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Hydrodynamic Aspects of a Ship in Weather Routing within the Context of Slow Steaming

Abstract

The review paper addresses the intricate relationship between ship hydrodynamic performance and the implementation of weather routing within the context of slow steaming. The maritime industry, as a vital component of global trade, has faced increasing pressure to reduce its environmental footprint and operational costs. Slow steaming, characterized by reduced cruising speeds, has emerged as a sustainable approach to minimize fuel consumption and greenhouse gas emissions. Weather routing, on the other hand, optimizes ship routes based on meteorological and oceanographic conditions, with the aim of enhancing both safety and fuel efficiency. Ship hydrodynamics, encompassing resistance, propulsion, maneuverability, and seakeeping, directly impact a ship's performance. The relationship between these hydrodynamic aspects and weather routing in the context of slow steaming is crucial for optimizing fuel efficiency, reducing emissions, ensuring safety, and minimizing operational costs in the maritime industry. By integrating these factors, ship operators can achieve a more sustainable and efficient approaches to sea transport within the context of slow steaming and weather routing.

Keywords: ship, hydrodynamic performance, weather routing, slow steaming

1. Introduction

Due to a number of circumstances that call for more ecologically friendly and effective shipping methods, the global maritime industry undergoes tremendous change. The critical challenge of achieving net-zero greenhouse gas (GHG) emissions by 2050 has been set by the International Maritime Organization (*IMO, 2023*). The increasing use of "slow steaming," a technique in which ships purposefully lower their speed to save fuel and cut emissions (*Bialystocki and Konovessis, 2016*), has been one of the most significant advances in achieving these goals. In addition to being beneficial for the environment, this strategy has allowed shipowners and operators to save a substantial amount of money (*Cariou et al, 2019*). The adaptability of slow steaming in the maritime sector is inevitably connected to a ship's ability to sail through diverse weather conditions with the utmost efficiency and safety. Useful insights into the optimization of ship routing and environmental sustainability are provided by reviewing existing research, as well as the IMO and MARPOL regulations (*IMO 2022, IMO 2023, MARPOL 2022*) as the basis for the development of slow steaming. The novel approaches are being integrated to allow for safer and more effective slow steaming (*Kim et al, 2022*). The relationship between slow steaming and weather routing is supported by ship hull hydrodynamics, including hull shape, appendages and hull coatings.

Within the context of slow steaming, this review paper seeks to offer a deeper understanding of the complex interaction between weather routing and ship hull hydrodynamics. The hydrodynamic aspects of a ship have an important role in slow steaming and weather routing, as optimizing routes based on meteorological conditions becomes crucial to enhance fuel efficiency and navigate safely through varying weather patterns. Considering the climate change and sensitivity of the Earth's atmosphere, the regulatory requirements for ships are frequently changed and adapted (*Zincir, 2023*). Not only is it essential to understand the hydrodynamic principles that strongly influence ship performance in different weather scenarios, but it is also has a major role in determining the future of the maritime sector as it continues its path toward greener and more efficient horizons.

1.2. The concept of slow steaming

Slow steaming is a common practice in the shipping industry where ships operate at speeds significantly below their maximum capabilities. Cargo ships intentionally slow down in order to minimize fuel consumption and carbon emissions. It represents a strategic approach that balances economic considerations, regulatory compliance, and environmental responsibility in the maritime sector. The speed reduction is usually around 2-6 knots, and as a result fuel consumption is reduced (*Sanguri 2012*). The achieved lower fuel consumption directly impacts the ship's emissions, making slow steaming a major contributor to compliance with environmental regulations. Instead of sailing at a speed of 20 to 24 knots, a ship sails at a speed of about 12 to 19 knots (*Lee and Song, 2017*). The exact reduction in speed may depend on several factors such as fuel prices, market conditions, ship type, route, and environmental consideration. With major financial, environmental and performance related benefits, slow steaming offers an effective way to reduce operating costs in today's economically challenged environment.

