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Data analysis on marine engine operating regions in relation to ship navigation

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ABSTRACT

Data analysis techniques to understand marine engine operating regions as a part of the ship energy efficiency management plan (SEEMP) are proposed in this study. The SEEMP enforces to improve ship energy efficiency under various emission control measures by collecting and analyzing vessel performance and navigation data. The required data analysis techniques to analyze such data sets are presented under the engine-propeller combinator diagram (i.e. one propeller shaft with a direct drive main engine). These techniques consist of implementing Gaussian Mixture Models (GMMs) with an Expectation Maximization (EM) algorithm to classify and Principal Component Analysis (PCA) to analyze frequent operating regions of a marine engine in a selected vessel. Three marine engine operating regions are noted under the combinator diagram and GMMs capture the shape, orientation and boundaries of those operating regions. Then, PCA is used to understand the structure of each GMM with respect to ship performance and navigation parameters. Hence, this approach can be used in the SEEMP to monitor ship navigation with respect to marine engine operating regions.

1. Introduction

1.1. Ship energy efficiency

Modern vessels are equipped with various onboard sensors and data acquisition (DAQ) systems to collect ship performance and navigation parameters. Such vessel related parameters are collected as large scale data sets that should be analyzed to evaluate vessel performance levels under various weather conditions. Ship speed, power and fuel consumption requirements are often studied under such vessel performance levels. Hence, marine engines in vessels can play an important role in such performance evaluation processes. However, various data analysis techniques should be developed to understand such vessel performance levels under ship operation data. Furthermore, these data analysis techniques and respective results can be a part of the ship energy efficiency management plan (SEEMP) and that help to draw conclusions on vessel performance levels.

It is believed that the SEEMP (IMO, 2009a and 2012) can play an important role in commercial ship operations in the future years as a mandatory mechanism in shipping. That enforces to improve vessel operational conditions and implement technology advancements for more energy efficient shipping fleets. The energy efficiency operational indicator (EEOI) can be used as a benchmark level for the SEEMP. Hence, the proposed data analysis techniques under vessel performance and navigation data facilitate for achieving the respective ship energy efficiency objectives that are assigned in the SEEMP (IMO, 2009b and 2012).

The SEEMP consists of four phases: planning, implementation, monitoring, self-evaluation and improvements. The first phase relates to vessel and shipping company specific measures, where goal setting type initiatives to improve ship energy efficiency should initiate with human resource development strategies of the shipping company. At the implementation phase, the same should be established with several procedures by documenting the implementation progress and developing the required condition monitoring (CM) facilities (Perera, 2016a, 2016b and Perera and Mo, 2016a). At the monitoring phase, ship performance and navigation data should collect and analyze to observe vessel energy efficiency under the implementation procedures. One should note that the proposed data analysis techniques can be used in this phase, extensively. At the self-evaluation phase, various voluntary reporting and review processes should be conducted and lessons learned should also be documented for further improvements. To achieve SEEMP objectives, the crew should have proper knowledge and training on energy management approaches in their vessel. These energy management approaches should be facilitated by onboard ship performance and navigation data and the respective data analysis techniques during the monitoring phase of the SEEMP. The final results of such data analysis techniques can increase the understanding of efficient operational conditions of the vessel.

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1.2. The recent studies

This study proposes several data analysis techniques to understand operating regions of marine engines in relation to ship navigation as part of the SEEMP. A limited number of engine related ship navigation studies are presented in the recent literature (Armstrong and Banks, 2015) and summarized in this section. A comparison among four different procedures to optimize a combined Diesel and organic Rankine cycle system (i.e. inclusion of engine control variables) with the ship operational profile of a chemical tanker is presented by Baldi et al. (2015). A coupled dynamic-thermodynamic engine simulation in time-domain is developed to evaluate engine performance across full range of operational conditions of a vessel by Murphy et al. (2015). Furthermore, the respective engine performance curves for such marine engines under computer simulations are presented by Morsy et al. (2011).

However, these studies are limited to various empirical models and such models often fail to accommodate large scale data sets of ship performance and navigation parameters. Therefore, this study proposes appropriate data analysis techniques to overcome such situations. The proposed approach consists of understanding operational regions of a marine engine under the respective engine-propeller combinator diagram by considering ship performance and navigation data. Hence, the respective results can be used in the ship operation phase to identify optimal engine-propulsion operating conditions as a part of the SEEMP (Perera et al., 2015a, 2015b).

Appropriate engine-propulsion configurations (i.e. optimal conditions) reduce respective power/fuel consumption and exhaust emissions in ships, significantly (Trodden et al., 2015). That can be identified by observing vessel operations under engine-propeller combinator diagrams as further discussed in this study. The combinator diagram (i.e. the relationship between main engine (ME) power and shaft speed) facilitates as the basis to identify appropriate engine-propulsion configurations under the respective data analysis techniques. Frequent operating regions of the engine-propulsion combinator diagram with the respective ship performance levels (i.e. speed and power conditions) can be identified under the same. The optimal engine operating regions can be extracted from such frequent operating regions and that knowledge can be used to improve ship performance levels. Such optimal engine operating regions can be identified by observing data structures of each frequent operating region of the engine propeller combinator diagram. Hence, a ship performance and navigation data set of a selected vessel (i.e. one propeller shaft with a direct drive main engine) is considering to implement the respective data analysis techniques as the main contribution of this study.

