Optimal Energy Resources Scheduling of Hybrid Diesel/Battery Ships in Shallow Waters

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Abstract. In this paper, optimal energy resources scheduling for a hybrid diesel/battery ship that sails in shallow water is studied. Sailing in shallow waters increases the impact of water depth on the ship's resistance. Changing the ship's resistance affects the speed, consumed fuel and consequently the operation cost. This paper proposes a non-linear model to find the optimal operation of diesel generator and battery bank for supplying the ships' engines considering the impact of variable water depth of the traveling route on the ship's operation cost. To this end, first, different types of resistance are calculated for the understudy real case ship. Then the impact of the water depth on the resistance is investigated, and finally, the optimization problem is formulated and solved using a Genetic Algorithm. Simulation results show the efficiency of the proposed scheduling method in decreasing the total operation cost while considering the different operational constraints.

Keywords: Real-time scheduling · Energy management · Cost optimization

1 Introduction

The utilization of diesel generators is known as one of the common techniques to generate power in marine vessels [1]. Energy storage systems can also be used in parallel with the diesel generators to cover part of the fast electricity demand fluctuations that the diesel generators cannot secure. Moreover, charging the batteries via cold-ironing at harbors and use their energy during the sailing can help in reducing the greenhouse gas emission caused by diesel generators [2]. Optimal energy resources management is an important issue for cost-effective and reliable operation of ships. This problem has been widely studied in the literature so far. Studies [3–5] present energy management strategies for fuel cell/battery hybrid zero-emission ships considering different assumptions. The work in [6] applies a non-linear method for deriving a control strategy of a ship with only a hybrid energy storage system as the energy resource. The authors of [2] tackle the energy management problem of an all-electric ship using dynamic programming. In [7], model predictive control is adopted with integrated perturbation analysis and sequential programming algorithms to solve

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the optimal scheduling problem of a ship with hybrid batteries and ultra-capacitors. In [1], optimal energy resources scheduling of a ship with diesel generators, photovoltaic panels, batteries, and cold ironing is solved. The work in [8] studies the energy management of a hybrid diesel//battery ship alongside with a high efficient combined cooling and heat power plant.

To the best of our knowledge, most of the studies in the marine vessels' energy management are performed assuming sailing in deep waters and ignore the impact of water depth on the efficiency of the engines. In shallow waters, the ship's resistance is affected by the water depth [9]. Thus, the efficiency of the engines at different portions of the traveling route will be different and to find the optimal power scheduling of the ship during the sailing, the changes in the water depth should be included in the behavior model. In this paper, the optimal energy management of a hybrid diesel/battery ship that sails in the shallow waters is studied. Main contributions of this paper are as follows:

1. Formulating the main resistance coefficients for an understudy case ship.
2. Proposing a non-linear model for energy management of the hybrid ship in shallow waters by considering different operation constraints.
3. Proposing an optimization process that calculates the optimal speed leading to minimal cost for each water depth of a given traveling route and vessel.

The rest of the paper is organized as follows. In Sect. 2 the problem is defined. In Sect. 3 ship's resistance is formulated. The relation between fuel consumption and engines power is determined in Sect. 4. An optimization method is proposed in Sect. 5. Numerical results are shown in Sect. 6. Finally, Sect. 7 concludes the paper.

2 Problem Definition

A hybrid diesel/battery ship that sails on a specific route in shallow water is considered. The ship information is presented in Table 1. The rated power of the diesel generator is 1000 kW. Batteries capacity is 120 kW. The depth of the water at different points of the traveling route is known. Following the water depth in different locations, the ships' resistance for sailing varies. Thus, the consumed fuel for reaching a specific speed in different locations will be different. The goal of this paper is to adjust the speed of the ship in different portions of the traveling route such that the minimal operation cost is obtained.