The history of slow steaming in the maritime sector is a combination of evolving methods and solutions to various economic and operational constraints. The slow steaming approach dates back to the 1970s, when the maritime industry was trying to find ways to increase efficiency while also facing rising fuel costs and environmental concerns (*UNCTAD 1970, Tenold, 2019*). Many shipowners were forced to reduce their ships' speeds to save fuel during the oil crisis of the 1970s and early 1980s. With rapidly rising oil prices, slow steaming was considered a cost-effective method (*Gately, 1986*), but was not yet recognized as a standard practice at that time. Growing interest in slow steaming as a way to reduce GHG emissions emerged in the late 1990s, and this approach continued to develop as concerns about environmental sustainability and emissions from the maritime sector grew (*Kågeson, 1999; Cariou and Wolff, 2006).* In the early 2000s, the shipping industry faced overcapacity and economic constraints (*Kemp, 2015*). Due to an excessive number of available ships and falling freight rates, shipowners were looking for new ways to cut expenses, and slow steaming re-emerged as a more systematic and strategic approach. The impact of the shipping industry on the Earth's climate has been frequently addressed since the early 2000s (*Harrould-Koleib, 2008*). In addition to consuming the most polluting fuel and contributing to global warming, shipping emissions have been identified as a serious health risk to humans. Some studies from 2007 showed that every year particle emissions from shipping are responsible for around 60,000 cardiovascular and lung cancer fatalities (*Corbett et al, 2007*). In light of these concerns and emerging regulations, the concept of slow steaming evolved into a systematic practice in the 2010s. The global financial crisis of 2008 also had a significant impact on shipping, particularly the liner industry. After realizing that slow steaming can save operational costs and maintain profitability during a recession, several container carriers have adopted it as a survival tactic (*Kalgora and Christian, 2016*). Large liners, container ships and bulk carriers later adopted slow steaming as a regular operating method.

Since the International Maritime Organization (IMO) actively promotes and encourages measures to improve fuel efficiency and reduce GHG emissions in the maritime industry, slow steaming is recognized as a way to reduce fuel consumptions, reduce emissions, and increase ship efficiency, while at the same time providing consistent timetable of sailings. Along with the methodical deployment of slow steaming, technological developments have been key to optimizing its implementation (*Kim et al, 2019*). Ship designs (*Esmailian et al, 2022a, Esmailian and Steen, 2022b*), marine engines (*MAN Diesel and Turbo, 2014, Zhu et al, 2020*), and fuel efficient technologies have been created to improve the performance of ships operating at lower speeds (*Prpić-Oršić et al, 2016, Tsitsilonis and Theotokatos, 2018, Yuan et al, 2022*). Although slow steaming is not a specific IMO regulation, the IMO has taken various steps to encourage and support its adoption. In favor of slow steaming, the IMO has developed an Energy Efficiency Operational Indicator (EEOI) with the goal of reducing GHG emissions from current ships by 40–70% by 2050 (*IMO, 2023*). The IMO has recommended three basic strategies to achieve this goal: increasing ship size, reducing speed, and using new technologies. In 2015, the IMO has come up with the energy efficiency design index (EEDI), which indicated gradual improvements in the energy efficiency of newly built ships, with the reduction of CO2 per tonne-mile (*IMO 2015*). Today, the maritime industry still has to strike a balance between the benefits of slow steaming, such as lower emissions and fuel costs, and the requirement to maintain efficient cargo transport (*Vakili et al, 2023, Kalajdžić et al, 2022, APEC 2019*). To maximize the benefits of slow steaming and maintain timetable reliability, data-driven decision support systems, weather routing, and optimal voyage planning are used (*Vettor et al, 2020, Shih et al, 2023, Borén et al, 2022*). The development and implementation of slow steaming in the shipping industry reflects economic, environmental, and operational changes and concerns (*McFarlane, 2022*). As the industry progresses, slow steaming continues to respond to ongoing challenges and opportunities (*Mallouppas and Yfantis, 2021, Tadros et al, 2023*).

