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# A Model-Based Evaluation of Wave Collision Effects on the Multi-Objective Optimization of Hybrid Ships Sizing

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***Abstract*— Ship hybridization has increasingly attracted attention to accomplish the 2050 emission goals. However, despite the recent benefits of utilizing a hybrid ship power system, additional power fluctuation sources in an All-Electric Ship (AES) power system have evolved. These variations must be thoroughly examined at the vessel design and control level. Otherwise, the optimum performance of the ship power system in various sea situations cannot be theoretically guaranteed. One of the crucial circumstances under which propellers generate power variations in the AES's power system is wave collision. This paper focuses on the effect of ship motions on the sizing and control optimization of hybrid ship propulsion systems at the design level. First, a model-based approach is proposed for integrating the in-and-out-of-water effect into an existing load profile from a specific journey. By utilizing the proposed strategy, a load profile can be modified to represent the power fluctuation of the extreme conditions. Then, a nested double-layer multi-objective optimization problem for sizing and controlling hybrid vessels is presented. The influence of incorporating wave collision on the sizing optimization of hybrid vessels is investigated using the presented optimization approach and model-based load profile adjustment. It is shown that the in-and-out-of-water effect resulting from ship movements in extreme conditions can substantially impact the sizing of the all-electric ship's components. In addition, it can significantly increase the diesel fuel consumption of the vessel. Therefore, the ship motions should be considered to ensure an optimum design and control in various operation conditions during the ship's lifespan.**

***Keywords*— Ship hybridisation, All-electric ships, Hybrid propulsion system, Wave collisions, Ship power system***

## I. INTRODUCTION

The shipping industry presently accounts for 3% of global greenhouse gas emissions. As a result, the maritime sector and port authorities must begin to engage in decarbonization to implement zero-emission technology [1]. There are several challenges to implementing full-scale usage of zero-emission fuels on maritime vessels [2]. However, the IMO's (International Maritime Organisation) decision to target a reduction of 50% of greenhouse gas emissions from maritime transport by 2050 is a significant step toward complete decarbonization [3]. Alternative sources of power with minimal environmental effects are becoming essential due to growing concerns about global environmental pollution [4]. Therefore, regarding the original mechanical propulsion systems, diesel-electric propulsion systems are employed to decouple power generation and consumption. Moreover, due to the relatively high energy density, hydrogen fuel cells have recently gained attention in addition to batteries as an alternative energy source for AES [5]–[7]. A typical hybrid ship powertrain for a hybrid ship is shown in Fig. 1. In this structure, various types of movers propel the propellers, and different sources provide power for the electrical system [8]–[10].

On the other hand, the design and control of the ship power system have become more challenging due to the ship hybridization approach for lowering greenhouse gas emissions [11]. Various studies in recent years concentrated on sizing, control, and energy management in hybrid ships and investigated their benefits, challenges, and obstacles. A power management system is proposed in [12], which is based on enhancing propulsion system control in a twin-screw ship power system. Thus, the developed power management strategy can reduce the AES design level requirement for energy storage systems. An optimal sizing method for a hybrid ship power system, including PV, diesel, and energy storage systems, is presented in [13]. In order to reduce CO2 emissions, diesel fuel, and investment costs, a technique to determine the optimum size of the ESS, PV, and diesel generator in a ship power system is presented in [14]. Optimization of the design with varying installation positions is performed in [15], both with and without taking component failure into account. A power management system based on open-water characteristics of the propulsion system is suggested in [16]. The presented approach increases the mechanical components' lifespan during speed changes in various operational conditions. The transportation electrification applications for hydrogen fuel cells are

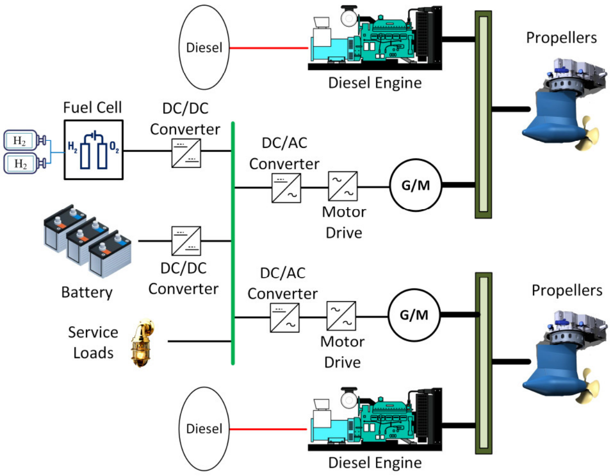

Fig. 1 The assumed hybrid propulsion system for analyzing the performance of the optimal design.

