \) is the sum of the system inertia matrix and the added mass matrix. \( C_{RB} \in \mathbb{R}^{5 \times 6} \) is the Coriolis-Centripetal matrix. \( C_A \in \mathbb{R}^{5 \times 6} \) is the constant infinite frequency added mass matrix. \( \nu_r = \nu - \nu_c \in \mathbb{R}^{5 \times 6} \) is the relative velocity between vessel velocity \( \nu \) and sea current velocity \( \nu_c \). \( B \in \mathbb{R}^{5 \times 6} \) is the constant infinite frequency potential damping matrix. \( G \in \mathbb{R}^{5 \times 6} \) is the restoring matrix. \( \tau \in \mathbb{R}^{5 \times 6} \) is the control force vector produced by the propeller system. \( \tau_H \in \mathbb{R}^{5 \times 6} \) is a vector of time-varying hydrodynamic forces. All the detailed definition and computation of above matrices and vectors could be found in reference [5].

5. Results and discussion

In this study, the propulsion power plant of a typical feeder container ship S175, with a length of 175 m and a weight of 24610 ton, is simulated using the model described above. The vessel is driven by tracking control with a type-2 fuzzy controller [6], along with a desired trajectory in the presence of time-varying hydrodynamic disturbances. The MAN 6S60ME engine is equipped for this vessel as the main engine [7, 8]. The main engine is a two-stroke marine diesel engine with one turbocharger unit. The maximum output power is 14280kW, considering 15% sea margin and 10% engine margin for fouling ship hull and heavy weather, in order to satisfy the maximum serving speed of approximate 20 knot for this container ship. The main engine specifications are given in Table 1. One five-blades fixed pitch propeller of 6.5 meter is directly connected to the main engine via shafting system [9].
Table 1: Specifications of the marine diesel engine

<table>
<thead>
<tr>
<th>Engine</th>
<th>6S60ME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>600 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>2400 mm</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>6</td>
</tr>
<tr>
<td>Maximum continuous rating (MCR)</td>
<td>14,280 kW</td>
</tr>
<tr>
<td>Engine speed (100% of MCR)</td>
<td>105 rpm</td>
</tr>
<tr>
<td>Specified fuel oil consumption (100% of MCR)</td>
<td>168 g/kWh</td>
</tr>
<tr>
<td>Turbocharger type</td>
<td>Conventional T/C</td>
</tr>
</tbody>
</table>

Initially, the engine model was calibrated so that the simulation results for various response of the engine governor rack position are in good agreement with the respective ones given by the engine manufacturer [4]. Comparisons of simulation and experimental results in terms of specified fuel oil consumption (SFOC) and engine indicated output power under different engine speed are shown in Figure 4. The low calorific value for the test fuel is 42,700kJ/kg. The predicted fuel consumption rate and engine output power are well agreed with measured data. The accurate predictions of fuel consumption rate and engine output power under various engine loads are essential for the fuel consumption forecast during the actual ship voyage.

![Figure 4 Comparison of simulated and measured results](image)

(a) Specified fuel oil consumption  
(b) Indicated engine power

![Figure 5 Relationship between engine load and vessel speed](image)

Then the calibrated engine model in conjunction with the propeller model is used to drive the S175 container ship tracking along the desired trajectory. The calibrated vessel sailing speed under various engine response are depicted in Figure 5, together with the vessel data related with engine loads from literature [10]. The simulated results deviate from the reference data for lower engine loads, mainly
because of the inadequate prediction of wave or weather effect on resistance load, but the error is still acceptable. Another reason may be due to the ignorance of other thrusters or auxiliary engines which are responsible during the maneuver process. In the future, the ship voyage model implanted with the marine propulsion model will be used to study the fuel consumption and exhaust emissions under different sailing conditions.

6. Conclusion

The mathematical model of the overall ship propulsion plant, implemented in the container ship voyage model in the MATLAB/Simulink environment, was presented. The predicted results of fuel consumption, engine delivered power and vessel speeds were validated with measured data under different engine response. The whole ship voyage model will be used to predict fuel consumption and exhaust emissions under different sailing conditions in further study.

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Acknowledgements

This study is supported by the research project “Analysis of Energy Consumption and Emissions by Shipping Lines” funded by Singapore Maritime Institute

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Biography

Feiyang Zhao obtained Ph.D. degree in 2013 from State Key Lab of Engine of Tianjin University in China, majored in diesel engine combustion simulation. Now she is a research fellow working on optimizing the operation and fuel management for vessel propulsion system in NUS.