1.2. Weather routing

Weather routing, as part of ship voyage planning, is defined as determining the optimal ship route, taking into consideration fuel consumption, ship characteristics and most importantly, weather forecasts and sea states (*Shao et al., 2011*). Weather systems can be complex since they constantly change, with wind speed and direction varying over time. Deciding how to navigate through such a complex system can be difficult. Given a performance model and expected weather along a route, ship weather route modeling attempts to identify a path where multiple variables, such as time, fuel consumption, or risk, are optimal (*Dickson et al., 2019*). Numerous data must be taken into consideration, including environmental aspects such as wind speed, wave height, and current, to ensure that the chosen route is the best option. A competent weather routing system considers the local weather both in real time, and in the future. The most up-to-date meteorological data and its accuracy are essential for consistent route adjustments. Since weather forecasts are the basis of weather routing, their uncertainties must be considered, due to the fact that forecast providers use different algorithms and numerical methods, many of which never fully disclosed due to confidentiality reasons. Some uncertainties in ship routing have been studied in the past, incorporating both deterministic and stochastic factors, where the problem was treated as a multi-stage stochastic dynamic process under the constraints of ship operational requirements, ship dynamic responses, and probabilistic environmental conditions (*Chen, 1978*). Approaches to optimal ship routing have varied over the years, with different methods used, ranging from modeling the weather routing problem as a constrained graph problem, a constrained nonlinear optimization problem or as a combination of both (*Walther et al., 2016*). Recently, different methodologies have been investigated for predicting of uncertainties associated with ship fuel consumption and ensemble predictions, with fuel consumption predictions repeated for each part of the ensemble and compared with probabilistic approaches in which wave parameters are modeled (*Vettor and Guedes Soares, 2022*). Artificial intelligence and optimization algorithms inspired by nature are gaining popularity, with genetic algorithms used in ship routing increasing the ability to find an optimal solution (Zhou et al., 2023), while improving algorithm robustness through various evolutionary strategies.

The significant risks and uncertainties associated with weather routing must still be taken into consideration, as they directly affect the safety of the ship and her operative efficiency. In adverse conditions, the ship is exposed to significant environmental forces. As a result, a number of dynamic factors cause the ship's speed to decrease (*ITU, 2014*). The change in ship speed has been studied even under severe environmental conditions (*Sasa et al., 2019, Prpić-Oršić et al., 2020, Vitali et al., 2020*). The importance of ship motions and added resistance due to wave effects and different sea states were early recognized as important factors in ship routing (*Kwon, 1981*). A statistical analysis of the effects of waves on ships was also studied (*Chen et al., 2021*), which further emphasizes the importance of ship motions during navigation.

Weather routing is of great significance for a number of reasons including risk reduction, cost savings, and safety (*Zis et al., 2020*). Weather routing can help ships avoid dangerous weather conditions including storms, hurricanes, and rough seas. Such conditions can seriously compromise the stability of the ship and the safety of its crew. Ships can operate more efficiently if they stay clear of severe weather and take advantage of favorable winds and currents (*Vettor et al., 2020*). Fuel consumption and GHG emissions are significantly reduced by using effective weather routing. As the maritime sector is under increasing pressure to reduce its environmental impact, weather routing is also seen as key to achieving sustainability goals (*Mander, 2017, Taskar and Andersen, 2020*). By preventing fuel wastage, minimizing equipment wear and tear, and the possibility of cargo damage due to rough seas, weather routing can result in significant cost savings. By providing ships with access real-time weather forecasts and information, weather routing helps reduce these various risks. This helps in the decision-making process and preventive actions taken by ship operators to avoid accidents, damages, and delays. Ship operators can better allocate resources, such as crew, fuel, and maintenance, to ensure the safe and efficient operation of the ship by having knowledge about the weather conditions along the planned route.

