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Research paper

Design and Optimization of Ship Propulsion Systems for Improved Efficiency

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Abstract

New rules due to contemporary environmental issues and high and volatile fuel prices are the main reasons for reducing operating expenses with more environmental friendliness. Reducing fuel consumption is the main reason. Due to current economic constraints and worldwide regulations, reducing energy usage and saving even more on ship fuel is needed. From an industry point of view of the ocean, there are technical solutions and standards for operating ships in energy-efficient modes. But there are also other intricate problems facing the shipping industry nowadays that are choosing the best technique and keeping it under continuous surveillance during a passage. The fuel saving could be lower than anticipated because of real-time environmental conditions like sea state and weather, even if the route of the ship is optimized. As per the Ship Energy Efficiency Management Plan (SEEMP), the aim of this project is to create and construct a Decision support System (DSS) for optimizing energy utilization with the help of real-time decision support and thereby improving energy efficiency in shipping operations. Real-time energy monitoring and making optimal decisions during operation of the ships are also facilitated through the DSS. In developing the DSS, which will help improve energy use in ship operations when at sea and on land, we shall choose an energy model software and optimization method from existing literature.

Keywords: *Ship Energy Efficiency; Operational Measures; Fuel Savings; Decision Support System.*

1. Introduction

Based on their combined experience in a variety of maritime energy efficiency areas, two globally superior IAMU institutes conducted a research study entitled "Improving Energy Efficiency of Ships through Optimization of Ship Operations." The research team examined means of reducing operational fuel in ships currently at sea and devised a strategy to identify alternatives with lower energy usage. They cooperated with World Maritime University (WMU) and Istanbul Technical University (ITU). This project report outlines the research findings on energy-efficient operation feasibility and how a Decision Support System (DSS) is designed to increase the energy efficiency of ship operation according to the Ship Energy Efficiency Management Plan (SEEMP) based on real-time monitoring of energy consumption and optimization. As a response to economic and regulatory issues at the international level, the project intends to maximize fuel consumption while minimizing energy consumption. The particular elements of the research are the installation of a Decision Support System (DSS) which will be operated by the ship's captain, crew, and shore-based ship operating staff. Apart from that, there will be an energy-efficient ship operation decision support system that will be created through combining optimization algorithms and energy modeling software in the literature. The system will be applied ashore as well as onboard [6].

The complexity and intricacy in offering ship operators a systematic process for the identification of energy-saving measures make it more complex. With the rise in the cost of oil and greenhouse gas emissions, the decision-makers must be assisted in predicting working fuel consumption so that they are able to adopt the most appropriate energy efficiency measures. To reduce the complexity of the problem and enhance ship-voyage control energy efficiency, DSSs will notify the operator about the status [8]. Ship operating company decision-support system, i.e., captain and/or company operating units, will be developed using Artificial Neural Networks (ANN) as the main objective of this project [4]. Through real-time monitoring of energy consumption and enhancing it with a real-time decision-support system, the technology facilitates an improvement in ship operating energy efficiency under SEEMP [10]. Real-time monitoring of energy consumption and optimal decision-making are facilitated by the creation of a ship operation decision support system. By combining energy modeling software with optimisation algorithms from literature, we will establish a decision support system that can be utilized by ships on land and sea in order to operate more economically effectively [2].

2. Review of literature

Different steps that are used in the system design are connected, as theorized by Guzzella and Sciarretta (2007). They encompass the selection of the system architecture, identification of component sizes, and the control of components. Silvas (2015) states the problem during design is adequately addressed as a nested problem. The application that is designed defines the solution to the multi-layer problem. Vessel duty cycle is the duration when the vessel is in operation.