Table 1. Ship information

ρ_s	S	L	ϑ	g	∇	B	T	β	LCB
1.005	490.77	49.830	1.188e−6	9.8	485.5	11.297	1.920	0.7874	−4.696

3 Ship's Resistance Formulation

The relation between the speed and engines' power is as below [10]:

$$P_x^e = R_x V_x \tag{1}$$

P_x^e is the engine's power (kW), R_x is the resistance, and V_x is the speed (m/s) at portion x of the traveling route. Ship's resistance is formulated as below:

$$R_x = C_x^T \frac{\rho_s}{2} V_x^2 S \tag{2}$$

C_x^T is the total resistance coefficient, ρ_s is the mass density, and S is the wetted surface of the ship. C_x^T is calculated as below [10]:

$$C_x^F = C_x^F + C_x^R + C_x^A + C_x^{AA} + C_x^{AS} \tag{3}$$

C_F represents the frictional resistance coefficient, C_x^R is the residual resistance coefficient, C_x^A is the incremental resistance coefficient, C_x^{AA} is the air resistance coefficient, and C_x^{AS} is the steering resistance coefficient. The frictional resistance coefficient is formulated as below [10]:

$$C_x^F = 0.075\left(log_{10}^{\frac{V_x L}{\vartheta}} - 2\right)^{-2} \tag{4}$$

L is the length of the waterline and ϑ is the coefficient of kinematic viscosity. C_x^R is obtained as a function of the Froude number using the curves that are drawn for standard sizes of the ships [10]. The Froude number is as below:

$$F_{n,x} = V_x/\sqrt{gL} \tag{5}$$

g is the standard gravity. In order to know which curve should be used for finding the relation between C_x^R and $F_{n,x}$ two below factors should be calculated.

$$\varphi = \nabla/LBT\beta \quad \mu = \mathrm{L}/\nabla^{1/3} \tag{6}$$

∇ is the volumetric displacement, B and T are the breadth and draught of the ship, respectively, and β represents the mid-ship section area coefficient. Based on the obtained values of φ and μ for the understudy ship, the proper curve that represents the relation between C_x^R and $F_{n,x}$ is obtained using the diagrams in [10]. This curve can be used for the ships in which $B/T = 2.5$. In the case that this ratio is different, the value of C_x^R needs to be updated as follows [10]:

$$C_x^R = C_x^{R\left(\frac{B}{T}=2.5\right)} + 0.16 \times 10^{-3} \times \left(\frac{B}{T} - 2,5\right) \tag{7}$$

The real samples that are extracted for the curves are presented in Fig. 1. A fourth-degree polynomial function is fitted with these data samples using cftool in Matlab software as below:

$$10^3 C_x^R = 0.00942 \times V_x^4 - 0.1827 \times V_x^3 + 1.413 \times V_x^2 - 4.927 \times V_x + 6.75 \quad (8)$$

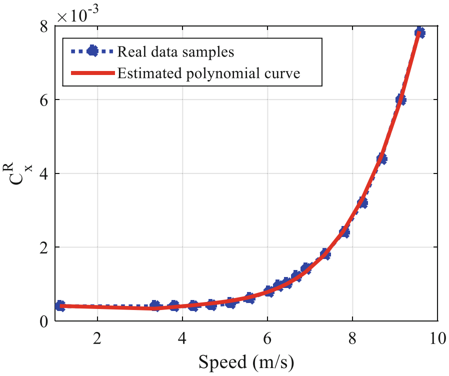

Fig. 1. Estimating the C_x^R curve

The incremental resistance coefficient C_x^A depends on the length of the waterline and for understudy ship is equal to 0.4×10^{-3}. In this paper, we consider that $C_x^{AA} = C_x^{AS} = 0$.

Now, the impact of water depth on the resistance is formulated. Figure 2(a) compares the ship's resistance for shallow waters and deep waters as a function of depth Froude number. The depth Froude number for water depth h_x at portion x of the traveling route is defined as below:

$$Fr_{h_x} = V_x / \sqrt{g h_x} \quad (9)$$

Experiments show that for speeds around $V_x^c = \sqrt{g h_x}$ the resistance increases significantly. There is no mathematical formulation that presents the relation between resistance and water depth. However, based on the information in Fig. 2(a), an approximated formulation is proposed to model this relation:

$$\gamma_x(V_x) = 1.01 - 0.01 V_x + \frac{10}{\sqrt{2\pi g h_x}} \exp\left(- \frac{V_x - \sqrt{g h_x}}{\left(\sqrt{2\pi g h_x}/5\right)^2} \right) \quad (10)$$