2. Ship Hydrodynamics

There is a close connection between the ship's hydrodynamics, i.e. resistance, propulsion, controllability (maneuverability), seakeeping and weather routing within the context of slow steaming, Figure 1. These aspects are interconnected and play a key role in optimizing ship performance, especially when slow steaming strategies are employed in combination with weather routing. The relationship between these hydrodynamic aspects and route planning is crucial for optimizing fuel efficiency, reducing emissions, ensuring safety, and minimizing ship operational costs (*MAN Energy Solutions, 2018*). By integrating these factors, ship operators can achieve a more sustainable and efficient approaches to maritime transport in the context of slow steaming and weather routing. Some hydrodynamic aspects of the ship are discussed further in this chapter

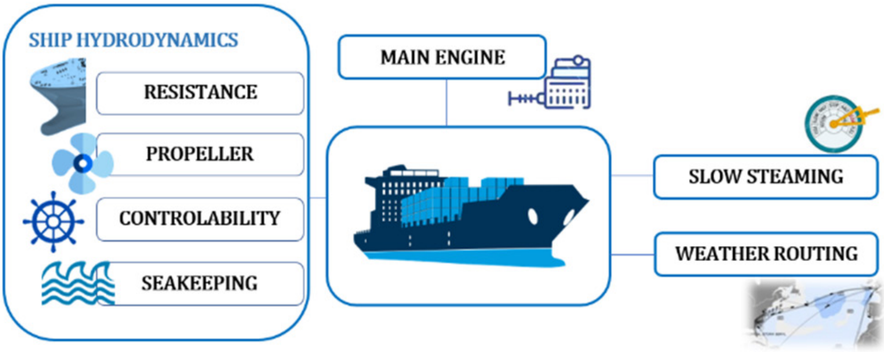

Figure 1. Hydrodynamic aspects of a ship in slow steaming and weather routing

2.1. Ship resistance

Ship resistance is a fundamental aspect of hydrodynamics. Understanding and minimizing resistance is vital when implementing slow steaming, as reducing resistance can lead to significant fuel savings. This usually refers to the resistance of the ship in calm water. Increased ship resistance is a common consequence of adverse weather conditions, characterized by strong winds and rough seas and is referred as additional resistance. This resistance represents an increase in resistance compared to calm water. Consequently, unfavorable weather conditions cause a reduction in ship speed and higher fuel consumption. Ship operators can maximize the effectiveness of slow steaming by choosing routes with better weather conditions, which will in turn reduce additional resistance.

In the last century, there was a constant increase in sailing speed, which affected changes in the shape of the ship's hull. One of the most striking changes is the bulbous bow. The main task of the bulb is to generate a bow wave system that will partly reduce the wave-making resistance. However, this positive effect usually relates to a narrow range of ship speeds around the design draft and speed for which the hull shape is designed. Some ship types, such as container ships, have experienced a significant reduction in operating speed over the past decade. Container ships constructed before 2008 were designed for higher operational speeds, which have now been replaced by slow steaming speeds. These trends in the maritime industry have required modifications of ship's bows and propeller retrofitting. Recent researches have focused on finding the optimal bulbous bow of container ships, while simultaneously reducing operating costs (*Yin et al, 2019*). Danish shipping and logistics company Maersk A/S was the first to start modifications of its ships, which were originally designed for a speed of around 24 knots, but the rest of the industry followed them soon after. In 2014, the French shipping company CMA CGM retrofitted ten of its ships for slow steaming, and in 2018 ordered nine LNG-powered container ships with bows optimized for lower speeds (*The Loadstar, 2018*). The German liner company, Hapag-Lloyd AG, also aims to meet the IMO's CO2 reducing targets by 2030 with its retrofit program involving one hundred ships (*Ships Monthly, 2023*).