According to Tadros et al. (2020), shipping carries approximately 70% of global trade and is the most energy-efficient means of transportation of international merchandise. The International Maritime Organization (IMO) has, by 2050, a target to reduce half of the greenhouse gas emissions compared to the year 2008 (IMO, 2018). Traditional ship propulsion systems must undergo a drastic shift toward zero-or low-emission solutions, but if they are to meet this pressing need while simultaneously lowering worldwide shipping fuel consumption and greenhouse gas emissions. Propulsion of ships by variable pitch propellers (CPPs) was a primary application of the combinator curve-based control method. The nominal combinator curve converts the vessel (or lever) speed setpoint into the reference values for pitch and RPM of the pro-peller. To change the vessel speed, the lever is pulled by the skipper. But performance parameters such as noise, cavitation, safety, efficiency, and maneuverability have to be traded one against the other in an attempt to achieve an optimum combinator curve [3]. An-other problem of difficulty in determining the ship's propulsion optimal operating point. Experimental information and exper-tise, on the contrary, are of utmost importance for the correct calculation of the prime mover fuel consump-tion and propulsion efficiency at any point of opera-tion. Cavita-tion, overload, and loss of manoeuvrability are problems found in diesel-mechanical propulsion plants with constant combinator curves [1] [7]. Through the application of a permanent adjustment in the propeller pitch angle with operating setpoints obtained from combinator curves, all these constraints are removed and cavitation-free operation is enhanced. In addition, an online combinator curve optimization technique is presented by Balsamo et al. (2011) to calculate optimal operating setpoints using propulsion efficiency optimization without cavitation. The reliability of such esti-matesof ship resistance, wake fraction, and thrust deduction fraction—cannot be assured to be valid for real ship operation, but they are used as a basis for this calculation.This method is used only for stationary ship movement and cannot be applied to accelerate or decelerate the ship.Poor fuel efficiency and excessive emissions are indicators of the ineffectiveness of these engines in running under part-load or under frequent changes of operation [5]. [9] Compare the fuel consumption rate of the gas turbine, diesel engine, and compound gas-steam system. For Zahedi et al. (2014), where the minimum specific fuel consumption (SFC) of the diesel engine is obtained, the engine is in an optimal condition.

Greater maneuverability, reduced engine reversing, and simple thrust change are some of the benefits of Controllable Pitch Propellers (CPPs). Due to these advantages, vessels that travel under various sea states and loads, like fishing vessels, tugs, offshore vessels, cargo vessels, passenger vessels, and ferries, perform very satisfactorily [11]. As there is a separate variable for the pitch of pro-peller blades of CPPs, their movement seems three-dimensional. When the vessel is traveling in the positive direction of speed and is not making an emergency brake or reversing with oppo-site-direction push, this research considers improving CPP propulsion in the first quadrant.

A relative rotative efficiency of a propeller is used to correct for fluctuation in torque absorption for the conditions of open water flows and mixed wakes [12]. The relative rotative efficiency is very insensitive to ship speed, and is usually a quadratic function of speed, as established by [15]. At any instant, the wake fraction is the ratio of the ship's axial velocity loss to its speed. Wake field modifications due to waves are heavily ship form and, more precisely, after-body shape dependent. In addition, cavitation, which is referred to as "cold boiling," takes place when the ambient atmospheric pressure of the propeller blades is below the vapour pressure [7]. Low propulsion efficiency, noise, corrosion, and even propeller damage are some of the undesirable consequences of cavi-tation. Different propeller pitches lead to different cavitation patterns. Model and full-scale cavitation inception comparison for different pitch angles has been discussed in [14]. The tip vortex is very strong in modest speeds and relatively lower pitches. Tip vortex and sheet cavita-tion are rear-related flaws due to high RPM and propeller pitch. The most prevalent type, tip vortex cavitation, is noisy but largely doesn't impact propeller erosion to any serious extent [13].

Cavitation can never occur completely in the real world. You can cut an operation-safe region within the cavitation bucket and induce cavitation if you do not want to face extreme problems such as propeller damage and decreased efficiency. The operation should ideally stay within the safe region. In this work, here, we confirm the presence of cavitation by checking the calculated cavitation number against that of an operating data-driven cavitation bucket. Marine optimization has utilized various machine learning models, but to date, few have contrasted the methods in context. While SVMs are good for handling data with high dimensions, Random Forests are transparence and noise tolerant. Nonetheless, they are less efficient in dynamic, nonlinear control and do take a lot of prepro-cessing. Although ANNs are highly appropriate for optimization of marine propulsion due to the fact that they inherently learn about difficult relationships and have the ability to be trained to learn from flows of real-time data, no general real-time decision aid systems exist that can execute across a range of ship types and sea conditions, something that is lacking in current literature. This paper addresses that deficiency.