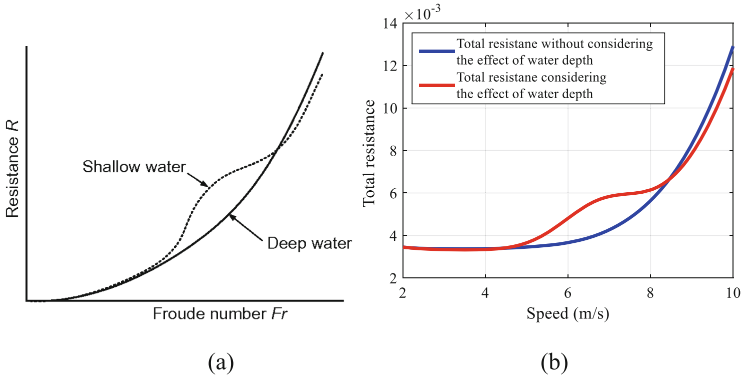

Fig. 2. Comparing the ship's resistance for deep and shallow waters, a) experiment results in [9] b) proposed formula for estimation

The ship's resistance after considering the impact of the water depth is obtained from the following formulation:

$$R_x^C = \gamma_x(V_x) \times R_x \tag{11}$$

Figure 2(b) compares the total resistance with and without considering the shallow water impact on the resistance for 4.5 m water depth using Eq. (10).

4 The Relation Between Fuel Consumption and Power

We use the formulation below to find the mass of fuel consumption for a specific output power of the diesel generator at portion x of the traveling route [11]:

$$FC_x^{DG} = SFOC \times P_x^{DG} \tag{12}$$

P_x^{DG} is the output power of the diesel generator (kW) and FC_x^{DG} is the fuel consumption (g/h). $SFOC$ represents the Specific fuel oil consumption (g/kWh). The SFOC curve for a diesel generator is depicted in Fig. 3 [11].

As shown in Fig. 3, SFOC depends also on P_x^{DG}. This curve is also estimated with a fourth-degree polynomial function. Considering that SFOC in 100% output power of the power generator is 211 g/kWh [11], we obtain the following formulation for SFOC using cftool in Matlab software:

$$\begin{aligned} SFOC\left(P_x^{DG}\right) = {} & 2.04 \times 10^{-10} \times P_x^{DG^4} - 6.88 \times 10^{-7} \times P_x^{DG^3} + 0.87 \times 10^{-3} \times P_x^{DG^2} \\ & - 0.474 \times P_x^{DG} + 300.8 \end{aligned} \tag{13}$$

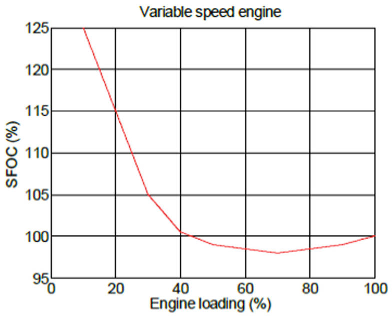

Fig. 3. SFOC curve for a diesel generator

5 Optimization Process

The sailing route is divided into several portions, each of which has a different water depth. The length of each portion x is D_x. Our goal is to find the optimal value for ship's speed i.e., V_x at each portion that minimize the total operation cost. This will estimate what would be the post state (cost) if a given speed is used [12]. So, V_x is the decision making variable. Since the ship is a hybrid diesel/battery ship the cost of both fuel and battery should be considered in the optimization. We define the objective function as follows:

$$\min Cost = \sum_{x \in X} C^F FC_x^{DG} t_x + C^{CH}\left(B_0^s - B_{n_x}^s\right) + \sum_{x \in X} C^{BD} B_x^{Dch} t_x \tag{14}$$

