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Review and Development of Ship-Engine Matching for a Robust Propulsion System Design

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ABSTRACT

The traditional procedure for engine-propeller matching stems from using empirically derived propeller performance curves with superimposition of the actual engine-hull-propeller performance curves. Every matching problem aims to determine the optimal operation point of the ship where there will be efficient fuel-thrust conversion, leading to the prevention engine overload. However, from the beginning of research into the optimal matching problem, it was suggested that such a problem can be treated optimally as a controlled system problem. The above identified gap focuses on a solution-based control system design for the matching problem. A model of the propulsion system has been proposed based on energy transferred between the engine and propeller, and propeller and ship hull. The output parameters are the ship-propeller-engine-hull performance characteristics. A review and development of the matching simulation was conducted, resulting to the design of the propulsion system considering the control system approach. Therefore, it was concluded that the developed system could be advanced for implementation with models in a towing tank experiment for self-propulsion assessment if fully developed. This will pave the way for a practical implementation in actual ships, contributing to sustainable development in ship operations and autonomous ships of the future.

Keywords: *Matching, Propulsion system, Ship Hull, Engine, Robustness, Propeller, Design*

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1. INTRODUCTION

In global trading and commerce, shipping contributes critically to the distribution of goods across nations (Lun, et al., 2023). For this reason, ships must be designed to meet service requirements and safety standards. Additionally, the economic value of a vessel depends to some extent on its size, shape, and service condition. In term of size, a full ship could handle as much cargo as possible compared to a narrow ship, accounting for its economic value. However, the fuller the vessel, the higher the power required for propulsion. Hence, a trade-off is needed. The vessel's shape can also be a major sabotaging factor to the size factor. This has led to many separate research works on ship hull form optimization. Also, the condition of the hull form in service has been shown to increase the vessel's operational cost. This condition relates to deterioration in the hull surface due to corrosion, fouling, and mechanical de-featuring.

The effect of hull form deterioration and shape increases the operational costs. The implication is that the hull forms can cause an increase or decrease in the power requirement, which is translated into higher or lower fuel consumption (Udo, et al., 2024). The ship's economic value can also be affected by losses in the power transmission the prime mover produces. This covers the engine's deterioration and the shaft line's transmission losses.

In transmission losses, flaws in propulsion system design have been widely investigated. Optimal consideration is, therefore, required in propulsion system design. Such consideration is achieved through optimal matching of the ship engine, hull, and propeller characteristics (Lin, et al., 2015; Tran & Kim, 2023). This process ensures proper fuel-to-thrust conversion for a wide range of operating conditions thereby actualizing better system performance efficiency (Molland, et al., 2017).

Achieving this involves using several performance characteristics in the form of charts developed for various components of the propulsion systems such as propellers, pumps, compressors, hull, etc. However, changes in service conditions of all propulsion components have been observed to make such design a complicated process. Some of these service conditions are; weather variation, changes in the draft, gross change in resistance mostly when the tow is on, changes in hull resistance due to fouling, etc. (Sprenger, et al., 2017). Several efforts have been applied in addressing propulsion system design considering the above-mentioned challenges. In a quest to

address the problem of propulsion system, this present study aims to develop and propose a control system design perspective for a robust design of the system. The next section highlights some of the efforts, seeking to provide solutions to the ship propulsion system design, anchoring matching techniques.

2. EXTENT OF PAST WORK

The matching of a ship's hull to an engine for a robust system design is a design process that enhances the optimal operating conditions for ships. This type of design enables ships to work safely with low fuel consumption and enhances the full power utilization of the engine. It enables ships to attain their design speeds at every operating condition. This entails designing a ship to match her engine, propeller, and hull systems (Tran & Kim, 2023).

Most of the propulsion systems of conventional ships are made of diesel engines coupled to fixed-pitch propellers and hull forms. The power produced by the engine is converted into thrust via the propeller to overcome the total hull resistance and advance the ship. The selection of each component of the marine propulsion system is an essential process to increase the system's efficiency (Zalacko *et al*., 2021), reduce the amount of fuel consumption, and comply with the stringent regulations on emission regulated by the International Maritime Organization (IMO) (Tadros et al., 2020). Besides the rapid technological advancement in engine design (prime mover) (Altosle et al., 2017), the various research works have been conducted either by numerical or experimental approaches to achieve maximum propeller efficiency by finding the optimal propeller geometry while at the same time ensuring the durability of the propeller by reducing cavitation problems.

