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Development of a real-time two-stroke marine diesel engine model with in-cylinder pressure prediction capability

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HIGHLIGHTS

- Development of a quick two-stroke marine diesel engine model.
- Proposition of speeding up overall calculation by abandoning cycles.
- Improvement of calculation speed of 0D cylinder model using a novel way.
- In-depth investigation of the accuracy and dynamic attributes of the model.
- Appropriate where the real-time and in-cylinder pressure are required.

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ABSTRACT

The in-cylinder pressure is an important parameter for the diesel engine but it fails to be used in the common scenes, like the control, hardware in loop, and virtual reality, for its lack of real-time capability. In order to have this capability, the conventional diesel engine models are ameliorated (named as MG model, the merged diesel engine model). These parameters that exclude the in-cylinder pressure and indicator torque are calculated by mean value model, the widely used model for real-time applications, to keep on its speed. The other parameters are calculated by the 0D model. To improve the in-cylinder pressure calculation speed, the simplification and asychronization are used. The compression, combustion, and expansion processes are calculated the same as 0D assumption but the exhausting and scavenging processes are simplified by two linear functions. Its calculation time saves about 33.3% comparing to the conventional 0D approach. The boundaries of cylinder model are asynchronous with the scavenging and exhausting manifolds by abandoning cylinder cycles at reasonable intervals so that the time can be reduced further. In practical coding, the in-cylinder pressure needs to be calculated by a parallel thread to realize asychronization. In the case that abandons 4 cycles every 5 cycles the calculation time saves nearly 80% further. Only during the dynamic process, is the reduced time positively correlated with the number of abandoned cycles. The proposed model is calibrated against shop test data, whose predicting accuracy is comparable to the 0D model. The maximum relative errors of steady MG model and steady 0D model are 3.96% and −3.23%, and the mean relative errors are 1.38% and 2.18%. In the case that abandons 4 engine cycles, the maximum relative error of explosion pressure is 0.363% during the dynamic process. This model can be used in real-time HIL, controller design, engine analysis, and simulator.

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0. Introduction

Tens of thousands of ships are sailing all over the world. Marine transportation plays an important role in the world trading [1]. Reducing the harmful emissions and improving the thermal efficiency of diesel engine have become the focus in the shipping industry. A number of measures including the optimization of diesel engine control system and the usage of clean energy are being taken to meet those strict environment regulations [2–4]. Because of reducing time-consuming and expensive test cost, the simulation model of diesel engine attracts the most attentions in research works and has become the powerful tool in the optimization of the electric controlled diesel engine [5,6]. The innovative solutions, like

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Nomenclature

P	power [W]
c_p	heat capacity at constant pressure [J/(kg K)]
η	efficiency factor
Π	pressure ratio
p	pressure [pa]
c_v	heat capacity at constant volume [J/(kg K)]
Q	heat [J]
M	torque [N m]
φ	crank angle [°]
D	diameter [m]
e	relative error
m	mass [kg]
T	temperature [K]
k	isentropic index
α	the air fuel equivalence ratio
h	specific enthalpy [J/kg]
u	specific internal energy [J/kg]
H_u	lower heating value [J]
H	enthalpy [J]
A	area [m^2]
R	gas constant [J/(kg K)]
n	revelution [r/min]

Acronyms

MG	merged diesel engine model
SFOC	specific fuel oil consumption
CMCR	contracted maximum continuous rating
VLCC	very large crude oil carrier

Subscripts

f	fuel
z	cylinder
e	exhaust manifold/engine
t	turbint
p	premix combustion
w	wall
s	scavenging manifold
c	compressor/compression
d	diffusion combustion

the in-cylinder pressure sensor, make it possible to consider in-cylinder pressure in the controller design [7–10]. At present, however, the pressure prediction model fails to meet the strict requirements of predicting pressure with fast speed, high accuracy, good mechanism and dynamic response. In that case, it is essential to develop a diesel engine model having these capability at the same time.

Generally, the widely used diesel engine models can be categorized as CFD (Computational Fluid Dynamics) model, thermodynamic model, mean value model and empirical model. The CFD model is often used in diesel engine design and performance analysis [11–13]. It is labeled with high accuracy and time consuming resulting from the calculation of finite element method. The thermodynamic model provides a relatively rapid way to calculate the performance of diesel engine. Its combustion process can be described by multi-zone, two-zone and single-zero assumptions [14–19]. In order to get better accuracy, the measured data is needed. The model provides the ability to predict the overall performance of engine that can be used in engine performance analysis [14–18] and engine controller design [19,20]. The mean value model regards the work process as a continuous mass and energy flow, and the average performance over the engine cycles can be obtained. Owing to the simplification of the in-cylinder process, this model calculates faster than the 0D model but more measured data is required to keep the accuracy. It is found from the papers that MV model is widely used in engine analysis [5,21], controller design [20,22–24], hardware in loop [25,26], and fault diagnosis [27,28]. The empirical model is developed based on the identification of input-output data. It calculates fast but has low accuracy and no mechanical sense [29–31]. As the complexity of CFD model and thermodynamic model, some software packages, like the GT-Power, AVL AST, KIVA, Start-CD, STAR-CCM+, and AMESim are available and have been widely used [12,13,32–35].

The single-zone zero dimensional model (also known as zero dimensional model or 0D model) and mean value model are the best candidates for predicting engine performance in real time owing to the suitable compromise among calculation speed, output accuracy, mechanical sense and measure data dependency. According to mean value approach, the mean indicator power, mean exhaust gas temperature and mean scavenging air mass can be predicted but the transient in-cylinder pressure, which is valuable for the judgment of diesel engine performance, cannot access [36]. On the contrary, in the 0D model, the cylinder sub-model is solved by crank angle so that the transient in-cylinder pressure, temperature, mass, indicated power can be predicted, which in turn takes up much time of CPU compared with the mean value model [37]. In both models, the marine diesel engine is primarily divided into the compressor, air cooler, intake or scavenging manifold, cylinder, exhaust manifold, and turbine. Except cylinder sub-model, models made from zero dimensional assumption and mean value approach are almost the same.

In order to obtain faster calculation speed and more predictable parameters, a number of ideas have been proposed. These ideas can be classified as substitution that uses a fast model, like the map or the neural network, to displace the complex computation [38]; combination that hybridizes the advantages of other models and switches to the best one in accordance with the working condition [18,39]; and simplification that reserves the key information and simplifies the unimportant process according to the objective of research [40,41]. Nikzadfar [38] replaced the cylinder model by two neural networks. One was used to predict aspirated air, torque and exhaust temperature, the same as mean value cylinder model, and the other was used to predict soot and NOx. Maroteaux [18] combined a mean value model for the engine periphery, a single zone in-cylinder model for the intake-compression-exhaust strokes and a two zone model for the combustion process. Baldi [41] used a zero dimensional model to predict the close process of a diesel cycle and a mean value model to predict the open process of a diesel cycle. By using the ideas of substitution, combination, and simplification, the performance of engine model is enhanced.

In practical application, the scavenging process is judged by the pressure in scavenging manifold instead of the in-cylinder pressure during scavenging which attracts little attention. On the other hand, the compression pressure, the explosion pressure and the rate of pressure increase during combustion are the most key information for engine performance. Based on those studies and ideas, the proposed MG model divides the in-cylinder pressure calculation into enclosed part and open part, which largely lower down the calculation. In that case, the pressure during the open

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