X is the set of all portions. t_x is the time point of leaving route portion x (h). C^F is the fuel price ($/g), C^{CH} is the cost of charging the batteries at harbor before starting the journey, and C^{BD} is a cost that refers to batteries degradation due to discharging. B_x^{Dch} is the discharged power of batteries in portion x. n_x is the number of traveling route portions. B_0^s and $B_{n_x}^s$ are batteries state of charge (SOC) at the beginning and the end of the journey, respectively. The first term in (14) represents the total fuel consumption cost. FC_x^{DG} in (14) is obtained as a function of P_x^{DG} using (12) and (13). The second term is the cost of charging the batteries at harbor before starting the journey. The third term is a cost that is imposed due to batteries degradation by discharging [5]. The following constraints are considered in the optimization process:

Diesel generator's constraint:

$$0 \le P_x^{DG} \le \overline{P^{DG}} \tag{15}$$

$$\left(P_x^{DG} - P_{x-1}^{DG}\right)/t_x \le \overline{R} \tag{16}$$

$\overline{P^{DG}}$ is the rated power of the diesel generator. $\overline{R}$ is the power ramp rate of the diesel generator (kW/h), and t_x is formulated as follows:

$$t_x = D_x / \left(3.6 \times 10^3 V_x\right) \tag{17}$$

Engines' power consumption constraint:

$$0 \leq P_x^e \leq \overline{P^e} \tag{18}$$

P_x^e is obtained by (1) considering (2)–(11). $\overline{P^e}$ is the rated power of the engines. Batteries operation constraints are as follows [13]:

$$\underline{SOC} \leq B_x^s \leq \overline{SOC} \tag{19}$$

$$B_{x-1}^s + e^{Ch} B_x^{Ch} t_x \leq \overline{SOC} \tag{20}$$

$$B_{x-1}^s - B_x^{Dch} t_x / e^{Dch} \geq \underline{SOC} \tag{21}$$

$$B_x^s = B_{x-1}^s + e^{Ch} B_x^{Ch} t_x - B_x^{Dch} t_x / e^{Dch} \tag{22}$$

$\overline{SOC}$ and $\underline{SOC}$ are upper and lower operation bounds of the batteries, respectively. B_x^s is the batteries SOC at portion x. B_x^{Ch} is the charged power in batteries at portion x. e^{Ch} and e^{Dch} are charging and discharging efficiencies. Ship's acceleration constraint is presented as below:

$$|V_x - V_{x-1}| / \left(3.6 \times 10^3 t_x\right) \leq \overline{a} \tag{23}$$

$\overline{a}$ is the maximum allowable acceleration (m/s^2). Traveling time constraint is:

$$\underline{T} \leq \sum\nolimits_{x \in X} t_x \leq \overline{T} \tag{24}$$

Fuel consumption constraint is formulated as below:

$$\sum\nolimits_{x \in X} FC_x^{DG} t_x \leq \overline{FC} \tag{25}$$

$\overline{FC}$ is the maximum allowable fuel consumption for the journey. This constraint can be considered for either the limitation of the fuel tank or greenhouse gas emission. Power flow constraint is presented as follows:

$$P_x^{DG} = P_x^e + B_x^{Ch} - B_x^{Dch} \tag{26}$$

The proposed formulation (14)–(26) is a non-linear optimization problem. Genetic Algorithm tool in Matlab software is used to solve this optimization.

6 Numerical Results

This section presents simulation results. Relevant ship information is presented in Sect. 2 and Table 1. Upper and lower bounds for the SOC of batteries is assumed to be 80% and 20% of the batteries capacity, respectively. Fuel cost, Battery charging cost and the cost related to the battery degradation is 0.0037 \$/g, 0.16 \$/kWh, and 0.045 \$/kWh, respectively [1]. Lower and upper limits of the traveling time are 40 and 50 min, respectively. The power ramp rate of the diesel generator is 0.720 kW/h [8]. The acceleration for the ship is also limited to 0.0083 m/s^2. Batteries charging and discharging efficiencies are 0.85 and 1 [4]. The length of each portion of the route and the respective water depth are presented in Fig. 4. Simulation results are presented in Fig. 5. In Fig. 5(a), the ship's speed is presented in knots, where one knot is equivalent to 0.5144 m/s. The speed at each portion of the route is different based on the water

