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Optimising the engine-propeller matching for a liquefied natural gas carrier under rough weather

C.H. Marques[a,b,*], C.R.P. Belchior[a], J.-D. Caprace[a]

[a] Ocean Engineering Program/COPPE, Federal University of Rio de Janeiro, RJ, Brazil
[b] School of Engineering, Federal University of Rio Grande, RS, Brazil

HIGHLIGHTS

- Shipping is a key component of the world economy that uses engines and propellers.
- A comprehensive approach to perform the optimisation of engine-propeller matching.
- Actual weather conditions and technical constraints were considered.
- An evolutionary optimisation algorithm was applied to minimise fuel expenditure.
- The result of the case study shows a gain of 19%.

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ABSTRACT

Dual-fuel Diesel engines have become the most interesting alternative for liquefied natural gas carriers (LNGCs) since they are able to use boil-off gas as fuel. However, there is a lack of studies about the optimisation of propulsion system selection considering weather conditions in an integrated approach. Thus, the present work aims to provide a comprehensive approach to perform the optimisation of engine-propeller matching for an LNGC under rough weather. A weather condition was included in the assessment of total resistance and thereby affected the propeller's open water efficiency, shaft speed and brake power. Constraints were included to the approach in order to avoid propellers that could present issues concerning strength, cavitation and vibration. A differential evolution optimisation algorithm was applied to minimise the fuel expenditure of propulsion for a round trip. The case study was designed using an LNGC with cargo capacity of 175,000 m^3 sailing in laden condition from Lake Charles to Tokyo Bay, via Panama Canal, and returning in ballast. All suitable matchings for 5346 propellers were found in 2.8 h and over 28% of them were constrained. The method has shown gains up to 19% of fuel expenditure reduction. The required brake power was approximately 20% higher for rough weather than for still water. Therefore, the approach used here has shown a significant gain and highlighted the value of exploring a broad range of propellers and engines in an integrated manner, as well as considering the weather condition.

1. Introduction

Liquefied natural gas carriers (LNGCs) are specialised ships designed to transport liquefied natural gas (LNG). They are equipped with insulated double-hulled tanks, designed to contain the cargo slightly above atmospheric pressure at a cryogenic temperature without any means of external refrigeration. Despite the high degree of insulation, some vaporisation inevitably occurs because of the unavoidable heat transfer from the surroundings to the cargo. This evaporated LNG, known as boil-off gas (BOG), induces a pressure increase in the tank, and therefore a certain amount of the vapour phase must be taken out of the tank to avoid dangerous overpressure [1]. Usually, this outlet gas flow is used as fuel by the marine energy system to reduce the ship's main fuel consumption [2].

For many years steam propulsion plants were practically the only option for LNGCs due to their capacity to burn BOG directly in the power boiler. However, advances in the design of dual-fuel Diesel engines, shipboard BOG re-liquefaction plants and marine gas turbines have provided meaningful alternatives to the traditional steam power plant [3]. Moreover, propulsion systems based on slow speed two-

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[*] Corresponding author.
E-mail address: cristoferhood@oceanica.ufrj.br (C.H. Marques).

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stroke Diesel engines driving fixed pitch propellers with on-board reliquefaction systems have been successfully used in large LNGCs [1].

When conventional fuel prices are higher than the LNG price, the operational expenditure (OPEX) of propulsion systems unable to use BOG as fuel is increased. Additionally, conventional fuels are not as clean as the BOG, since natural gas is considered environmentally friendly [4]. An alternative to overcome these drawbacks is applying dual-fuel Diesel engines, which are capable to work in two operational modes: Diesel mode and gas mode. In Diesel mode they work as a conventional Diesel engine, burning ordinary liquid fuels such as marine gas oil (MGO), marine Diesel oil (MDO) and heavy fuel oil (HFO). In gas mode, though, they burn essentially a gaseous fuel, and only a little fraction of liquid pilot fuel is required to start the combustion process [5].

Since the prime mover is usually operated until the end of the ship's lifetime, its selection is one of the major steps in merchant shipbuilding projects. Based on interviews with a group of technical experts and managers of selected shipping companies, Bulut et al. [6] defined six major selection criteria. Power is at the top of the list because the engine needs to be capable to provide enough power to satisfy the ship's operational profile. Fuel consumption is a significant indicator of financial feasibility because fuel expenditures represent an expressive component of OPEX.

The propulsion system for the fulfilment of certain purposes of a ship may exhibit various alternative forms, differing from each other with respect to the type and number of components and with different component design specifications. Furthermore, this system operates under conditions that change with the weather, a fact that must be considered in the design phase of the system to obtain the best performance throughout its lifetime. The large number of feasible alternatives, from the point of view of system design specifications, makes the use of optimisation techniques rather advisable to find the optimum solution.