2.1. Main contributions

This paper introduces a new optimum combinator surface idea that maps propeller setpoints of RPM and pitch against desired thrust and advance speed. A preferred push is established as an input to the standard combinator curve, which is moved to the combi-nator surface. The key contributions of the method are discussed in the following:

1) The most effective combinator surface is achieved by maximizing the ship's propulsion efficiency to make each combinator surface setpoint fuel-economic under any ship loading conditions or sea state. Combinator surface propulsion reduces the fuel burned while accelerating, decelerating, and cruising.
2) Surface combinator optimization does not need estimates or measurements of wake fraction, ship resistance, or thrust deduction fraction. Due to this, erroneous measurements and estimates are no longer responsible for ship propulsion guiding problems.
3) The operator can attain the target speed with high or smoothing acceleration and maximum propulsion using the combinator surface acceleration and deceleration trajectories, rather than the lever.
4) The human error in the choice of combinator curves is eliminated as soon as the operator is no longer needed to perform this function. Of particular importance to the shipping industry for application by lean-crewed and autonomous ships are:
5) Five, the combinator surface facilitates cavitation study for any conceivable combination of advance speed and thrust necessário.

3. Materials and methods

Managers' situational awareness (the operating units of the company and/or the ship captain) is served by DSSs created to increase energy efficiency in ship operation while also making it simple to understand. Two scenarios are utilized to present and showcase the created DSS, which may serve as a helpful tool for ship operators to take into account economic as well as environmental factors while making operational decisions. Lastly, an information system for facilitating the captain, crew, and shore-based ship management companies to make sound decisions will be developed. Ship operators will better comprehend how efficiently the ship operates, to their benefit in the long run.

Energy awareness promotion, engine, fuel management, system energy management, hull and propeller, and voyage performance are the six broad categories into which the actions fall. Two causes—unintentional and voluntary—are to blame for weather route optimization in the majority of cases. It is up to the captain and the navigator to determine if they can slow down deliberately. When the crew cannot handle external fac-tors such as weather or sea drag, they suffer involuntary loss of speed. On adverse weather conditions, a vessel's resistance is significantly diminished, subjecting it to unwanted environmental pressure. Thus, some force dynamics cause loss of the vessel's speed. The vessel uses more fuel due to higher resistance of the vessel, since more power from the engine is needed. To make up for this, there are weather routing companies. These companies involve collecting meteorological data, analyzing water and wind conditions, predicting how a ship will react to future conditions, and then recommending the most appropriate route considering the current weather.

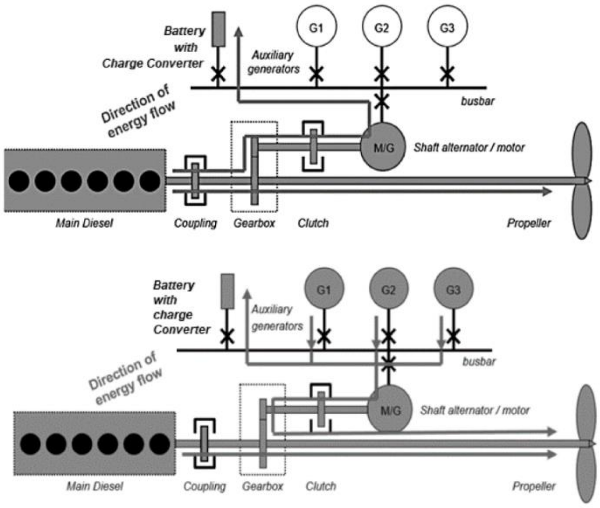

Fig. 1: Propulsion System.

Weather routing data can be given to ships by email or computer software. Visual information can also be communicated in different applications, such as ship-to-ship messaging and ship management, by using computer software. Wind, wave height, and currents increase the distance of the shortest route between two harbors. Bridge computers and advanced technology together offer fuel-efficient routes with the help of weather routing services in real time. It has been many methodologies, including artificial neural networks, which have become alternatives to the conventional estimation methodologies in recent years. Artificial neural networks are computer programs that possess the ability to perform automated processes such as learning, generation, and discovering new in-formation. Problems too com-plicated or intractable for solution by tradi-tional methods are the ones that led to the science of artificial neural networks, which specializes in pro-cessing adaptive data. Researchers who conduct prospective estimation have now started utilizing artificial neural networks as a substitute for more conventional approaches to estimation. ANNs are computing systems that are intended to solve complex problems. They are a system that is intended to replicate the manner in which the brain performs any task. The model contains Artificial Neural Network (ANN) of two hidden layers with 16 and 12 neurons respectively. The ten input parameters are vessel speed, draft, trim, propeller pitch, and fuel flow. The output layer gives the recommendation of optimal control suggestions for propulsion setting. The output uses a linear activation function, while the hidden layers apply ReLU activation function. About 20,000 records of historical operational data from various types of ships were used to train the network. The data included a 70% training set, 15% validation set, and 15% test set. 0.001 learning rate was used in train-ing with the Adam optimizer. For the purpose of giving transparent integration with current control interfaces, the ANN is fed real-time sensor readings onboard and calculated using a modular API connected with the ship's Energy Management System (EMS).

