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A semi-empirical ship operational performance prediction model for voyage optimization towards energy efficient shipping

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A B S T R A C T

Voyage optimization is a practice to select the optimum route for the ship operators to increase energy efficiency and reduce Green House Gas emission in the shipping industry. An accurate prediction of ship operational performance is the prerequisite to achieve these targets. In this paper, a modified Kwon's method was developed to predict the added resistance caused by wave and wind for a specific ship type, and an easy-to-use semi-empirical ship operational performance prediction model is proposed. It can accurately predict the ship's operational performance for a specific commercial ship under different drafts, at varying speeds and in varying encounter angles, and then enables the user to investigate the relation between fuel consumption and the various sea states and directions that the ship may encounter during her voyage. Based on the results from the operational performance prediction model and real time climatological information, different options for the ship's navigation course can be evaluated according to a number of objectives, including: maximizing safety and minimizing fuel consumption and voyage time. By incorporating this into a decision support tool, the ship's crew are able to make an informed decision about what is the best course to navigate.

In this study the Energy Efficiency of Operation (EEO) is defined as an indicator to illustrate the ratio of main engine fuel consumption per unit of transport work. Two case studies are carried out to perform the prediction of ship operational performance for Suezmax and Aframax Oil Tankers, and the results indicate that the semi-empirical ship operational performance prediction model provides extremely quick calculation with very reasonable accuracy, particularly considering the uncertainties related to the parameters of interest for the case study data. Within the case studies, the additional fuel consumption caused by the combined hull and propeller fouling and engine degradation is included in the model as a time-dependent correction factor. The factor may assist the ship owner/operator to determine the hull coating selection, and/or the dry-docking and main engine maintenance strategy.

1. Introduction

Energy efficient shipping is a prerequisite for the reduction of the Green House Gas (GHG) emissions to the levels anticipated within the next decades. The continuous growth of the world population and the increase number of developing countries led to the increasing dependence of the world economy on the international trade. For 2007, it was estimated that shipping emits 1046 million tonnes of CO_2 from exhaust emissions, accounting for 3.3% of the global CO_2 emission during that year. CO_2 emission from International shipping alone were estimated to account 2.7% of the global CO_2 emission in 2007, and the carbon dioxide emissions from international shipping was projected to triple by the year 2050 (IMO, 2009). These findings alerted the International Maritime Organization (IMO) and led to the introduction of the first maritime energy efficiency regulations that entered into force on the 1^{st} of January 2013 (IMO, 2011). The aim of the regulations is to reduce carbon emissions by decreasing the amount of fuel consumed. This can be achieved by optimizing the ship's design, deploying new energy efficient technologies, or by improving the ship's operation. The regulations require both new and existing ship above 400 GT to have a ship specific Ship Energy Efficiency Management Plan, SEEMP (IMO, 2012).

An additional drive towards a more energy efficient shipping is the requirement to remain competitive within a fierce market. Although marine engines used for commercial shipping use the cheapest type of 'bunker fuel', the cost of IFO 180 has risen sharply with other petroleum products, increasing from \$170/t in 2002, and from \$230/t in 2005, to nearly \$700/t in July 2014 (Bunker Index, 2014). With such high fuel prices, the bunker costs could account for 50–60% of a ship's total operating costs (Wang and Teo,

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2013). The rising fuel price has supported the increasing need for energy efficiency to survive in highly competitive and capacity oversupplied shipping market.

It is important to realize that an optimum route cannot only be evaluated in terms of fuel consumption. Normally, the voyage optimization has multiple, often conflicting, objectives, such as: minimizing costs regardless of arrival time; punctual time of arrival; safety; and passenger comfort. In most cases, improving one objective may reduce efficiency of another. Each attribute therefore requires a weighting of importance. For example, some shipping companies' business models prioritise on-time arrival and shorter transit times over reduced fuel consumption. For other companies, providing a 'green service' has a higher priority.

Most existing techniques and software solutions for voyage optimization extract the ship's operational performance from a database build on results from similar ships (in terms of type and size). However, the performance of each specific ship in various voyage conditions (speed, fouling and propulsion system degradation, and draft) may be quite different, especially under severe weather conditions. This highlights the need for real-time, flexible ship-specific modeling in order to provide increased accuracy of ship operational performance prediction for voyage optimization. Another common disadvantage of many existing voyage optimization software solutions is that they only present to the ship's master the recommended route. The users of the software cannot test their intended route and compare its performance to the software recommended route. As a result, captains may develop mistrust to the recommended route and proceed according to their own judgement.