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investigated in [17] – [20]. AES power system is optimized by employing a complex three-step optimization with a specific goal for each stage in [21]. A multi-objective optimal strategy for mitigating the AES's power system fluctuations employing propulsion system participation is proposed in [22]. To achieve an economically efficient operating point, the presented method balances the propeller torque/speed change and the energy storage charge/discharge rate.

According to the state-of-the-art mentioned above, the powertrain design for hybrid ships becomes increasingly complex as additional sources are included in the power system, such as diesel engines, fuel cells, and batteries. Although several studies explore the optimization approaches for ship hybridization, their primary focus is the design level. Furthermore, the ship motions are substantial in wave-encountering situations [23]. However, the mentioned studies did not take into account the impacts of wave collision conditions under extreme conditions and the corresponding power system control requirements on the sizing of the power system sources. As a result, they cannot theoretically guarantee that the optimization output will function effectively for a maritime vessel whose sufficiently long operational power profile corresponds to vessel-wave conditions.

To address the stated challenges, this paper evaluates the effects of wave collision in extreme conditions on the sizing and control of an all-electric ship. For this purpose, first, a model-based approach is proposed to integrate the wave effects on existing load profiles for optimization problems. Then, a multi-objective nested double-layer optimization technique is deployed for sizing and controlling ship components. Utilizing the proposed optimization approach regarding the modified operation profile, the effects of wave collisions on the hybridization design are investigated for a particular type of vessel.

The rest of the paper is organized as follows: section II describes the aspects and methodology of the proposed strategy for integrating the wave collision impacts in an existing load profile. Then, the multi-objective optimization method is described in section III. The main objective functions and their constraints are explained in this section. After that, section IV defines two scenarios regarding an actual load profile to investigate the effectiveness of the proposed approaches. In addition, the influence of the in-and-out-of-the-water thrust loss in design optimization is discussed according to the optimization results. Finally, the results of the study are concluded in section V.

## II. PROPOSED APPROACH FOR INTEGRATING WAVE IMPACTS IN OPERATION PROFILES

This section describes the proposed model-based approach to integrating wave impacts on an existing load profile from a specific journey. Fig. 2 depicts the proposed method for enhancing available load profiles based on ship motions during wave collisions. The developed framework interconnects the hydrodynamic and electric aspects of an all-electric ship. Therefore, it can theoretically incorporate the power fluctuations resulting from the in-and-out-of-water effect into the load profile. The hydrodynamic section of the proposed method includes the ship motion model, the in-and-out-of-water effect model, and the propeller model. The main focus of this part of the model is to thoroughly model and investigate the effects of the ship's motions on propellers' torque and consumption power. In the ship motion model, the ship angles are explored according to the ship and encountering wave characteristics. The in-and-out-of-water effect model analyses the propellers' immersion depth concerning the ship angles during vessel-wave encountering situations. In addition, the in-and-out-of-water impact on thrust seeks to determine the thrust loss and appropriately modify the thrust delivered by the propellers. This paper employs the provided term in [23] to explore the in-and-out-of-water impact thrust loss. This expression, which is commonly used in maritime control systems for exploring the thrust loss factor, is represented in the equation (1).

$$TLF = \begin{cases} 0, & Constr.a \\ 1-[0.675\times(1-\frac{0.769pid}{r})^{1.258}], & Constr.b \\ 1, & Constr.c \end{cases} \tag{1}$$

In the equation (1), *pid* is the propellers immersion depth, which is determined by the wave collision model. In addition, *r* is the radius of propellers, and *TLF* is the resulted thrust loss factor. Furthermore, *constr.a*, *constr.b*, and *constr.c* are the immersion depth constraints for each stage. They are typically determined by analyzing the experimental results