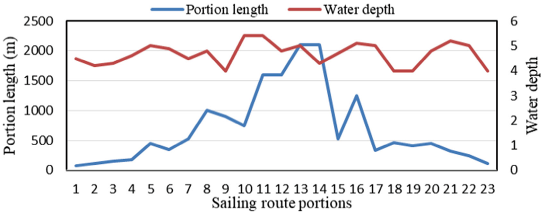

Fig. 4. Sailing route portions' length and water depth

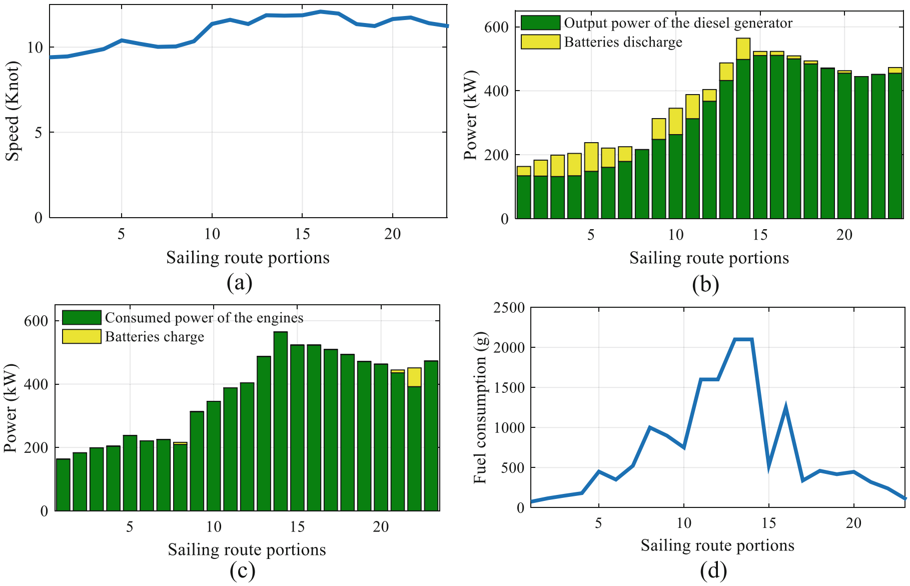

Fig. 5. Simulation results, a) ship's speed scheduling, b) power generation scheduling c) power consumption scheduling and d) fuel consumption of the diesel generator.

depth and operation constraints. It can be seen that the speed variation has been kept smooth as much as possible which makes it practical, and provides a comfortable journey to the passengers. Power generation and consumption flow in the ship are presented in Fig. 4(b) and Fig. 5(c), respectively. As shown in Fig. 5(b) the output power of the diesel generator is smooth and fast power fluctuations caused by the engines are supplied by the batteries. The fuel consumption process is illustrated in Fig. 5(d), which is dependent on both power generation by the diesel generator and the length of each route portion. According to Fig. 4, portions 13 and 14 have the longest distances and consequently high power consumption. The total operation cost obtained is 230 $, where 96.5% of that cost is related to the fuel consumption cost as the main source of energy. Total fuel consumption is 60 kg which is equal to the maximum limit of fuel consumption, and the total traveling time is 46 min.

7 Conclusions

In this paper, the optimal energy management of a hybrid diesel/battery ship that sails in shallow waters is studied. Sailing in shallow waters relates the ship's resistance to the water depth and this affects the efficiency of engines and consequently the total operation cost. In order to study these impacts, first, the ship resistance is formulated. Then the impact of the water depth on the resistance is mathematically quantified, and finally, a non-linear optimization problem is proposed to find the optimal speed of the ship in different portions of a traveling route. Simulation results show the efficiency of the proposed method in achieving a speed scheduling program that leads to a smooth and stable traveling for the ship while satisfying the operation and time table constraints. Moreover, the simulation results highlight the role of batteries in reducing the power fluctuations of the diesel generator caused by the engines.

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