THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Methods for the Evaluation of Wingsails with a Crescent-Shaped Profile

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Gothenburg, Sweden, 2023

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Abstract

Seaborne transportation accounts for a large proportion of greenhouse gas (GHG) emissions. The International Maritime Organization (IMO) has stipulated that GHG emissions should be reduced by 50% before 2050 compared to 2018. The use of wind-assisted ship propulsion (WASP) is considered one of the most effective ways to reduce GHG emissions. Therefore, the present study aims to establish multidisciplinary numerical models for predicting and evaluating the propulsive performance and structural response of WASP systems.

Conceptual designs of a set of telescopic wingsail rigs are generated. Numerical simulations, including computational fluid dynamics (CFD) simulations and finite element analysis, are performed for dimensioning and optimizing wingsail structures for ships to understand the fluid–structural interaction (FSI). Since the deformation of the wingsail structure that the surrounding flow excites is so large, the interaction between the flow and structure creates a coupled problem. Analysis of a crescent-shaped wingsail using an in-house software ShipCLEAN, which is based on a generic ship energy model, is conducted to evaluate this wingsail's propulsive performance in comparison with other WASP concepts.

It is concluded that wingsails with a sectional profile and significant camber have much better propulsive performance than those with conventional airfoil profiles because the potential thrust force coefficient is approximately 30% higher. It is also found that the external loads on the crescent-shaped wingsail show notable periodic oscillations due to strong flow separation, so it can be inferred that wingsails can suffer from remarkable vortex-induced vibration. This raises higher requirements on the strength and rigidity of the wingsail structure. Tip vortices are found to have negative impacts on thrust, and the sail can strongly influence the wake flow. It is also concluded from the structural analysis that the strength, especially the von Mises yield and compressive normal stress, is most critical among the assessment criteria that are considered when evaluating the wingsail structure. Using a strong frame to bear global bending and introducing a cubic-shaped mast prevents stress concentration and reduces the weight of the structures.

Keywords: crescent-shaped profile, light weight structure, rigid wingsail, wind-assisted ship propulsion.

Preface

I am deeply grateful for the support and contributions of so many individuals, institutions, and organizations that have helped me to complete this thesis over the past two years.

First and foremost, I want to express my sincere appreciation to my supervisors, Carl-Erik Janson, Hua-Dong Yao, Jonas W. Ringsberg, and Bengt Ramne, for their invaluable support and guidance throughout my licentiate journey. Their expertise, insights, and encouragement have been essential to my success, and I could not have completed this work without their contributions.

To Carl-Erik Janson, I want to express my appreciation for his extensive knowledge and expertise in the field of fluid dynamics. His insights and advice have been invaluable in shaping my research and helping me to develop a deep understanding of the fundamental principles of fluid mechanics

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I want to extend my love and congratulations to my girlfriend, Jingnan Zhang, who will be defending her PhD in June. Her dedication, perseverance, and intelligence have been an inspiration to me throughout my academic journey, and I am incredibly proud of her achievements. I am deeply grateful for her presence in my life. I know that she will go on to achieve great things, and I am honored to be able to share in her journey as we pursue our academic careers together.

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Heng Zhu
Gothenburg, March 2023

Contents

List of appended papers

This thesis consists of an extended summary and the following appended papers.

For Papers I and II, the author contributed to the ideas presented, planned the paper, did most of the modeling, simulation, and post-processing work, and wrote most of the manuscript.

For Paper III, the author contributed to the ideas presented, planned the paper, did some of the simulation work, did most of the modeling and post-processing work, and wrote most of the manuscript.

Paper I Zhu, H., Yao, H.-D., Thies, F., Ringsberg, J. W., & Ramne, B. (2023). Propulsive performance analysis of a rigid wingsail with crescent-shaped profiles based on unsteady RANS CFD. *Submitted to Ocean Engineering.*

Paper II Zhu, H., Yao, H.-D., & Ringsberg, J. W. (2023). Unsteady RANS and IDDES studies on a telescopic crescent-shaped wingsail. *Under review in Ships and Offshore Structures.*

Paper III Zhu, H., Bikkireddy, S., Ringsberg, J. W., Yao, H.-D., & Ramne, B. (2023). Structure analysis of lightweight sail structures for wind-assisted ship propulsion. In J. W. Ringsberg & C. Guedes Soares (Eds.), *Advances in the Analysis and Design of Marine Structures: Proceedings of 9th International Conference on Marine Structures (MARSTRUCT 2023, 3–5 April 2023, Gothenburg, Sweden)* (pp. 327–335). CRC Press. http://dx.doi.org/10.1201/9781003399759-36.