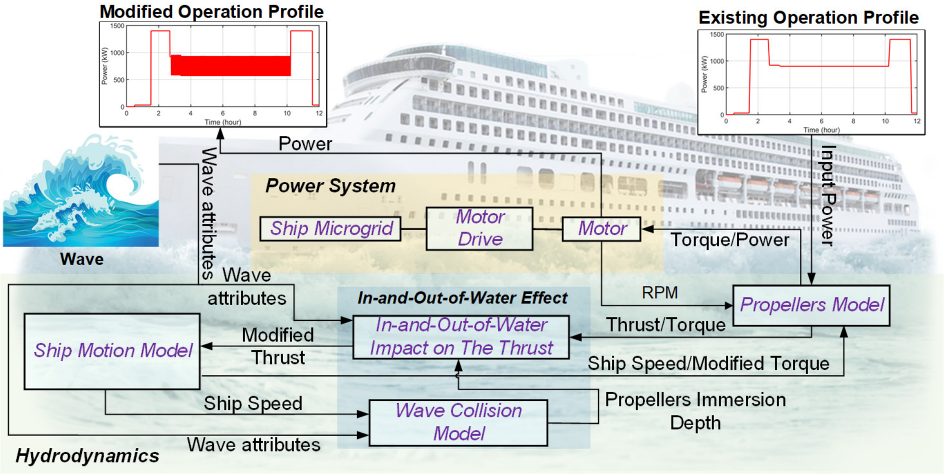

Fig. 2 The proposed model-based approach for integrating wave effects into an existing load profile for assessing the power system sizing optimization.

regarding the ship and its propellers. In this study, they are considered as below equations [24].

$$\begin{aligned} &Constr.a \rightarrow pid / r < -0.48 \\ &Constr.b \rightarrow -0.48 < pid / r < 1.3 \\ &Constr.c \rightarrow pid / r \geq 1.3 \end{aligned} \tag{2}$$

Furthermore, the propeller model analyses the torque and thrust of the ship propulsion system. Two indices that depend on the propeller's geometrical features can be utilized to determine the torque and thrust of propellers. The following expressions are deployed in this paper to model the propeller's performance. Further detail can be found in [11].

$$T = K_T\left(\frac{A_E}{A_o}, \frac{P}{D}, J_A, R_n, z\right)\operatorname{sgn}(n)\frac{n^2 \rho D^4}{4\pi^2} \tag{3}$$

$$Q = K_Q\left(\frac{A_E}{A_o}, \frac{P}{D}, J_A, R_n, z\right)\operatorname{sgn}(n)\frac{n^2 \rho D^5}{4\pi^2} \tag{4}$$

In these equations, $n$ is rotational speed, $z$ is the number of propeller blades, $\rho$ is the fluid density, $A_E/A_o$ is the propeller blade area, $P$ is the pitch of the propeller, $D$ is the diameter, $J_A$ is the advance coefficient, $R_n$ is Reynold's number, $T$ is the thrust, and $Q$ is the toque. In addition, $K_T$ and $K_Q$ describe the open-water characteristics as determined by a towing tank test. The model in this paper is based on the characteristics of a Wageningen B-series propeller [16]. These characteristics are shown in Fig. 3. The power system model includes the hybrid ship power system and its corresponding control system.

The load profile and wave properties that currently exist are inputs of the suggested technique shown in Fig. 2. The propulsion system's thrust and torque are then modified in accordance with the desired operational condition. As a result, the propulsion system's power consumption varies while considering the ship's motion, propellers immersion depth variations, and the in-and-out-of-water effect. The proposed strategy calculates the propulsion system's updated electric power consumption and outputs the result. Thus, the suggested approach potentially enables adding various wave classes to the current load profiles. This technique yields a model-based design approach that is more accurate and aids in enhancing the performance and reliability of maritime vessels under various operational conditions at the design and control levels.