Previous studies have investigated the hydrodynamic performance of the hull and propeller as separate units using experimental, analytical, and numerical methods (Han, et al., 2012; Nazemian & Ghadimi, 2021; Udo, et al., 2024). Some studies also investigated the combined hull, engine, and propeller interactions or matching to determine the resistance, dynamic, and propulsion performances (this is detailed in Table 1.1). However, the foremost studies on the interaction of hull, propeller, and engine underscored the need to treat the matching problem as a control system

problem. (Woodward, 1976). This direction has not been fully researched. Some of the recent work in this area were spotted as follows:

Two examples of a theoretical approach coming from a control system perspective of engine-propeller were reported by van Spronsen and Tousain (2001) and Xiros (2004), where, in both cases, a linearized model was used by applying H∞ controller techniques to prevent diesel engine overloading (Van Spronsen & Tousain, 2001; Xiros, 2004). Despite their high value, the drawback was that the used plant models were not directly related to the commonly used parameters and therefore had less interest to marine system engineers and hydro-dynamist. Another example, involving research into the dynamic behavior of propellers in waves, was conducted by van Terwisga *et al*. (2004). The description of the influence of the propulsion control system settings on the prime mover was strongly simplified (Van Terwisga, *et al*., 2004).

An application of the concept of linearization of the ship propulsion was introduced. Clarke (1980) introduced this concept earlier (Clarke, 1980). He includes ship inertia but ignores shaft speed dynamics and implicitly controls either shaft speed, engine power, or engine torque, or even ship speed, only for a fixed pitch propeller. Added resistance owing to maneuvering was taken into account; however, disturbances of wake speed were not considered. Normalization of the developed equations and their derivations was lacking in general and in clarity.

Another related work on the linearization of the ship propulsion plant was reported by Blanke (1981) and repeated by Fossen (1994) (Blanke, 1981; Fossen, 1994). The linearized model received treatment from the perspective of maneuvering/motion control. This model incorporated many features that will be used in the present work in conjunction with the dynamics of ship and shaft speed using engine torque as the input of the linearized model, added ship resistance as a result of sway and disturbance of wake speed caused by waves. The model is restricted to fixed pitch propellers. Also, the coefficients that were used to describe the propeller performance were only implicitly related to derivatives in the open water propeller diagram.

The linearized model and, in particular, the main differential equations are not normalized, which makes the derivation from the linearized model equations to the final transfer functions unnecessarily complicated and not transparent, and therefore makes it hard for others to use the model. Also, the linearized model is not fully linear, as some products of perturbations are still

present. A notable effort to linearize a gas turbine-driven ship propulsion system is reported by Kidd *et al.* (1985). However, the derivation there does not take into account the system inputs related to ship resistance and propeller wake-field disturbances. The most important shortcoming is however the non-transparent linearized propeller model, which does not match the generally available propeller data from open water diagrams. Finally, a simulation model was described, but no results were shown, which makes it hard to assess the model. It may be concluded that linearized models were developed in the eighties of the last century, but for several reasons did not appeal to the maritime industry and seem not to be used frequently anymore.

This work intends to revive linear models and indicate when and where they could have some use. The author believes that, due to its transparency and clear link to well-known parameters and variables, the linearized propulsion system model as derived in this work should appeal to marine system engineers, control engineers, and hydro-dynamicist. Its transparency allows for modular expansion, of which an example is already given by Shi (2013), where an early version of the theory, as reported in this work, is used to analyze the dynamic performance of a trailing suction hopper dredger. Moreover, the linearized model of the propulsion system was extended with a linearized model of the dredging system, including an engine-driven dredging pump and suction pipe. Other extensions related to drag head resistance and non-symmetric propeller load between the shaft lines were also made.

Earlier work related to time domain modelling of dynamic performance is reported by Healey et al. (1995); Bachmayer et al. (2000); Blanke et al. (2000), and Pivano et al. (2006). Non-linear time domain modelling of water jets is reported by Altosole et al. (2012) and Campora et al. (2011). The work regarding the stability analysis of the core system can be extended by considering the stability of a controlled propulsion system, including actuators, such that the effect of controller gain settings on stability margins can be made explicit. Another aspect that can be taken up is the systematic gathering and analysis of τ_v and τ_n for a variety of ship types.