List of other papers by the author

In addition to the appended papers, the author of this thesis authored or co-authored the following publications and manuscripts.

Paper A Zhu, H., Nikmanesh, M. B., Yao, H. -D., Ramne, B., & Ringsberg, J. W. (2022). Propulsive performance of a novel crescent-shaped wind sail analyzed with unsteady RANS. *Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2022), June 5–10, Hamburg, Germany* (Vol. 85925, p. V007T08A053). http://dx.doi.org/10.1115/OMAE2022-79867.

Paper B Zhu, H., Yao, H.-D., & Ringsberg, J. W. (2022). Unsteady RANS and IDDES study on a telescopic crescent-shaped windsail. *Proceedings of the 7th International Conference on Ships and Offshore Structures (ICSOS 2022), October 17–19, Ålesund, Norway*.

Paper C Zhu, H., Chernoray, V., Ringsberg, J. W., Yao, H.-D., & Ramne, B. (2023). Structure analysis of lightweight sail structures for wind-assisted ship propulsion. In J. W. Ringsberg & C. Guedes Soares (Eds.), *Advances in the Analysis and Design of Marine Structures: Proceedings of 9th International Conference on Marine Structures (MARSTRUCT 2023, 3–5 April 2023, Gothenburg, Sweden)* (pp. 781–787). CRC Press. http://dx.doi.org/10.1201/9781003399759-86.

Paper D Zhu, H., Thies, F., Ringsberg, J. W., & Ramne, B. (2023). Development and performance analysis of a crescent-type sail for WASP applications. *Proceedings of the International Academic Conference on Shipping, Sustainability & Solutions 2023 (SSS 2023), March 2–3, Hamburg, Germany*.

Paper E Pradhan, P., Yao, H.-D., Joshi, V., Zhu, H., Ringsberg, J. W., Zhao, X. (2023). Actively controlled propulsion of lined-up triple foils with flapping motions. *Manuscript to be submitted to Physics of Fluids.*

Nomenclature

A_S	Sail area [m^2]
C_D	Drag force coefficient [-]
C_L	Lift force coefficient [-]
C_M	Moment coefficient [-]
C_p	Pressure coefficient [-]
C_T	Thrust force coefficient [-]
E	Young's modulus [GPa]
F_D	Drag force [N]
F_L	Lift force [N]
F_S	Side force [N]
F_T	Thrust force [N]
H	Sail height (spanwise length) [m]
L_c	Chord length [m]
P	Pressure [Pa]
Q	Q-criterion [s^{-2}]
Re	Reynolds number [-]
V_{AW}	Apparent wind speed (inlet velocity) [$\mathrm{m/s}$]
V_S	Ship speed [$\mathrm{m/s}$]
V_{TW}	True wind speed [$\mathrm{m/s}$]
V_X	Streamwise velocity [$\mathrm{m/s}$]
V_Z	Spanwise velocity [$\mathrm{m/s}$]
y^+	Dimensionless wall–normal distance [-]
α	Angle of attack [°]
α_c	Critical angle of attack [°]
θ_{AW}	Apparent wind angle [°]
θ_{TW}	True wind angle [°]

μ Dynamic viscosity [$\mathrm{Pa \cdot s}$]

ν Poisson's ratio [-]

ρ Material density [$\mathrm{kg/m^3}$]

ρ_{air} Air density [$\mathrm{kg/m^3}$]

σ_{Mises} Von Mises stress [MPa]

σ_{ij} Stress [MPa]

σ_{yield} Yield stress [MPa]

τ Wall shear stress [MPa]

ω_X Streamwise vorticity [$\mathrm{s^{-1}}$]

ω_X^* Non-dimensional streamwise vorticity [-]

ω_Z Spanwise vorticity [$\mathrm{s^{-1}}$]

ω_Z^* Non-dimensional spanwise vorticity [-]

1 Introduction

This chapter provides the background for this thesis, as well as a literature review, the aims and motivations of the present research.

