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Simulation of a two-stroke diesel engine for propulsion in waves

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Abstract

Propulsion in waves is a complex physical process that involves interactions between a hull, a propeller, a shaft and a prime mover which is often a diesel engine. Among the relevant components, the diesel engine plays an important role in the overall system dynamics. Therefore, using a proper model for the diesel engine is essential to achieve the reasonable accuracy of the transient simulation of the entire system. In this paper, a simulation model of a propulsion system in waves is presented with emphasis on modeling a two-stroke marine diesel engine: the framework for building such a model and its mathematical descriptions. The models are validated against available measurement data, and a sensitivity analysis for the transient performance of the diesel engine is carried out. Finally, the results of the system simulations under various wave conditions are analyzed to understand the physical processes and compare the efficiency for different cases.

Keywords: Two-stroke diesel engine; Propulsion in waves; System simulation

1. Introduction

Ships traveling in waves encounter various challenges. The added resistance due to waves and wind causes the ship speed to drop and lowers its maneuverability. The speed drop will increase the propeller loading and decrease the efficiency, for which the main engine may struggle to produce the required torque. Furthermore, the load torque on the main engine varies periodically due to the variation of the propeller inflow, induced both by wave mechanics and ship motions. In harsher weather, the propeller may even come out of water, which will result in a sudden loss of propeller torque and a rapid increase of the engine shaft speed. This may lead to overspeeding of the main engine, and the speed protection could trip the engine. The effects of waves on the ship's propulsion is a complex phenomenon involving the interactions between environmental loads, the vessel dynamics and the propulsion system response as shown in Fig. 1 Taskar et al. (2016).

The diesel engine provides necessary power to the propulsion system, and it plays a dominant role in the system dynamics. Most marine diesel engines are equipped with turbochargers, and their transient characteristics, so-called “turbo-lag”, make them a slower part of the overall system. Therefore, it is crucial to understand the dynamics of the diesel engine system in relation to the overall system response during the design of the system, especially for sizing the main engine.

Energy Efficiency Design Index (EEDI) introduced by the International Maritime Organization (IMO) has provided an important framework for reducing green house gas (GHG) emission from the shipping industry. However, the formulation for EEDI favors reducing the installed power of the main engine, which might tempts the designers to do so without applying innovative designs (Papanikolaou et al., 2014). If so, the vessel may not have the sufficient power to maintain its speed or maneuverability in harsh weather. On the other hand, adding a design margin for possible off-design conditions without a proper analysis may be a costly solution. In this regard, finding the optimal power rating of a propulsion plant has become more important than ever.

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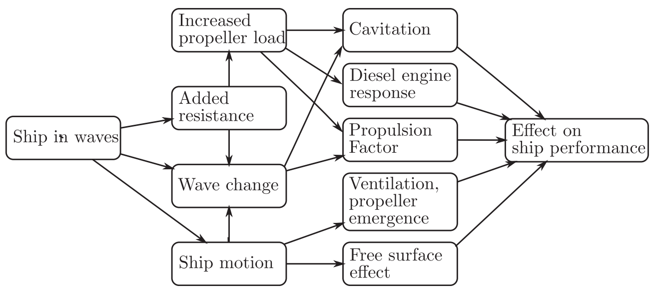

Fig. 1. Effect of waves on the ship propulsion (Taskar et al., 2016).

Using dynamic numerical simulations for a hull-propeller-diesel engine system can be a good tool in the optimization process, saving time and cost of ship designs. A number of system analyses by simulations are found in the literature. The work by Kyrtatos et al. (1999) and Campora and Figari (2005) both utilized a high fidelity model of the diesel engine which simulate physical processes for combustion, heat transfer or a gas exchanging process in a phenomenological way. In these engine models, an engine cycle is simulated at crank angle resolution so that the high frequency torque variation and the efficiency of each engine cycle can be obtained from the physical based models. In the former paper, the propeller torque is given as time-series data from measurements. Therefore, there are limitations to generalize the result of the simulation. In the latter work, simulations were validated to the full-scale measurements during maneuvering operations. In the simulations, a logical telegraph gave identical telegraph commands, which were obtained during the measurement, to the engine governor and the pitch controller of the propeller in order to compare the simulated response of the physical systems to measurements. Still, the effect of the waves is not accounted in the model and could be a potential reason for the gaps between the simulations and the measurements.

A study by el Moctar et al. (2014) provides a unique method coupling Computational Fluid Dynamics (CFD) analysis with a dynamic engine model. In this work, the diesel engine is modeled as a parametric model where only the mechanical dynamics of the system is accounted for. However, the model provides proper boundary conditions for the CFD analysis which simulated the vessel and its propulsion system in the sea trial cases under mild sea conditions. This work shows potential for using the tool for verification of ship designs in the final stage: however, due to the computational intensiveness of CFD calculations, it is difficult to utilize it as a tool for the wider search of design parameters.

Using such high fidelity models is valuable for the analysis of the propulsion system in waves because the systems are often in the off-design conditions where the model parameters from the steady state analysis are not available or applicable. However, the challenge is that the diesel engine itself is a complex system to model and requires extensive parameters and thorough validation of the model. Therefore, a systematic method to build and evaluate such a model is necessary.

In this paper, we try to achieve: i) to provide a systematic procedure of building the dynamic system model for hull-propeller-diesel engine simulations with a particular emphasis on modeling a diesel engine and ii) to provide the insights into the response of the propulsion system in waves by analyzing the result of the numerical simulations. In the first part of the paper, the modeling framework and the modeling process is presented. Then, the descriptions of the physical and mathematical models of the subsystems are given in detail, followed by validation of the individual models. The results of dynamic system simulations are provided for various wave cases with the explanation of relationship between the system response and the physical processes. Finally, the analysis of the system efficiency is presented for the simulation cases, and the influence of transient loads on the diesel engine efficiency is evaluated.

2. Modeling framework

Building a numerical simulation model is an iterative process where a modeler should identify definite goals of the simulation and, thereby, determine the relevant physical models, then find a way to implement them into computerized models. Therefore, it is beneficial to define the modeling framework before starting the process. The modeling framework includes the following:

- definition of the purpose of the simulation,
- selection of the physical processes to be modeled,
- selection of the proper models to describe the physical processes,
- definition of the system variables and system-level interface structure.

2.1. Purpose of the simulation

The purposes of the simulation for the propulsion system in waves are: (1) to simulate the time-domain response of the propulsion system in waves, (2) to simulate the propeller-diesel engine interaction, in particular, in terms of shaft speed and efficiency and (3) to observe the engine system behavior in such conditions. In order to achieve the goals, the engine system model should be able to provide dynamic shaft torque and predict the cycle efficiency of the engine under transient load conditions. In addition, the simulation speed should be at least in the same order of magnitude as real-time.

2.2. Scope of the system model and description of the diesel engine process

The overall propulsion system model is shown in Fig. 2. It includes essential parts of the vessel that interact with each other, namely a vessel hull, a propeller, a mechanical shaft, a diesel engine and a governor, or a speed regulator. Among them, the governor does not exchange energy with others, but it plays a crucial role in the transient behavior of the diesel engine and eventually the whole system. Therefore, it should be included as a part of the system. While the diesel engine is

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