A collection of their values and ratios could perhaps give valuable insight into the differences and similarities between the behaviour of the propulsion plants of, for instance, fast and slender lightweight ships compared to slower full-bodied ships. Besides all aforementioned aspects, it is strongly recommended to strengthen future development by, in parallel to the theoretical path,

pursuing both a model-scale verification and a full-scale validation path (Stapersma & Vrijdag, 2017a; Vrijdag & Stapersma, 2017b; Vrijdag & Martelli, 2021). With this in mind, the present work is directed towards the continuous development and implementation of the theory of engine-propulsion model with the control system perspective.

Three types of matching problems have been identified in the above review. The first is that the matching problem is mostly investigated as a design problem wherein the propeller parameters are calculated at the design condition to avoid cavitation, corrosion, fouling, and underwater noise. Here, the variations due to changes in design conditions are considered. The second involves the situation where the off-design conditions due to the hull, engine, and propeller deteriorations are contemplated. In the third type, the investigations are neither design nor off-design conditions. It treats the matching problem as a pathway to solving the matching problem. To enable an effective discussion of the research reviewed, a framework was developed and presented in section D below.

3. METHODOLOGY

The methodology is divided into two parts. In the first part a scoping review of past work and the derivation of mathematical equations for the system based modeling of propulsion system. The review was based on scholarly work published between 2014 and 2025 in google scholar. Keywords “Matching” and “interaction” of ship hull, propeller, and engine were used. The year, author(s), and major conclusions from the review were extracted as presented in Table 1.1. Also, it summarizes the types of matching problems studied in each finding. The second part of the work provides steps for the development of a MATLAB-SIMULINK program for implementing the equations derived.

(a) Scoping Review Based on Keywords: “Matching” and “Interaction”

Table 1.1: Summary of Works in Matching Problem

Year	Author	Type of Problem Solved	Major Conclusion
2014	(Mehdipour, 2014)	First type	A computational method was used to simulate the performance of a propeller, with its main objective being the analysis of two techniques.
	(Win, 2014)	First type	A CFD method was used to assess the performance of a conventional propeller developed by the author.
	(Gaggero, et al., 2014)	First type	The wake-field was simulated using the traditional and semi-empirical methods and the direct numerical method (RAN) to compare their differences and evaluate the effect of wake in cavitation initiation and noise.
2015	(Hunsucker & Swain, 2015)	Third type	Development of an instrument for measuring the frictional drag of the hull in service
	(Lin, et al., 2015)	Third type	The development of a selection system for the propeller and engine was successfully done, wherein a case study ship was simulated. The result was found to be efficient and reliable.
	(Lindholdt, et al., 2015)	Second Type	Developments in these areas would help to determine the optimal choice of hull coating, the optimal time to conduct underwater hull cleaning (partial or complete), the optimal time between dry dockings with new coating application, and the benefits of a full abrasive blasting of the hull.

(Table 1.1 cont'd)

2016	(Bialystocki & Konovessis, 2016)	Second Type	The effect of off-design conditions. e.g., weather changes should be further investigated by developing an algorithm.
	(Taskar, et al., 2016)	Third type	An effective method for modeling wake in waves was demonstrated, enabling the study of different aspects of the propulsion system in waves. It was shown that engine propeller responses, power, propeller speed, and torque fluctuations can be obtained through coupled simulations by using realistic engine and propeller models.
	(Regener, 2016)	Third type	A methodology for effective wake determination was illustrated using CFD to study the effects of hull wake on propeller behavior.
2017	(Geertsma, et al., 2017)	Third type	The review of various control strategies was conducted to enhance the real-time design of power and propulsion systems for ships.
	(Naz, 2017)	Third type	A numerical approach was developed to study the interaction of the wake on the propeller and rudder.
	(Wang, et al., 2017)	Third type	An optimization control method was developed for hovercraft-engine-propeller matching.
	(Danian, 2017)	Third type	Experimentally conducted a study on propeller-engine matching using a DC motor.
2018	(Ogar, et al., 2018)	Third type	The developed method was deployed for matching a controllable pitch propeller to a gas turbine-driven ship.
	(Marques, et al., 2018)	Third type	The development of an optimization method for matching the propeller and engine was conducted.
2019	(Uzun, 2019)	Third type	The development of a time-dependent fouling mathematical model for hull resistance performance assessment
2020	(Anggriani & Baso, 2020)	First and second types	A methodology was established to simulate the propeller and hull characteristics.