1.1 Background and motivation

1.1.1 The renascence of sailing

Sailing involves the wind acting on sails, wingsails, or kites to propel ships navigating on the surface of the water. This is an ancient method of transportation that dates back thousands of years. The history of sailing can be traced back to 6000 BC and onwards in Mesopotamia, where small boats were used for transportation and fishing (Carter, 2002). In the Near East, excavations have provided evidence for sailing boats having existed between 6000 and 4300 BC (Snell, 2008). The earliest pictorial representation of sailing in history is a sailboat made in ancient Egypt around 3100 BC (Casson, 1995). The Austronesians produced the first ocean-going sailing yacht in present southern China, which led to an expansion across the South Pacific between 3000 and 1500 BC (Mahdi, 1999). The Greeks and Phoenicians then boosted seaborne trade with the development of sailing and shipbuilding technology by around 1200 BC (Johnstone, 2013). In the Mediterranean, single-yarded lateen sails arose by around 100 BC (Campbell, 1995). During the early period of their use, sailing boats could only sail downwind, but at the start of the AD period, people from the Malay Archipelago crafted large ships and were able to sail against the wind (Ellis, 2005).

Over time, sailing technology evolved and became more advanced. By the 14th century, European sailors had developed a new type of ship, known as the caravel, which was faster and more maneuverable than previous designs. During the 15th–19th centuries, termed the Age of Sail (Gaynor, 2013), fore-and-aft sails were invented and developed in Europe, which improved the upwind sailing ability of European vessels (Castro et al., 2008). However, sailing relies on the weather, which is variable. Therefore, the use of wind power as the primary source of propulsion for ocean-going ships significantly declined after the invention of steamships during the Industrial Revolution.

By the 1920s, few sails were applied to ocean-going ships. However, the development of sails never ceased (Atkinson et al., 2018). In 1979, oil prices suddenly increased significantly, which is known as the "1979 oil crisis." This event led to an exploration of developments in potential alternative propulsion systems (Viola et al., 2015). Sail technology, an ancient means of propulsion, became popular again during this period (Satchwell, 1985).

Nowadays, transportation accounts for a large proportion of greenhouse gas (GHG) emissions. According to data from 2017, as shown in Figure 1, transportation accounted for 24% of the EU's GHG emission (EUROSTAT, 2019). Based on statistical data from 2014, approximately 90% of the world trade volume is transported by shipping fleets (International Chamber of

Shipping, 2014). Hence, thousands of ships that perform shipping tasks consume vast quantities of fuel for propulsion and discharge plenty of GHGs. For instance, a pure car and truck carrier (PCTC), may consume 30~60 tons of fossil fuel per day depending on how it is operated (Bialystocki & Konovessis, 2016). It is estimated that ocean-going ships globally consumed approximately 250~325 million tons of fuel per year from 2007–2012 on average, resulting in approximately 740~795 million tons of CO_2 emissions (Smith et al., 2015). A previous study forecasted that the current level of the world's transportation needs will probably double by 2050 (Gadonneix et al., 2011).

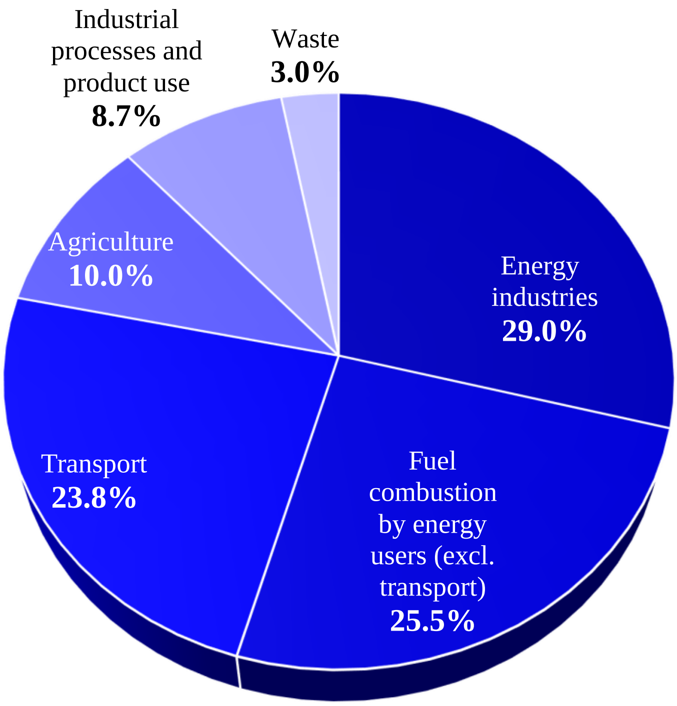


Figure 1. Share of EU greenhouse gas emission by source in 2017 (EUROSTAT, 2019).