3.1. Speed optimization

Time is critical in shipping. With the need to have ships built faster in order to match the expansion in trade globally. This includes more per unit of time volume of trade, lower cost of inventory, and punctual delivery of cargo as some of the economic benefits of quick ship speed. But with the increase in fuel prices higher and environmental concerns, a changed mindset towards ship speed has become the case. Therefore, the study of how to optimize the speed of a ship becomes indispensable now. All the parameters of the route are taken into account so that determining the best ship speed won't be the most time-consuming. The fuel saving potential of reducing speed needs to be weighed against other commercial and operational considerations. Determining the optimal journey speed entails taking into account all the expenses incurred in an attempt to achieve equilibrium between low-speed sailing, fuel usage, and demand in the market. The second fact is that the optimal speed varies as the voyage progresses because market requirements keep evolving. Rather, it needs to be adjusted based on information from parties of interest, i.e., maritime firms, charterers, and shipbrokers. Reduce the ship speed is the best fuel-saving approach. The nonlinear relation is between ship speed and fuel; ship speed is an important fuel-consuming parameter since it has a cubic relation with the needed propulsion power output. It takes six times as much required power output to get twice the ship speed. Fuel consumption decreases by about 27% due to a 10% decrease in cruise speed. A tanker vessel belonging to Maersk, for example, requires a speed of 16 knots in ballast and covers the standard distance between the Persian Gulf and Asia in 42 days.

3.2. Trim optimization

To reduce emissions and increase gas mileage, the trim must be optimized. Depending upon the draft and speed of the ship, the optimal trim can be determined. The ship hull creates reluctance due to its trim. As a general practice, accurate drafts are considered at the time of designing the hull shapes. With the adjustment in the trim of the ship with drafts, the resistance can be minimized. Even in the instance of a minimal draft, there may be considerable ship resistance if the trim is improper, based on the proper trimming condition for an enormous draft. While the trim of the ship is aligned, the fluid pressure resistance of the submerged area and the wave resistance of the movement of the ship are both influenced. Cost reduction and less emission are two consequences of trim optimization for a certain draft and speed.

In order to trim, fuel economy is influenced by fuel distribution, loads are stacked up, and ballast is tuned. Ballasting consumes more fuel than the ship itself because the ship has a greater displacement. As much as 5% improved gas mileage can be achieved by trimming optimization. Trim optimization involves some risk of operations and complexities because it disregards bending moments and shear stresses. Ballast transfer, design of the boat trim (scupper and drain placement), trim corrections because of the consumption of fuel and water, and weather control are some everyday concerns sailors encounter when sailing on a journey.

3.3. Design flow

Shorter routes hitherto took precedence over safer and more fuel-efficient ones. Placing a priority on ship safety, crew, and cargo, weather routing aims to maximize the voyage plan with regard to fuel consumption and energy expenditure. Part of weather routing, ships should be able to arrive in ports on schedule and well-furnished while in ports. It not only saves time, but also weather routing saves fuel up to 3%. Ship weather routing is the technique of finding the most efficient route of a voyage by modeling upcoming weather conditions, ship properties, and sea state. Depending on a variety of weather conditions, the most efficient path of the trip is found in accordance with its energy efficiency, safety, and comfort, or any combination thereof. Weather routing at its best stage considers the safety limit of the ship and optimizes the use of the expected time of arrival (ETA) with minimum fuel consumption and sailing time. Economic and environmental benefits through research in ship performance for the complete range of weather conditions are immense. Ship decision in a range of different weather conditions to deliver a safe, efficient, and cost-effective passage has far-reaching impacts on the owners and crew. The severe rate decreases by virtue of weather conditions, but the power consumption and fuel consumption of the ship increase.