(Table 1.1 Cont'd)

2021	(Roshan, et al., 2021)	Third type	The developed method demonstrated that propellers strongly affect the performance of a vessel by increasing the trim angle and decreasing resistance.
	(Wang, et al., 2021)		The development simulation of the COGAG power propulsion device was considered to study its steady-state operating characteristics and conduct a ship-engine-propeller optimization matching analysis based on economy and maneuverability.
	(Yang, et al., 2021)		A review of the propulsive characteristics was developed.
2022	(Sandjaja, et al., 2022)	First type	The study focused on the selection of optimal ship propulsion propellers, especially the type and number of propeller blades, using the engine propeller matching approach.
2023	(Tran & Kim, 2023)	Third type	A new approach was presented, leading to the determination of the actual characteristics of a ship in service. They also showed how to use the approach to solve a matching problem
2024	(Bayraktar, et al., 2024)	Third type	A method based on CFD was used to evaluate the propulsive performance of a planing hull vessel.
	(Jami'in & Primanjaya, 2024)	Third type	An improvement in efficiency was obtained using the developed methodology for a fishing vessel.
	(Fajar & Ratna, 2024)	Third type	An optimal matching power was evaluated after the engine's repowering.

(b) Development of Mathematical Model

Presented in this section are the equations derived for tackling the propulsion system characterization for the proposed control system perspective. The equations are based on the definitions from the previous investigations of ship hull, engine, and propeller interaction. Here, the engine was described as the driver of the propeller, which in turns drives the ship through the hull. The propeller is a load to the engine while the hull is the load to the propeller, leading to a situation where the propeller can be overload by the hull aging (time). The propeller then could cause overloading to the engine, endangering the engine and the shaft health. For this reason, the

mathematical models are based on time using the physical or rated characteristics of the propulsion system.

Ideally, the engine produces power P_{ENGINE} that is used in producing the propeller's torque given in terms of the propeller's power P_{PRO}. In the course of energy transmission, some losses are accounted for (Tran & Kim, 2023). This is called the power lost in transmission, P_{LossT}. Therefore, equation (1) defines the ideal mathematical model for the first subsystem of the propulsion system (Lin, et al., 2015; Tran & Kim, 2024):

$$P_{PRO} = P_{ENGINE} - P_{LossT}. \quad (1)$$

The propeller's power in terms of its torque is expressed by equation (2):

$$P_{PRO} = T_{ENGINE} \times \omega \quad (2)$$

where ω is the engine's angular speed, equivalent to the propeller's ideal angular speed. This is given by $\omega = 2\pi N_{ENGINE}$. Therefore, equation (1) can be rewritten as expressed in equation (3.3):

$$T_{ENGINE} \times \omega = P_{ENGINE} - P_{LossT}. \quad (3)$$

Since the propulsion engine will deteriorate in service and the transmission losses can increase owing to shaft imbalances, more detailed definitions for these two parameters are required:

$$P_{ENGINE}(t) = \frac{\partial(P_{ENGINE})}{\partial(t)} \times \partial(t) - k_1 \quad (4)$$

$$P_{LossT}(t) = \frac{\partial(P_{LossT})}{\partial(t)} \times \partial(t) + k_2. \quad (5)$$

In this manner, equation (3.3) is transformed as given in equation (6):

$$T_{ENGINE} \times \omega = \left(\frac{\partial(P_{ENGINE})}{\partial(t)} \times \partial(t) - k_1\right) - \left(\frac{\partial(P_{LossT})}{\partial(t)} \times \partial(t) + k_2\right) \quad (6)$$

Therefore, the propeller performance with respect to time will be affected, transforming equation (3.6) into equation (3.7):

$$T_{ENGINE} \times \omega - k_3 = \left(\frac{\partial(P_{ENGINE})}{\partial(t)} \times \partial(t) - k_1\right) - \left(\frac{\partial(P_{LossT})}{\partial(t)} \times \partial(t) + k_2\right)$$

The second subsystem of the ship propulsion system can be modeled according to equation (8):

$$M_s a = T_{PRO} \times t_f = T_{PRO} - R_{HULL} \quad (8)$$

where t_f is the thrust deduction factor, M_s is the mass of the ship.