In recent years, governments and organizations have made many important decisions to reduce GHG emissions. In 2017, the Swedish parliament decided that Sweden will be fossil fuel-free by 2045 at the latest. Swedish domestic GHG emissions from transportation will also be reduced by at least 70% between 2010 and 2030. Simultaneously, due to the agreement of the International Maritime Organization (IMO), shipping must become more energy-efficient, and before 2050, the shipping industry must reduce its GHG emissions to 50% of the level in 2008 (IMO, 2018).

There is no doubt that the set goals are ambitious. To reach them, the development and implementation of solutions must intensify, and the fossil fuel used in maritime transportation must be replaced by renewable alternatives. There are several renewable alternatives to fossil fuels that can be used in maritime transportation, including biofuels, hydrogen, wind power, solar power, and battery power. Among these, wind is a renewable resource that is readily available in large quantities, and wind energy is ideally suited to maritime transportation, as maritime transportation can use it efficiently and without unnecessary energy conversions. To achieve an energy-efficient and sustainable society, the use of wind power for the propulsion of maritime vessels should be maximized. Therefore, wind-assisted ship propulsion (WASP) for large commercial ships is considered a promising solution to reduce shipping's dependence on fossil fuels.

1.1.2 Principles of sailing

To make it more convenient to explain the methodology applied in this thesis, some of the principles of sailing are first introduced.

For ships using rigid wingsails, the thrust propelling the ships originates from the wind loads on the sails. Usually, the thrust force is transferred through the mast from the sails to the ship. The external loads on the sail depend on the speed of the apparent wind, which is the wind that the ship and sails are experiencing. Figure 2 presents the wind triangle, where the apparent wind speed, i.e., the wind speed relative to the ship, and the apparent wind angle can be calculated using Equations (1) and (2), respectively.

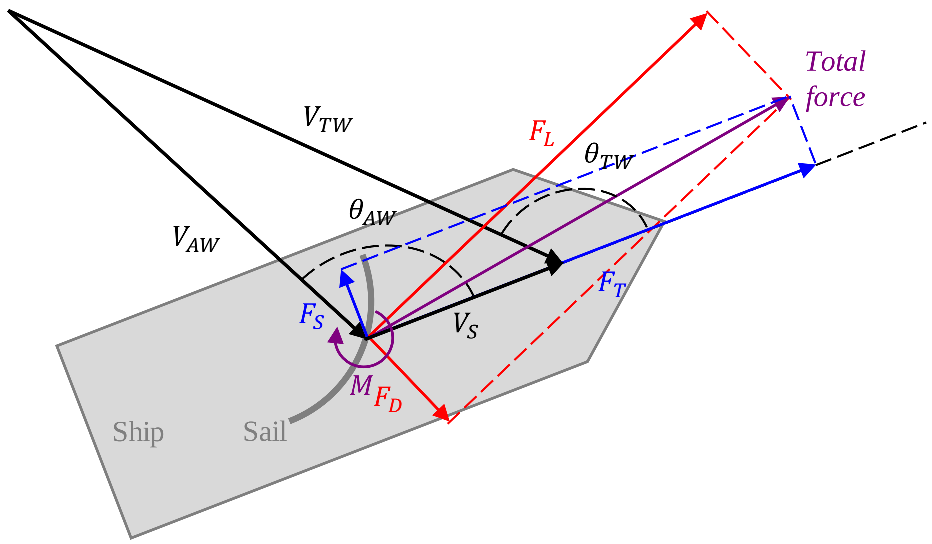


Figure 2. The wind triangle and loads on the sails.

$$V_{AW} = \sqrt{V_S^2 + V_{TW}^2 + 2V_S V_{TW} \cdot \cos\theta_{TW}} \tag{1}$$

$$\theta_{AW} = \tan^{-1}\left(\frac{V_{TW} \cdot \sin\theta_{TW}}{V_S + V_{TW} \cdot \cos\theta_{TW}}\right) \tag{2}$$