2.2. Ship screw propeller

Reduced ship speeds also affect the performance of the ship's propeller. Slow-rotating, large-diameter propellers have obvious advantages in terms of efficiency. Therefore, while trying to reduce fuel consumption, installing larger diameter and lower rotational speed propellers usually results in significant energy savings (*American Bureau of Shipping, 2014*). In addition to diameter optimization, several manufacturers offer improved propellers for existing ships that can save three to seven percent, depending whether the speed is reduced or kept constant. Some propeller manufacturers claim that fuel savings of up to 14 percent can be achieved with redesigned propellers (*MMG, 2023a*). By meeting the overall operational profile of the ship and providing good efficiency for several propeller design points, an improved propeller with generally greater usability can be obtained. Application of computational fluid dynamics (CFD) can be crucial for any retrofitting project, as it can give better insight into the wake field characteristics and enable a comprehensive propulsion analysis (*MMG, 2023b, Mikulec and Piehl, 2023*). For a quality retrofit, it is necessary to take into account the time the ship will spend sailing at a certain speed, as well to have knowledge of how trim affects fuel consumption on long voyages.

2.3. Ship controllability and seakeeping

Understanding of the effects that weather routing and slow steaming have on a ship's controllability, particularly at lower speeds, is crucial to ensuring safe marine operations. Ship controllability encompasses three distinct areas: course keeping (steering), maneuvering (course changing) and speed changing (*Bertram, 2012*), the first two of which are of great importance in terms of slow steaming. These performances vary with the ship's speed, its draft and especially its trim. IMO regulations provide minimum maneuvering requirements for all ships, but shipowners may set additional requirements. Innovative propulsion concepts and slow steaming trends do not address ship safety concerns, resulting in insufficient steering power for maintaining the maneuverability of ships in adverse weather conditions (*Bitner-Gregerse et al, 2016*). Although weather routing often recommends course adjustments to optimize fuel efficiency, this may not be sufficient in terms of safety. The ship's ability to maneuver changes significantly when operating at a lower speed, and often leads to her longer response time (Özkulluk and Nas, 2023). These effects should be considered for more careful navigation, especially in rough seas. Adverse weather requires proficient navigational skills to maintain control and safety in adverse circumstances, which can potentially affect overall safety.

Seakeeping is a field of hydrodynamics in which ship motions are considered, which as a rule cannot be controlled, or can be controlled to a very limited extent. Ship's design, hull form and motion control systems play a significant role in seakeeping (*Vettor et al, 2020*). When applying slow steaming and weather routing, the choice of route can expose the ship to different sea conditions. Understanding the ship's seakeeping characteristics is crucial for choosing routes that minimize passenger and crew discomfort and potential cargo damage during adverse weather conditions (*Pennino and Scamardella, 2022*). There is usually a maximum sea state value at which the ship can remain operational and all her seaworthiness criteria are met (*Vettor et al, 2020*). Assessing the response of a ship to waves requires deeper understanding because at reduced, off-design speed it can cause delays or course changes (*Tezdogan et al, 2015*). For this reason, seakeeping calculations and analyzes should be completed at both the design speed and the usual slow steaming speed. In order to provide purposeful insight for weather routing of ships, the seakeeping assessments should include different sea states, wave heights and directions.

2.4. Ship propulsion

Ship propulsion refers to systems used to create thrust to move a ship through the water. Most ships are powered by mechanical systems consisting of an internal combustion engine driving a screw propeller. Engine's performance, including fuel efficiency, is closely related to the ship's speed and propulsion characteristics. While resistance and propeller characteristics are usually treated independently during the analysis phase, the resistance of the ship, the characteristics of the ship's propeller as well as overall propulsion characteristics must be considered together during the synthesis of the ship design (*Gunes, 2023*).