## III. OPTIMIZATION PROBLEM DESCRIPTION

This section describes the optimization problem and its objectives, variables, and constraints for sizing and controlling a hybrid ship. The altered operating profiles and power system characteristics, such as quantity, power density, and state-of-charge of the battery, are included in the input parameters. The outer layer of the presented double-layered multi-objective optimization method approximately assesses the suggested structure's capital expenses (CAPEX). The energy management system is then optimized in the inner layer to reduce operating expenses (OPEX). The OPEX model calculates the use of hydrogen and diesel fuel. The MILP algorithm is applied to plan the components' working duration, start/stop, and associated power. In addition, NSGA-II is used to identify the most effective solutions to this multi-objective issue. In the outer layer optimization, three objectives must be concurrently optimized. They are 1) OPEX, 2) CAPEX, and 3) the consumed diesel fuel weight. These objective functions are represented in equations (5), (6) , and (7). Further details can be found in [25].

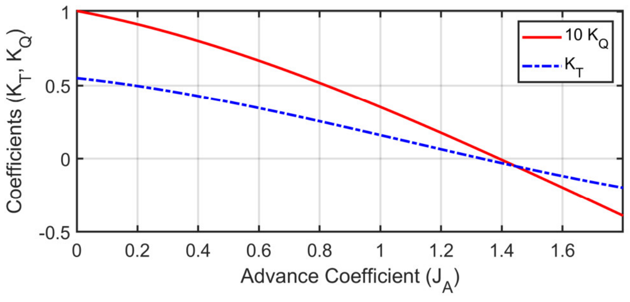

Fig. 3 The Wageningen B-series propeller's coefficients ($K_T$ and $K_Q$) in relation to the advance coefficient.

$$F_1 = OPEX(C_{Bat}, V_{Hydrogen}, W_{DE}) \tag{5}$$

$$F_2 = CAPEX(CI_{DE}, CI_{Bat}, CI_{FC}) \tag{6}$$

$$F_3 = W_{DE}(P_{DE}, N_{DE}) \tag{7}$$

In these equations, $C_{Bat}$ is the cost of onshore charging, $V_{Hydrogen}$ is the hydrogen fuel cost, $W_{DE}$ is the diesel fuel cost, $CI_{DE}$, $CI_{Bat}$, and $CI_{FC}$ are investment costs of diesel engines, batteries, and fuel cells based on their power/energy ratings, $P_{DE}$ is the power rating of diesel engine, and $N_{DE}$ is the number of diesel engines. As mentioned, the purpose of the inner layer is to reduce OPEX. Since batteries are discharged to their lowest SOC to reduce the consumption of diesel and hydrogen fuel, the inner layer does not consider the price of onshore power used to charge the batteries. The inner layer objective function is given in the equation (8).

$$OPEX = \sum_{h}[C_{Hydrogen}\sum_{N_{FC}} V_{Hydrogen}(t) + C_{DE}\sum_{N_{DE}} W_{DE}(i)] \tag{8}$$

where $C_{Hydrogen}$ and $C_{DE}$ are the prices of $H_2$ and diesel engines, respectively. The predefined parameters for the optimization problem in this study are listed in Table I. It is obvious that with differing unit pricing in various markets, the OPEX may change. The number and rating of diesel engines, batteries, and fuel cells are obtained according to the optimization method with respect to these parameters and the enhanced load profile. Accordingly, the impact of wave collisions on optimum sizing is discussed in the next section.

## IV. RESULTS AND DISCUSSIONS

In this study, an offshore support vessel is used to analyze the impact of wave collisions on the sizing and control of the ship. This type of vessel is commonly used for transferring crew. Table II displays the study vessel's characteristics that can be incorporated into the ship motion model. The related operating profiles are determined by measuring the primary

TABLE I PREDEFINED OPTIMIZATION PARAMETERS FOR THIS STUDY

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| DE Number | 2 | Electricity price | 0.16 $/kWh |
| Battery number | 1 | $H_2$ price | 0.2 $/Liter |
| Fuel cell number | 1 | DE investment | 300 $/kW |
| Diesel price | 1.5 $/kg | Bat. investment | 475 $/kW |
| FC investment | 2000 $/kW | | |

TABLE II THE STUDIED VESSEL CHARECTERISTICS

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Vessel length | 19.5 m | Vessel width | 7.5 m |
| Engine power | 720 kW | Max. speed | 24 knots |
| Cruising speed | 22 knots | Number of blades | 4 |

diesel engines during a historical voyage. The journey takes roughly 12 hours in total. The vessel travels to the operating location in around 1.5 hours. The return journey also lasts the same. The ship remains at its destination for 7 hours. The maximum power occurs when the ship travels to and returns from the region. The existing operation profile from the described trip is depicted in Fig. 4 (a). The ship is assumed to be hitting an irregular wave in accordance with standard sea states.