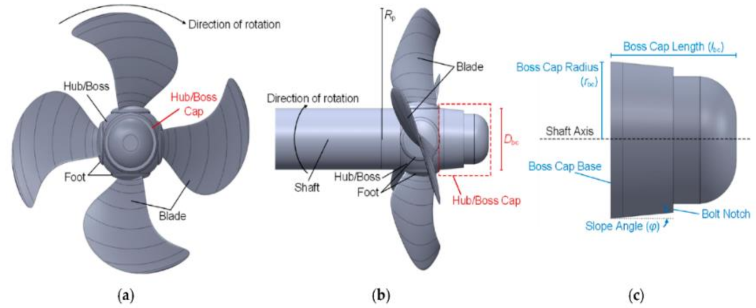

Fig. 2: Improve Ship Propeller Efficiency via Optimum Design of Propeller Boss Cap Fins.

Ships require increased drag and resistance if the rudder is yawed. Fuel can be saved through reducing how frequently and at what angles the rudder is moved in order to alter direction. Autopilot mechanisms can be used by the bridge staff as extra equipment to assist in maximizing steering and reducing the use of fuel. Since there is smaller rudder motion and sailing distance needed to stay on course, the ship gains less resistance and less power. Conventional autopilots are founded on linear relations between heading rate and rudder angle. They are appropriate for directional stability and small angles. Greater rudder angles might be required for stability and control during conditions when the ship is undergoing high dynamics as a consequence of poor weather, i.e., waves, currents, and strong winds. Draft, depth, and speed are factors that influence the turn rate and rudder angle of a ship. One advantage of adaptive autopilot systems is the good path accuracy. Steeply, they allow the rud-der to respond faster and with less bow deviation even in rough seas. Even where the autopilot is able to respond automatically to changes in weather and load, minimizing the need for manual control, there is still scope to maximize fuel economy by properly utilizing the autopilot. Different variables such as wind, waves, current, speed, trim, draft, and water depth must be addressed through compensation in the steering behavior. Instead of being optimization variables, speed and trim optimization are input parameters being monitored by the DSS. System measurements like engine load and resistance are controlled by these methods, which are vital operating context. These inputs are utilized by the ANN to generate control outputs for the system in general, which allows the operators to continue functioning optimally irrespective of the navigation or environmental condition without having to manually select these values.

4. Results and discussion

Electronic management and monitoring systems can be automated in order to enhance the main engine efficiency. They maximize engine performance, reduce emissions, and minimize fuel consumption. Engines need to be maintained and tested for performance periodically based on the manufacturer's guidelines to enable efficient functioning. Real-time monitoring systems enable ships to track engine performance against primary key performance indicators through which they can analyze engine performance conditions. You also use these technologies to detect any perfor-mance and maintenance problems and correct them. When the main engine is tuned to operate at its most frequent levels of load, you can conserve up to 1% of fuel consump-tion even under difficult situations. You can save money and reduce pollution by making fuel more efficient by putting the engine to operate at its most typical levels of load.

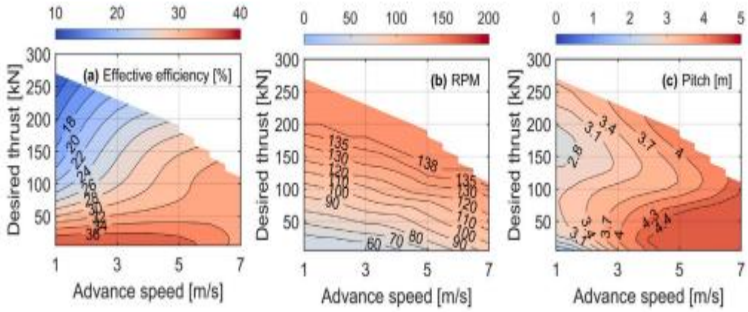

Fig. 3: Gear Ratio 2 Smoothed CS For Mechanical Mode. Propeller Pitch, Propeller RPM, and Effective Efficiency.

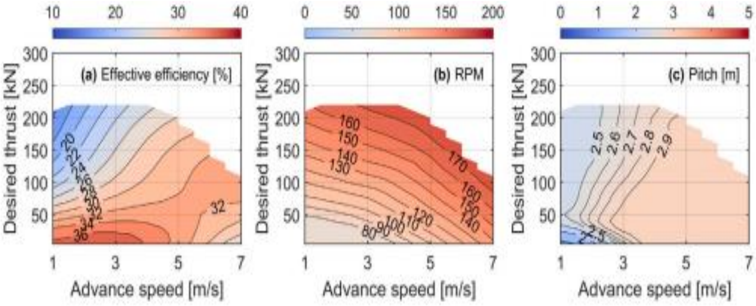

Fig. 4: Final (Unsmoothed) CS for Mechanical Mode with Gear Ratio 1 Including Propeller RPM, Propeller Pitch, and Effective Efficiency.