Since, the hull and propeller will deteriorate in service, resulting from corrosion, fouling, and cracks, a more detailed description is presented in equation (9):

$$M_s a = T_{PRO} \times t_f(t) - k11 = \frac{T_{PRO}(t)}{\partial(t)} - k22 - \left(\frac{R_{Hull}(t)}{\partial(t)} - k33\right) \quad (9)$$

where, T_{PRO} represents the propeller thrust ($T_{PRO} \times t_f$ is the thrust deduction), t_f represents the thrust deduction fraction, and R_{HULL} represents the hull resistance. The constants, k1, k2, k3, k11, k22, and k33 are time dependent, and can be derived using appropriate mathematical formulations.

The above mathematical models were used in combination with the open water characteristic equations to develop a MATLAB-SIMULINK model. The block diagram for the implementation for the models is presented in Figure 1.

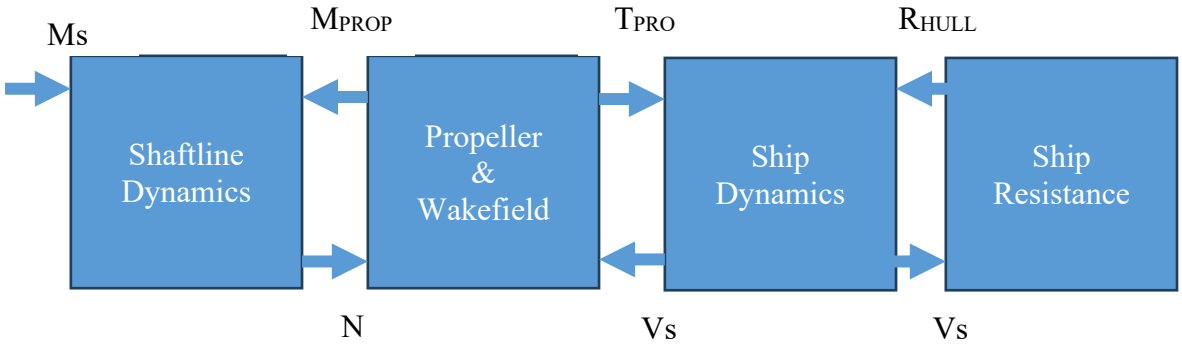


Figure 1: General Block Diagram for Model-Based Propulsion System Design **(Authors)**

A Simulink block diagram is also presented in Figure 2. The Figure included a control system through the feedback provided in the Figure.

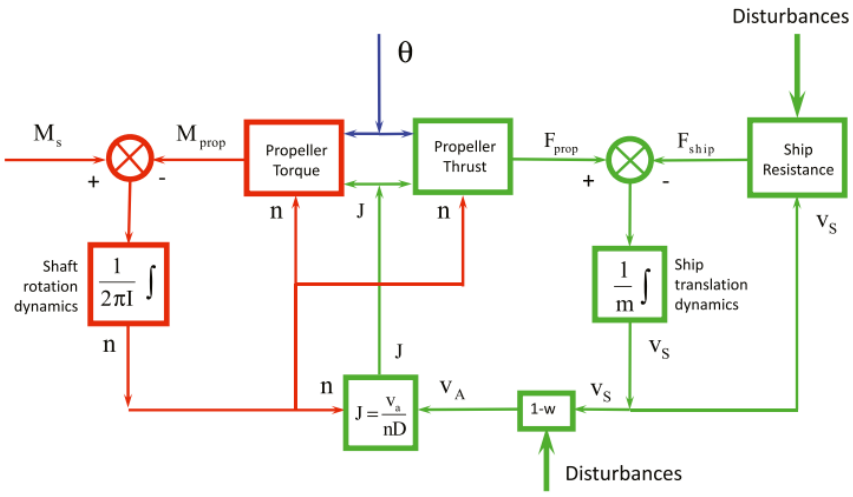


Figure 2: Simulink Block Diagram **(Authors)**

4. RESULT AND DISCUSSION

The result presented in Figure 3 is based on the conventional matching simulation for a typical ship. The data used were from a real ship operating with a gas turbine engine. In Figure 3, the propeller thrust, torque and open-water efficiency are compared against the vessel resistance at different loadings. Like K_T, the propeller torque coefficient (K_Q) is highest for bollard pull (J =0) and approximately zero when engine is shutdown. The residual value of K_Q (at K_T =0) for a vessel on tow is due the swirling current around the propeller which induces some torsion.