1.3. Engine propeller combination

Optimal engine-propulsion configurations are selected at the ship design phase with respect to vessel operational and navigation requirements. However, such configurations may degrade in ship navigation situations due to various environmental factors. The respective engine-propulsion interactions should be monitored in ship navigation and that information should be analyzed to evaluate vessel performance. These engine-propulsion interactions are often studied under the combinator diagram as mentioned previously. Therefore, a general overview of the engine-propulsion combinator diagram is presented in Fig. 1 consisting of a relationship between marine engine power (in a logarithmic scale) and shaft/propeller speeds. A direct drive situation, a marine engine (ME) is connected with a direct shaft to drive the propeller (i.e. fixed-pitch-propeller), is considered in this situation. In general, various ship navigation situations can be studied under such engine-propeller combinator diagrams (MAN Diesel and Turbo, 2011). Therefore, modern integrated bridge systems are often equipped with such onboard combinator diagrams to evaluate vessel performance levels in various environmental conditions. The respective engine fuel consumption (i.e. specific fuel consumption (SFC)) can also be incorporated into such combinator diagrams to evaluate real-time emissions in vessels.

The respective features of an engine-propeller combinator (see Fig. 1) are further explained in this section. As presented in the figure, the maximum and minimum constant speed lines of (A1) and (A2) and mean effective pressure (MEP) lines of (A3) and (A4) limit the initial engine operation region. One should note that the engine idling/clutch-in speed range (A5) is close to (A2). The intersection between (A1) and (A3) represents the nominal maximum continuous rating (MCR) point (A5) for the respective engine. Further limitations of the engine operation region are the respective 110% engine power limit, sea trial engine speed limit (B1) and engine overload limit (B2). However, vessels operate beyond these engine limits with additional engine power capabilities under some sea trial situations. The engine operating region is further limited by the maximum acceptable engine speed limit (C1), maximum engine power limit (C2) (that can be 100% of respective engine power), 100% mean effective pressure limit (C3) and maximum torque-speed limit (C4).

The specified MCR point (P1) of the engine is located at the intersection of the 100% engine power and speed limits. This limited engine operation region is divided into several circular regions (D1) of specific fuel consumption (SFC) levels. The smallest SFC region (i.e. small radius) represents the optimal fuel consumption rate (i.e. minimum SFC) of the engine. Therefore, the selection of propeller operating points in vessels should close to this optimal SFC region to reduce the respective fuel consumption for the same ship speed. In general, propeller configurations in vessels can be divided into two categories of: fixed-pitch-propellers (FPP) and controllable-pitch-propeller (CPP). A FPP design is for a specific operation speed with its optimal pitch condition. The CPP on the other hand can have additional flexibilities by changing its pitch condition with respect to engine speeds.

A light running FPP curve (E1) illustrates vessel operations under clean hull and propeller conditions in calm waters. The propeller design point (P2) and alternative propeller design point (P3) are also located in the same line. One should note that (P2) can move towards (P3) under the respective sea margin. i.e. the sea margin (F1) (i.e. up to 20% of respective engine power). However, the same curve can move towards the heavy FPP curve (E2) due to fouled hull and propeller conditions and/or rough weather, where (P2) (i.e. light running engine) can move towards (P4) (i.e. heavy running engine). A considerable ship speed reduction under engine heavy running conditions can be observed and a possible increase in the fuel consumption. Such heavy running situations can be avoided by appropriate dry-docking (i.e. cleaning hull and propellers) and voyage planning (i.e. weather routing and speed optimization) approaches (Fang and Lin, 2015). Similarly, (P4) can move towards (P5) under the sea margin (F1) in heavy running conditions of the engine. Furthermore, (P5) can move towards the specified MCR point for propulsion (P6) under the engine margin (F2).

If the marine engine has a shaft generator, then the engine should be able to supply an additional amount of power (F3) (i.e. (P6) should move towards (P1)) to the vessel. (P1) may intercept the ultimate heavy FPP curve in (E3) as it relates to the ship specifications (MAN Diesel and Turbo, 2011). If the marine engine has a shaft motor, then an additional amount of power can be injected (i.e. (P6) should move opposite to (P1)) into the propulsion system by auxiliary engines. However, (P1) and (P6) can also coincide in the combinatory diagram in some vessels without PTO/PTI facilities. The recommended engine operating point with the lowest operation SFC value (i.e. the optimal fuel consumption) is (P7). Therefore, each engine operating point should move towards (P7) to improve energy efficiency in the vessel. However, the engine operating point may move towards (P8), the continuous service rating of the engine, as per the vessel operational requirements.