Fig. 5 illustrates a schematic of this irregular wave and the regular waves that, when combined, form the initial wave. It is considered that two regular wave encounters the vessel. One strikes the ship from the port side, while the other hits it from the front. Table III lists the characteristics of the regular waves that produce the initial irregular wave. The figure presented in Fig. 4 (b) is obtained by deploying the load profile in Fig. 4 (a) and the colliding wave in Fig. 5 as inputs for the proposed model-based approach for altering the load profiles. In addition, a portion of Fig. 4 (b) is enlarged in Fig. 4 (c), making the in-and-out-of-water effect caused by ship movements during wave situations more obvious. It can be seen in Fig. 4 (c) that the power fluctuations caused by the thrust loss can be up to about 40 percent. Thus, it can have a substantial effect on the control system of the vessel in extreme conditions and should be considered at the design level. Therefore, it is expected that adding the in-and-out-of-water effect in the input of the provided optimization problem will significantly impact the outcomes. Two scenarios are defined to evaluate this. In the first scenario, the hybrid ship diesel engine, fuel cell, and batteries are sized according to the existing load profile, which is illustrated in Fig. 4 (a). In addition, the mentioned components are sized in the second scenario by employing the presented optimization strategy and the altered operation profile shown in Fig. 4 (b). As previously stated, this load profile is derived by including the ship motion effects in the electrical system during wave collision with the attributes of Table III. The suggested ship power systems are optimized according to the two operating profiles outlined.

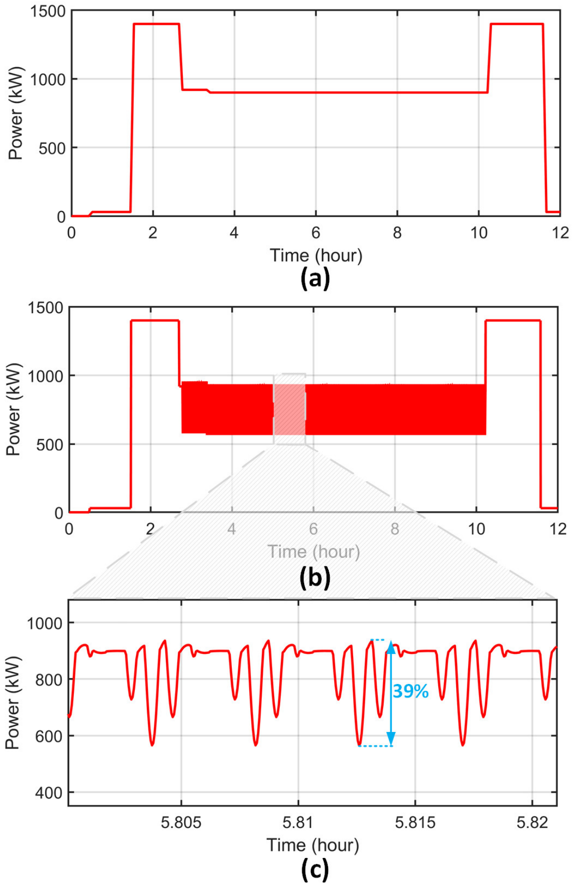

Fig. 4 The investigated operation load profiles: a) the existing operation profile from a specific journey, b) the modified operation profile to consider wave collision impacts using the proposed model-based method, and c) a magnified part of the modified operation profile for better comparison.