Minimum power demands onboard must also be kept in mind for optimum functioning of the ship's electrical and mechanical systems. Decreasing on-board power demands can decrease fuel consumption. Aside from the main power demands for propelling the ship, there are other shipboard support systems that need electric power. Bow thrusters, which enable a number of ships to handle at lower speeds, are among them, including cooling water pumps, ventilation fans, navigation and control systems, etc. Equipment for cargo handling is also energy-consuming while loading and unloading. Although freezing of frozen cargoes is required, other cargoes require heating, such as bitumen, heavy fuel oil, crude oil, and heavy oil. Priority should be given to power plant scheduling, staff training, and monitoring energy consumption to reduce energy consumption. Recent technology developments in process control and automation have provided new options for energy-saving applications such as automatic control of temperature, flow (pump and fan speed), and lighting.

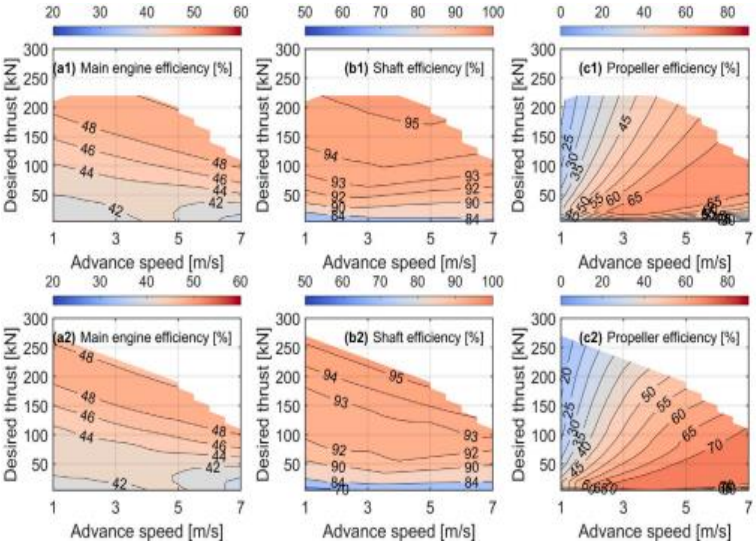

Fig. 5: The Mechanical Mode Component Efficiency Diagram. Efficiency of the Main Engine (A), Shaft Transmission (B), and Propeller (C).

Figure 5 indicates that there is an optimal gear ratio after which mechanical losses make the efficiency of the propeller decline. The figure indicates the necessity of voyage-specific adaptive gear control. In a bid to provide real-time efficiency, the ANN-based DSS is continually studying these patterns of variation and adjusts operating setpoints accordingly. Explanation of the content of the figure and its contribution to the action of the DSS must be provided with each reference to the figure.

The 1 and 2 that follow each letter is the gear ratio.

Vessels and world transportation networks wouldn't be operational without effective fuel propulsion systems. In this study, there's a new energy-efficient ship propulsion standard that employs optimal combinator surface design. New inputs for this novel technique are target thrust and advance speed, and the outputs are propeller RPM and pitch setpoints to drive propulsion control towards more efficient and environmentally friendly vessel operation.

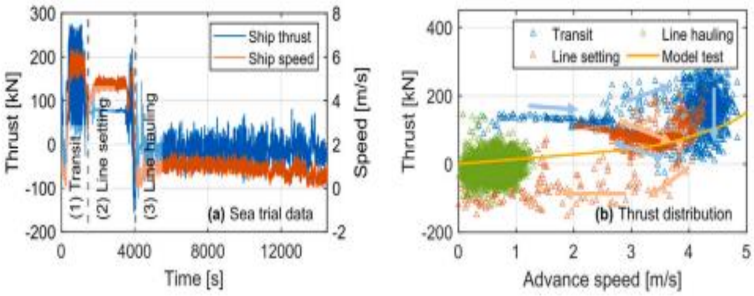

Fig. 6: Data From Typical Sea Trials for Line Laying, Line Hauling, and Ship Passage. (A) Sea Trial Data on Ship Speed and Thrust, and (B) Model Test Thrust Curve and Thrust Plot for Various Operating Stages.