The external loads on the sail include the force and moment, as Figure 2 shows. Per aerodynamics, the component of the total force on the sail that is parallel to the apparent wind speed is the drag force, while that perpendicular to the apparent wind speed is the lift force. On the other hand, practically, the component that is parallel to the ship speed is the thrust force, which can be calculated using Equation (3), while that perpendicular to the ship speed is the side force. The magnitude of the thrust force represents the propulsive performance of the WASP system, so one of the most important objects of a WASP concept is to generate the greatest possible thrust force. The side force does not account for the propulsion and causes heeling and rolling, as well as drift and additional induced resistance.

$$F_T = F_L \cdot \sin\theta_{AW} - F_D \cdot \cos\theta_{AW} \tag{3}$$

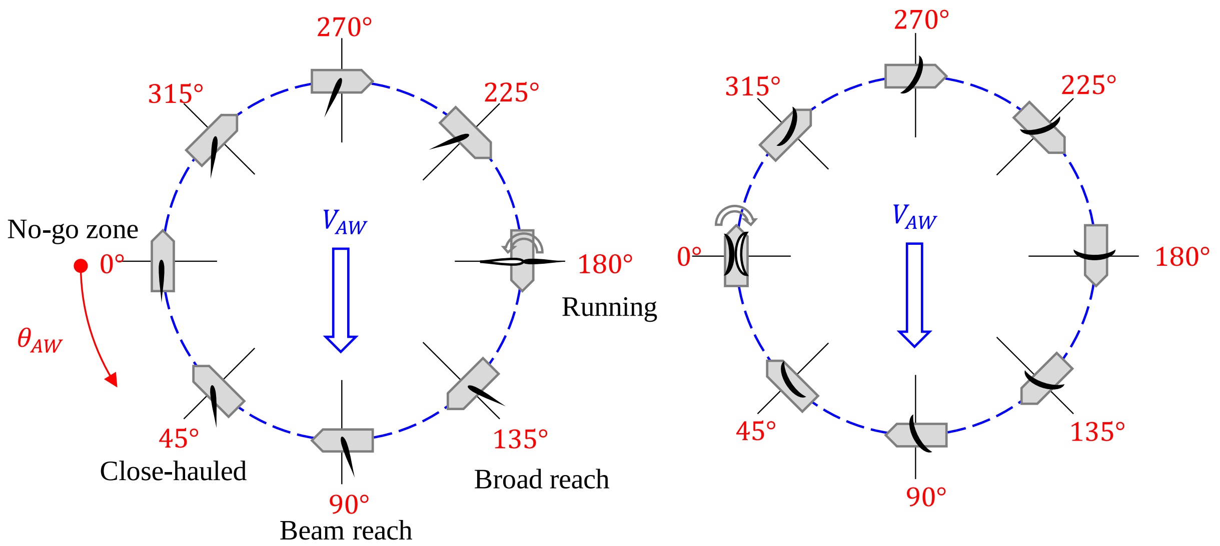
The non-dimensional force coefficients are represented by C_L in Equation (4). Similarly, C_D and C_T can be defined. The moment coefficient is defined using Equation (5).

$$C_L = \frac{F_L}{0.5\rho V_{AW}^2 A_S} \tag{4}$$

$$C_M = \frac{M}{0.5\rho V_{AW}^2 A_S L_c} \tag{5}$$

The power source of sailing is the wind, but the direction of travel relative to the wind is what determines its ability to generate forward motion. This direction is referred to as the point of sail and can be divided into segments of 45°, starting at 0° directly into the wind. The zones spanning 45° on either side of the wind are considered “no-go” zones (Cunliffe, 2016) since here, a sail is nearly unable to generate power from the wind (Kimball, 2009). When sailing on a course as close to the wind as possible, which is approximately 45°, the craft is “close-hauled”. At 90° off the wind, the craft is on a “beam reach”. At 135° off the wind, the craft is on a “broad reach”. When sailing in the same direction as the wind, which is 180° off the wind, the craft is “running downwind”. Between close-hauled and broad reach, the sail acts as a wing, with lift predominantly propelling the craft. Contrastingly, from broad reach to downwind, the sail acts as a parachute, with drag predominantly propelling the craft. For a craft with little forward resistance, such as ice boats and land yachts, this transition occurs further off the wind than for sailboats and sailing ships.

Compared with conventional airfoil profiles, such as the NACA 0015, profiles that are symmetric at both edges, i.e., the leading edge and the trailing edge share the same shape, will be operated differently when changing tack. Take the crescent-shaped profile as an example for comparison. The conventional NACA profile will always have the same leading edge, but the high-pressure side will become the low-pressure side when changing from one tack to the other, as shown in Figure 3(a). This type of profile operates like a modern Bermuda-type sail. However, a crescent-shaped profile will swap the leading and trailing edges when changing tack, but the same side will always be the high-pressure side and the opposite side will always be the low-pressure side, as shown in Figure 3(b). This makes wingsails with crescent-shaped profiles easier to operate under downwind conditions.