Studies dealing with ship propulsion optimisation similarly to this work are addressed below. Michalski [7] conceived an algorithmic method for preliminary selection of parameters of a ship fitted with a fixed pitch propeller and a Diesel engine. However, he took the engine as a constant figure of specific fuel consumption. Chen and Shih [8] addressed a two-objective optimisation problem regarding Wageningen B-screw series propeller design. Dimopoulos et al. [9] performed a study focused on the optimisation of synthesis, design and operation of a marine energy system for a cruise liner fitted with a combined gas turbine electric and steam system (COGES). Similar works about LNGCs with COGES are Dimopoulos and Frangopoulos [10] and Dimopoulos and Frangopoulos [11].

In order to minimise fuel consumption and carbon dioxide emission, Theotokatos and Tzelepis [12] presented an integrated simulation of a merchant vessel's propulsion system. However, that study dealt with the optimisation of the operating point for a single propulsion design. MAN [13] presented a comparison among machinery concepts for modern LNGCs fitted with dual-fuel low-speed Diesel engines. Lu et al. [14] developed a model to investigate the relationship between fuel consumption and sea states that a ship may encounter during its voyage, thereby optimising the ship's route. This was the only work that considered weather conditions, but a single propulsion design was used.

More recently, Baldi et al. [15] proposed a generic method for modelling a ship energy system with mechanical, electric and thermal demands, and for optimising load allocation on the different components of the system. Trivyza et al. [16] developed a multi-objective method that simultaneously optimises environmental and economic objectives to support decisions for the ship energy system synthesis. In addition, a simulation model of the integrated ship energy systems performance is developed. Sakalis and Frangopoulos [17] presented a general method to optimise the synthesis, design, and operation of integrated energy systems of ships and its application on a system with Diesel main engines. Simulation models of the system and its components were developed.

The need to reduce fuel consumption and environmental pollution has encouraged researches on waste heat recovery systems. In this field, a techno-economic analysis of exhaust gas waste heat recovery on ship propulsion installations appears in Theotokatos and Livanos [18], while a step further with optimisation is taken in Benvenuto et al. [19]. In Yang and Yeh [20], the thermodynamic and economic performance of an organic Rankine cycle system operating on the exhaust gas thermal energy of a marine Diesel engine is firstly studied, followed by system optimisation. In Kyriakidis et al. [21], a system with exhaust gas recirculation and multi-stage waste heat recovery is optimised.

The lack of studies about engine-propeller matching optimisation might arise from the lack of engine models suitable for optimisation problems. In general, models must be calibrated for every single engine, thus being inappropriate for iterative procedures such as optimisation. Marques et al. [22] presented the state of the art on engine simulation models and improved an engine model dedicated to optimisation problems, developed earlier by Marques and Belchior [23]. The present study could be performed thanks to this improved model.

Some of the aforementioned references have addressed quite useful methods to simulate and optimise marine energy systems. However, neither of them studied the optimisation of prime mover selection considering dual-fuel Diesel engines driving propellers and weather conditions within an integrated approach. Therefore, the original contribution of this work can be summarised as follows: (a) The engine-propeller matching optimisation problem is tackled in a single step, instead of firstly optimising the propeller and then the engine. (b) Technical constraints are applied to avoid designs presenting propellers with strength, cavitation or vibration concerns. (c) The effect of weather conditions along the voyage is taken into account in the optimisation process. This results in a new methodology that improves the performance of the entire propeller-engine system considering the future operational profile of the vessel.

The methodology that has been developed, a case study, results and discussion as well as conclusion, are presented below.

2. Methodology

The method used consists in an optimisation process whose objective function to be minimised is the fuel expenditure with propulsion and the design variables are the propulsion parameters. Thus, the purpose is finding the synthesis of components and the component design characteristics that minimise the fuel expenditure with propulsion of an LNGC under rough weather. Herein, synthesis of components refers to the condition of the propulsion system to hold one or two main engines, each one driving a propeller. Component design characteristics refer to the propeller and engine specification. All of the computations were performed in MatLab. The proposed approach is explained below in flowcharts and an overview of each mathematical model is then addressed.

Fig. 1 shows the different computations that were followed, as well as their input and output data. Given a guess of optimisation design variables, that is, propulsion parameters, the first step is estimating the brake power and shaft speed in service for each route track, as detailed in Fig. 2. The next steps are computing the specified maximum continuous rating (SMCR) and then determining suitable engines, still considering the initial guess of design variables. The fourth step is assessing fuel expenditure with propulsion for each suitable engine. Having accomplished this, a simple search is performed for the engine with minimum fuel expenditure, which is the optimum for that guess of design variables.

All these steps are executed iteratively by the optimisation algorithm, and convergence is verified at the end of each run. If the algorithm converges, the optimum engine-propeller matching was reached; otherwise, a new guess of propulsion parameters is taken by the optimisation algorithm, as detailed in Fig. 3. Similarly, if there is no

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