Voyage optimization software can be evaluated according to:

- Technical status – the accuracy and practicability of ship operational performance prediction.
- User acceptance – the user friendliness.
- Economic performance – the evaluation of fuel saving based on voyage optimization.

These three evaluation principles are also the objectives of the research presented. This paper focuses on the development of an accurate and practical ship operational performance prediction model that can be used to select the optimum routes for minimum fuel consumption, taking into consideration average ship speed, encountering sea states and voyage time.

The ship operational performance model presented in this paper is developed by the modifying Kwon's method (Kwon, 2008) using a case study of ship's operational data (i.e. ship's noon reports) and sea trial data. The Kwon's method (Kwon, 2008) is an empirical method for the prediction of added resistance due to sea state and wave directions. The case study of ship's operational data is taken as the reference for the modified Kwon's method. This modified model can predict the ship's operational performance for a given wave and weather condition at different speeds, drafts and wave encounter angle in a semi-empirical way.

A decision support tool has been developed to select the optimum course according to the users' preference. The users can influence the selection of the optimized route by providing different weightings to the optimization objectives (see optimum route a–e listed in Fig. 10).

Besides the development of the ship operational performance prediction and the optimum routes selection, a time-dependent fuel consumption increase rate after ship dry-docking has been identified, which may be helpful in monitoring ship fouling and engine degradation condition. The identified fuel consumption rate of increase will further assist shipping companies with planning dry-docking and engine maintenance scheduling.

2. State of the art

2.1. Semi-empirical approaches for predicting the added resistance

The prediction of ship total resistance in waves (R_T) can typically be performed in two steps (ITTC, 2011):

a) Prediction of still water resistance, R_{SW}, at speeds of interest.
b) Prediction of added resistance in waves, R_{AW}, at the same speeds.

The prediction of ship total resistance in waves is obtained by summing the above mentioned predicted values:

$$R_T = R_{SW} + R_{AW} \tag{1}$$

several methods are available to determine the still water resistance of ships. In the presented analysis the Holtrop and Mennen method (Holtrop and Mennen, 1982) has been used.

The increase in resistance caused by waves, greater than the still water condition, can also be calculated using several methods, including Strip Method, Radiated Energy Method, Rankine Panel Method, Cartesian Grid Method, CFD Method, Experiment Method, Empirical Method, and Semi-empirical Method. In the following section, some of the semi-empirical methods for added resistance prediction are reviewed.

2.1.1. The approximated – Salvesen method

The Salvesen method (Salvesen, 1978) provides a basic formula for the added resistance calculation.

$$R_{AW} = -\frac{i}{2}k\ \cos\ \beta \sum_{j=3,5} \xi_j \left\{ F_j^{I*} + \hat{F}_j^D \right\} + R_7 \tag{2}$$

where $\hat{F}_j^{I*}$, is the complex conjugate of the Froude-Krilov part of the exciting force and moment, and $\hat{F}_j^D$ is very similar to the diffraction part of the existing force F_j^D, k is the wave number, $\beta$is wave heading direction, and ξ_j is the motion calculated by the strip theory. R_7 is given by

$$R_7 = -\frac{1}{2}\xi_I^2 k \frac{\omega^2}{\omega_e}\ \cos\ \beta \int_L e^{-2kds}(b_{33} + b_{22}\sin^2\beta)dx \tag{3}$$

Where, ξ_I is the incident wave amplitude, b_{33} and b_{22} are the sectional heave and sway damping coefficient, d is the sectional draft and s is the sectional-area coefficient. Details of formula 2 and 3 are presented in Salvesen (1978).

The Salvesen method is able to provide accurate results for the longer waves regions ($L/\lambda < 1.5$). Therefore, to extend its use for short wave length regions a correction is added to the original Salvesen method to produce the approximated – Salvesen method (Matulja et al., 2011). The correction contains an approximated formula proposed by Faltinsen et al. (1980):

$$R_{AW} = \frac{1}{2}\rho g \left(1 + \frac{2\omega U}{g}\right) \int_{L1} \sin^2 \nu n_1 dl \tag{4}$$

where, $L1$ is non shadow zone of the water plane area, U is ship speed, ω is Encounter frequency, n_1 is X component of the inward normal n to the water line, and ν is the angle between the tangent to the water line and the x axis.

The final step of the approximated – Salvesen method is:

$$R = a \quad \text{for} \quad L/\lambda \le 1 \tag{5}$$

$$R = a + b \quad \text{for} \quad 1 < L/\lambda \le 2 \tag{6}$$

$$R = b \quad \text{for} \quad L/\lambda > 2 \tag{7}$$