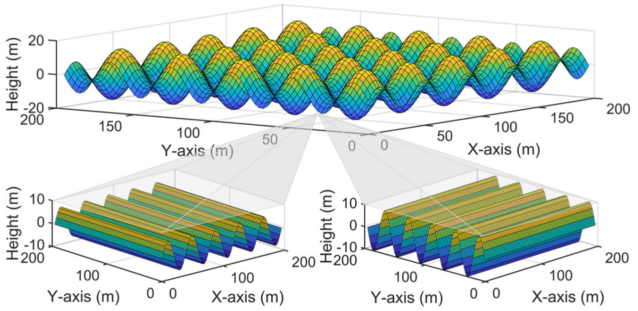

Fig. 5 The maritime environment's presumed heading and port regular waves and the resulting irregular waves that the studied vessel encounters.

TABLE III THE IRREGULAR WAVE CHARECTERISTICS

| Parameter | Port Wave | Front Wave |
|---|---|---|
| Height | 10 m | 7 m |
| Relative angle according to the ship | 90° | 0° |
| Time period | 7 s | 5 s |

Fig. 6 illustrates The OPEX concerning the CAPEX for the described scenarios. The trade-off between OPEX and CAPEX is depicted in this figure. It should be noted that without losing generality, maintenance and costs are overlooked in this evaluation. The hydrogen cost, diesel fuel cost, and onshore charging energy expense are considered in the OPEX. Fig. 7 displays the diesel fuel usage Pareto fronts in relation to CAPEX. It can be seen that when CAPEX rises, diesel fuel usage decreases. It is expected since it is caused by involving fuel cells and batteries, which are more costly than diesel engines. On the other hand, it is demonstrated that the operation profile in wave conditions consumes more diesel fuel for the same amount of CAPEX. Because in this case, the propulsion system should start/stop more often to compensate for the thrust loss produced by the in-and-out-of-water effect.

In addition, the significant fluctuations caused by the thrust loss during the in-and-out-of-water effect increased diesel fuel consumption by up to 15 percent in the presumed sea environment. Initially, the reductions in diesel use are relatively comparable in the two situations. Since electrical power sources are less expensive to operate and maintain than conventional diesel engines, it is critical to evaluate the economic performance of the suggested powertrains at the design level under a variety of operating circumstances. The diesel fuel consumption based on the output of the optimization method for power/energy ratings of the fuel cells, diesel engines, and the batteries for the existing and modified operating profiles are demonstrated in Fig. 8 and Fig. 9, respectively. It can be seen that the overall pattern for the power/energy ratings is similar in the two defined scenarios. In general, when the volume of diesel fuel consumption drops, the diesel engine size gets smaller while the batteries and fuel cell power/energy rating increase. Nevertheless, the

Table IV THE OPTIMIZATION PROBLEM SOLUTION FOR THE DEFINED SCENARIOS

| Load Profile | Battery (kWh) | Diesel Engine (kW) | CAPEX (k$) |
|---|---|---|---|
| Existing | 933 | 514 | 752 |
| Modified | 886 | 734 | 812 |

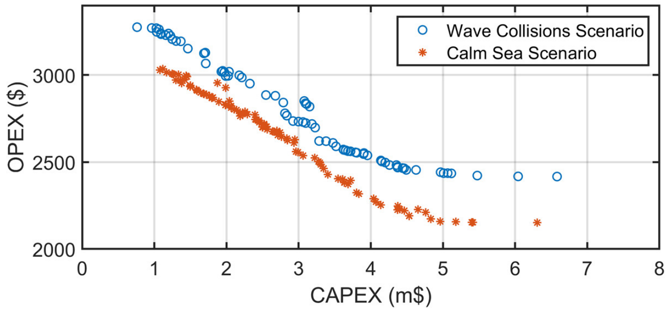

Fig. 6 The studied vessel's OPEX based on CAPEX under two alternative scenarios: a) The optimization problem's load profile is the actual load profile from the given journey, and b) The optimization problem's load profile is the outcome of the proposed model-based approach.

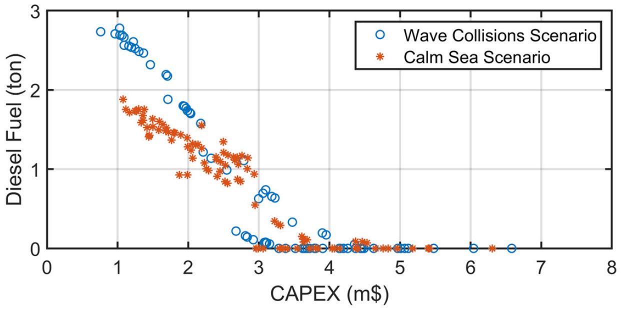

Fig. 7 The studied vessel's diesel fuel consumption regarding the CAPEX under two alternative scenarios: a) The optimization problem's load profile is the actual load profile from the given journey, and b) The optimization problem's load profile is the outcome of the proposed model-based approach.