(a) Symmetric profile (NACA 0015). (b) Crescent-shaped profile.

Figure 3. Changing tack with an aerodynamically symmetric profile and a crescent-shaped profile.

1.1.3 Concepts of wind-assisted ship propulsion

For wind energy to be relevant in maritime transportation, it is necessary for sail arrangements to significantly contribute to vessel propulsion under most of the wind conditions to which vessels are exposed.

The propulsion power of a sail is generated by the apparent wind that the arrangement experiences. The apparent wind is the vector sum of the headwind and the velocity of the true wind. Due to the headwind component, the apparent wind will, over time, always be more ahead than astern. Therefore, a sail arrangement needs to perform well when the wind is coming forward from abeam (between beam reach and close reach), and it needs to give driving force at small relative angles of the wind.

Different categories and innovative WASP technologies have been proposed, such as rotor sails, vertical airfoils (which are also termed ventifoils or suction wings), kites, wind turbines, and various wingsails (Khan et al., 2021). Several of these are already being used on passenger and merchant vessels, while some are still being subjected to further optimization or full-scale testing in research projects (Cairns et al., 2021). Lu and Ringsberg (2020) compared three sail technologies, the Flettner rotor, the DynaRig, and a wingsail, in terms of their actual fuel savings for a specific ship sailing on specific voyage routes. The study showed that WASP technologies reduce fuel consumption by several percentage points, but it was not as much as expected because the amount of fuel savings depended on many factors for each of the three technologies. One of the most crucial factors was the sail's performance in a wide range of angles of attack related to the ship's heading direction. A sail's performance also depends on the aerodynamic interactions among the multiple sails on the ship.

A wingsail is an innovative type of sail that is designed to provide lift on both sides, similar to an airplane wing. Throughout the years, some projects were undertaken to develop and evaluate different concepts for WASP systems using rigid wingsails to reduce fuel consumption in excess of 30% (Hamada, 1985).

Compared with other concepts, rigid wingsails have some advantages:

- Compared with traditional soft sails, the main advantages of rigid wingsails are that they maintain their shape in light winds and are more robust to control since there is no rope that can become entangled (Sauzé & Neal, 2008). Meanwhile, rigid wingsails have simpler structures and are easier to design and operate (Silva et al., 2019).
- Unlike kite sails, rigid wingsails can propel ships via drag force and lift force, allowing ships to navigate against the wind (Kimball, 2009). The area of a kite sail is limited by what can be handled during the setting and hauling of the kite.
- The Oceanbird project (Workinn, 2021) even aims to achieve a 90% reduction of fuel consumptions, which is much higher than Flettner rotors' saving of 8% on average (International Transport Forum, 2020), 30% for tankers (Tillig & Ringsberg, 2020), and around 50% for maximum potential (Traut et al., 2014). Furthermore, the Flettner rotating cylinder concept is also limited in the maximum diameter of the cylinder, and the height is limited since it must be able to withstand the harshest wind conditions that the ship is designed for. Due to the bluff body, Flettner rotors also suffer from added drag, resulting in extra resistance when the rotors do not operate (Khan et al., 2021). Moreover, rigid wingsails show better propulsive performance than Flettner rotors under downwind conditions, where the drag force mainly contributes to propulsion (Lu & Ringsberg, 2020).

A fixed wingsail can have a larger sail area than Flettner rotors, but the size of the wings is limited by the available surface on deck, where they are stowed. The solution to maximizing the sail area under normal wind conditions while limiting the area during harsher winds is to make the sail area flexible. By using telescopic rigging, the sail area can be adjusted according to the wind conditions at the time. By making the rig foldable, the structural stresses under extreme weather conditions are further reduced, as well as the drag during unfavorable wind conditions. In the Effship project (Allenström et al., 2012), a telescopic wingsail arrangement with a crescent-shaped profile was developed. In the project, numerical simulations were executed, and different sail arrangements were analyzed. The results showed that the telescopic wingsail arrangement with a crescent moon airfoil has a better overall performance than the Flettner rotor and kit sail arrangements. Although the C_L of the crescent-shaped wingsail is lower compared with the Flettner rotor, the wingsail usually has a much larger sail area, so it can generate larger thrust. This solution was patented in Sweden (Fagerlund & Ramne, 2010).