The primary propulsion system of almost all existing ships are designed and optimized to operate at a certain engine load and speed. The slow steaming reduced the actual cruise speed from design load levels, leaving the ship and her engine running at non-optimized load levels (*Saydam et al. 2022)*. A reduced maximum speed and specified MCR of the ship can be achieved by reducing the engine power output, which will optimize the actual load point relative to the design load point (*Wärtsilä, 2023*). The primary idea behind the benefits of adapting an engine for fuel savings comes from optimizing the ratio of the engine's maximum cylinder pressure to the mean effective pressure (MEP) of its cylinders. This can be combined with adding variable frequency drives to pumps and other auxiliary systems, or reducing the cooling capacity of such systems (*MAN Energy Solutions, 2019*). Slow steaming can effectively reduce fuel consumption and CO2 emissions, but the choice of the optimal propulsion system highly affects the potential of slow steaming (*Pelić et al. 2023*). Long-term operation of engine at reduced power can lead to issues such as fouling, carbon deposits, and incomplete combustion, which affect both efficiency and maintenance requirements (*Le et al. 2019*). Machinery and engine manufacturers may provide guidelines for operating at lower speeds to minimize wear and tear, and ship operators must to adhere to these recommendations to ensure the longevity of their assets.

3. Discussion

As a rule, the shipbuilding contract is concluded after serious and sometimes lengthy negotiations between the ship's client and the shipyard. The typical main requirement of a shipowner interested in a new shipbuilding contract, in addition to transport capacity expressed by a deadweight, capacity of cargo spaces, number of transported containers, etc., is the speed of the ship in sea trial condition, at 100% MCR. After the completion of the ship, before the handover, a sea trial is carried out, where the ship is exposed to forcing in order to confirm the contracted speed. When the ship achieves this speed, all stakeholders - the shipyard, the ship owner, the hydrodynamic institute that carried out the ship model testing, the main engine manufacturer, and the screw propeller manufacturer - are very satisfied. The fact that after that the ship in service will most likely never reach that speed again at that point is not important. This is a long-standing practice established in shipbuilding and the maritime industry has traditionally adhered to it.

The hydrodynamic aspects of the ship are traditionally approached through the following main stages: concept design, preliminary design, contract design, detailed design, design verification and validation, sea trial and operation. Overall design is usually approached by considering only design conditions of the ship. However, it is questionable how much of her time a ship will actually sail in these design conditions. It is very likely that most of her time the ship will be sailing in off-design conditions for which for example ship resistance and propulsion characteristics can be considerably different than the ones considered in the design. When slow steaming or weather conditions additionally change the conditions for which the ship is designed, it turns out that, for example, a fixed pitch propeller that is optimized for only one operating point cannot efficiently cover the entire range of conditions that can occur at sea.

All this indicates that during the ship design process it would be necessary to consider a wide range of conditions under which the ship could operate. One of the possible approaches would be that the towing tank institutions, as an unquestionable authority in ship hydrodynamics, to be involved in the design of the ships as early as possible, even in the concept design phase. These institutions, in close cooperation with the ship operators, shipyards and engine manufacturers, would analyze all possible scenarios that could arise for the ship during her service and bring the best possible solutions, especially as regards resistance, propellers and engines. What should be considered as a minimum is the operational range of ship speeds, drafts and trims. Towing tank institutions should start preparing for this approach in order to come in a position to offer such services as "one shop stop", i.e. offer under one roof all services related to the hydrodynamic aspects of the ship that ship operators in the future might need.

4. Conclusion

Slow steaming has become common practice on the main trade routes. In addition, weather routing is becoming more and more advanced, and developed tools enable shipping companies to save fuel, improve safety, minimize delays, and capture other benefits that allow them to operate more efficiently with fewer risks.

There is a close connection between slow steaming and ship hydrodynamics, and the hydrodynamic aspects, such as ship resistance and propulsion efficiency, become particularly important. Practical experience shows that a ship in service does not meet the conditions for which it was designed too much of its time, and that most of the time she sails in off design conditions. This primarily refers to the speed, draft and trim. Shipping companies should start a discussion about the need for a comprehensive and complete consideration of hydrodynamics for a ship that would sail in off design conditions, and towing tanks institutions as an unquestionable authority in ship hydrodynamics must prepare for answers to many questions that could appear.

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