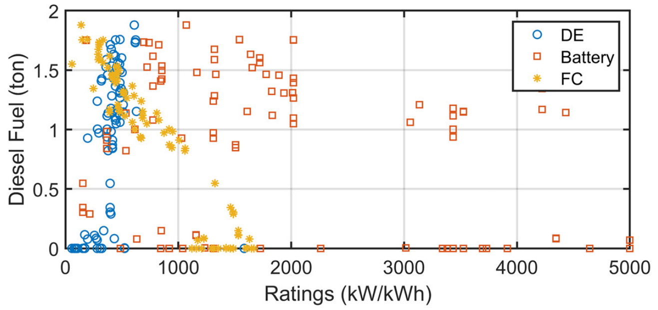

Fig. 8 The diesel fuel consumption of the investigated vessel based on the power rating of the fuel cells, diesel engines, and battery energy rating for the actual load profile from the specified trip.

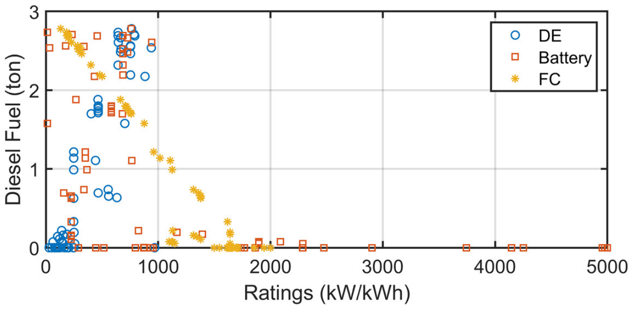

Fig. 9 The diesel fuel consumption of the investigated vessel based on the power/energy rating of the fuel cells, diesel engines, and battery for the modified load profile that is the outcome of the proposed strategy.

optimization solution's specific size and control outcomes vary concerning the operating profiles and other objective constraints. Table IV lists the optimum solutions for this study's predetermined scenarios based on the Pareto fronts. As expected, the wave collision increased the component sizing and CAPEX of the hybrid ship. It concerns the generated power fluctuations and the control system to mitigate them. Therefore, considering the power fluctuations caused by the wave encountering conditions at the vessel design and control level is critical at the design and control level.

## V. CONCLUSIONS

This paper evaluates the impacts of wave collisions on the sizing and control of a hybrid ship propulsion system. First, an interconnected model-based strategy is proposed for integrating the in-and-out-of-water effect into an operation profile from a historical journey. This approach can be used at the design level of maritime vessels to analyze the suggested powertrain and control system during extreme conditions. As a result, the performance of the power management and control system during various operating conditions becomes more reliable. After that, an optimal sizing approach of a hybrid ship using a nested double-layered multi-objective optimization method is presented. Employing the suggested optimization solution and the proposed method for integrating wave encountering effects to the load profiles, the influences of ship movements in extreme conditions on the design and control system optimization outcomes are investigated. It is shown that the in-and-out-of-water effect generated power fluctuation can be up to 40 percent in comparison to the calm seas. These significant fluctuations can increase diesel fuel consumption by up to 15 percent in the presumed sea environment. In addition, the effect of ship movements on the battery and diesel engine sizing of the suggested ship propulsion system powertrain is discussed. It is demonstrated that considering the power variations caused by the ship's motion can substantially impact the sizing of the hybrid ship. Thus, it should be considered at the design and control level for a reliable and optimal design and operation.

For future works, the optimization approach will be extended to account for the impact of the CO2 emission tax, which is planned to be implemented in the forthcoming years. Accordingly, the impacts of wave collisions during extreme conditions on GHG emissions, optimal design of future ships, and retrofitting of the existing vessels will be further investigated.

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