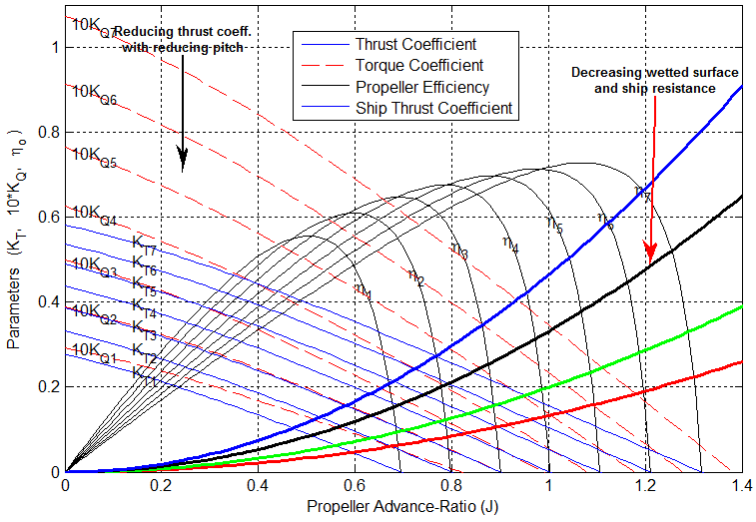


Figure 3: Propeller characteristic and hull resistance curves for EAR= 0.75

Figure 4 shows the developed Simulink program for the propulsion system with control system perspective. This program is under development, and its full implementation was not achieved (it

will form the second part of this study in the future). For this reason, there were no numerical results obtained.

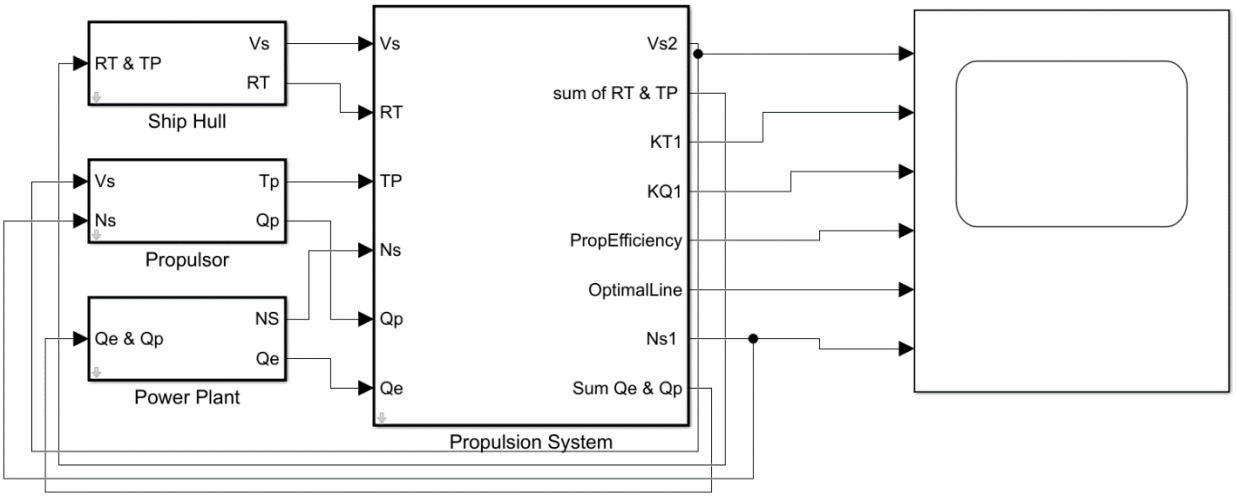


Figure 4: Simulink propulsion system design with control system perspective (Author)

5. CONCLUSION

The review and development of matching of engine, propeller, and hull were conducted in this study for propulsion system characterization. The methodology adopted uses a scoping review technique to analyze the matching problem, leading to the discovery of the most frequently used methods for the study. The derivation of the mathematical models was conducted based on the physical description of the propulsion systems and the ship aging. These relationships were based on the powers produced by the engine and the power consumed by the propeller. The engine performance (operational envelope) was imposed on the propeller performance of the ship at certain time constraints. The conditions considered are grouped into two: design and off-design conditions. The off-design conditions relate to the conditions of the hull and propellers. The engine condition was assumed to remain constant because the engine can easily be serviced at sea. In light of the above, the program was developed using MATLAB/Simulink. It was noted that the program was capable of predicting the performance characteristics of propeller. Full implementation of control actions for the propulsion system has been proposed using the mathematical equations derived in this work.

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CONFLICT OF INTEREST

The authors declare that, there is no conflict of interest in the production of this paper

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