The open-water and propeller prime mover efficiency mainly dictate the overall propulsion efficiency optimization of the combinator surface. A "near-optimal" propulsion setpoint can be achieved by the new combinator surface application that optimizes in a simple manner by bypassing ship resistance, wake fraction, and thrust deduction fraction forecasting. This is in contrast to working on an applied traditional combinator curve. In CPP ship propulsion systems, the combinator surface approach presented here is superior to combinator curve online optimization and traditional adaptive control on combinator curves. The operator cannot have any flexibility in the choice of combinator curves because he or she is not asked to make a decision. The vessel is able to make its preferred operating setpoint of the captain, permitting more precise adjustment and optimal operation, by constant revision of the setpoints of pitch and RPM.

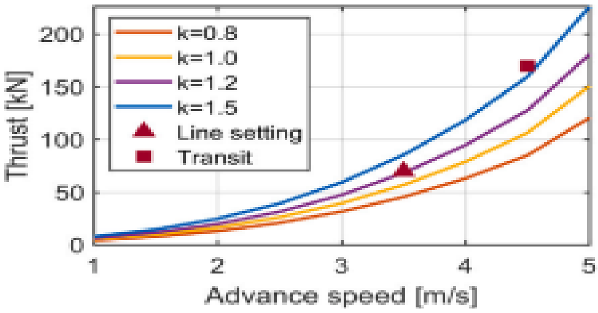

Fig. 7: The Thrust Curve from Open-Water Test (K=1) and Alternative Thrust Curves.

As opposed to classical combinator curves that use a constant ship speed and need an estimate of ship resistance as an input, the combinator surface method avoids this limitation. The combinator surface optimization process guarantees all setpoints satisfy all specs to make sure ships are operated safely and efficiently. We aim to deploy the combinator surface in a great variety of ships' propulsion control systems in the future.

5. Conclusion

With rising fuel prices and greenhouse gas emissions, the shipping industry has set reducing fuel consumption as top priority. As the energy efficiency of a ship is proportional to the amount of bunker fuel oil consumed, accurate estimation of fuel consumption is crucial in reducing fuel expenses and increasing energy efficiency in ship operations. Less greenhouse gas emission, conserved fuel, and lower fuel costs are all advantages of the ability of fuel prediction to detect wasteful fuel consumption operating conditions and recommend improved operating practices. It would be wonderful if shipmasters could depend upon a system that can assist them in deciding how to adopt operating practices so that their vessels become more energy efficient. For assisting shipping operators in making rational decisions about the operational modifications that improve energy efficiency, this project is mainly focused on creating an ANN-based decision support system (DSS). For assisting shipping operators in achieving a balance between economic and environmental effects, the proposed DSS presents a strategy framework for achieving it. Global results indicate that in comparison with the baseline Multi-ple Regression (MR) model, the neural network model makes a correct prediction of interaction between the input variable and ship fuel consumption. When used as an efficient decision support system for ship operators in predicting fuel consumption during different daily operation conditions, the strategy can be applied to different daily operation conditions. ANNs are first employed to estimate ship fuel consumption. Secondly, a real-time DSS is constructed to direct crew members toward more energy-efficient decisions. Ship design options might also be compared for fuel consumption and environmental considerations based on the prediction model and DSS. Developing a model to predict the trend of fuel usage by ships for different operating conditions can be supported by enlarging the sample size and testing more variables for more ships. One of the possible interpretations of results of this study may be that it offers an opportunity for additional research on how to approximate the fuel consumption of a large fleet of vessels from a combination of operating and technological parameters. This method can be applied to analysis of different types of ships with certain characteristics, for example, bulkers, containers, etc. High-fidelity real-time sensor measurements rely, and to their vulnerability is that errors or loss of data can affect prediction quality. Additionally, although on-board ANN computation is possible, it may be beyond the capability of present systems to manage. The researchers will investigate how DSS control loops can be incorporated in hybrid drive systems, such as battery-LNG hybrids, in the future. Further, there is also space to extend the system to offer policy-level implications with real-world efficiency insights, which can be used to implement compliant operation standards according to IMO regulations. As bandwidth is limited, edge computing approaches can significantly support enhancing system autonomy without adding latency at the same time.

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