Köhle et al. (2016) summarized the market potential and barriers of possible techniques of WASP, indicating that different solutions fit different applications. The proposed wingsail solution is one of few that can significantly contribute to the propulsion of larger tank and bulk transport ships on transcontinental routes (Allenström et al., 2012). While other solutions might be better for ships with a smaller displacement, such as RoRo and RoPax ships, for tank and bulk transport ships, the telescopic arrangement can be retrofitted, making energy saving for existing ships possible. It should be noticed that relative saving is very much dependent on the ship’s speed. A reduction in fuel consumption, i.e., relative savings, exhibits an upward trend with decreasing ship speeds. However, in most cases, the absolute amount of fuel saved, measured in tons of fuel, increases as the ship’s speed increases. Therefore, a full-scale installation is expected to give a 20% reduction in fuel use for existing route time plans. Nevertheless, if routes and time plans are adapted to wind and weather conditions, the potential reduction can be several times larger.

The present thesis is motivated to reduce the carbon footprint of shipping by developing an innovative WASP system that will enable ships to use wind power as a complementary energy source to reduce their reliance on fossil fuels. It focuses on developing a new and innovative WASP system that will utilize advanced materials and technologies. By promoting the use of wind power in the shipping industry, this work will support the growth of renewable energy and contribute to the transition toward a low-carbon economy.

1.2 Overview of methods

1.2.1 Wind load prediction

To evaluate the propulsive performance of a WASP system, it is important to predict the wind loads on the sail, which is an aerodynamic problem. To solve this, some methodologies, such as theoretical, numerical, experimental, and empirical methods, can be used. Theoretical methods use aerodynamic theories such as thin-airfoil theory to deduce wind loads. These methods are normally efficient, but they are always based on some assumptions, resulting in their applicability to real-world problems being limited. Model-scale experimental methods, such as wind tunnel tests, provide direct predictions for flow characteristics. However, executing experiments is often expensive, experimental results are usually difficult to visualize, and there are considerable scale effects that make it difficult to predict full-scale performance. Empirical methods provide quick but approximate solutions to fluid flow problems, sometimes being limited in their accuracy and reliability. Among these, numerical methods have some advantages: They can be used to simulate complex fluid flow problems with high accuracy, offer a way to model full-scale problems to investigate the behavior of fluids under various conditions, and provide visualizations and detailed information about fluid flow characteristics.

Numerous studies have been conducted by using numerical methods to study the performance of WASP systems based on rigid sails. Ouchi et al. (2011) performed full-scale CFD simulations to evaluate the propulsive performance of a nine-wingsail system and conducted a case study for evaluation. Viola et al. (2015) developed a numerical optimization procedure for a rigid wingsail using the Reynolds-averaged Navier–Stokes (RANS) equation solver, which offered an efficient parametric sail aerodynamic analysis method. Lee et al. (2016) studied a series of rigid wingsails based on the NACA 0012 profile, conducted numerical aerodynamic analysis using a viscous Navier–Stokes flow solver, and established a design optimization framework to maximize the thrust coefficient C_T. Ma et al. (2018) studied three typical airfoil-based sails using CFD simulations with the k–ω shear stress transport (SST) turbulence model. Persson et al. (2019) presented simplified approaches to model WASP systems, using a limited number of CFD simulation results to extrapolate propulsive performance under various conditions. Tillig and Ringsberg (2020) presented a novel approach to analytically capture aero- and hydrodynamic interaction effects on wind-propelled ships. Low aspect ratio wing theory was applied and modified to predict the lift and drag forces of hulls sailing at drift angles. The sails' aerodynamic interaction effects were captured by numerically solving the Navier–Stokes equations for incompressible, creeping flow. Malmek et al. (2020) developed two cost-effective aerodynamic methods to predict the performance of large-scale wingsails. One was based on the lifting line theory of potential flow in combination with pre-calculated two-dimensional RANS CFD data, and the other was a vortex lattice method (VLM). Zhu (2020), and Blount and Portell (2021) performed detached eddy simulation (DES) to study the performance of wingsails with a NACA 0015 profile under downwind conditions.

The studies mentioned above were mainly based on wingsails with conventional airfoil profiles, such as the NACA series. However, including camber in the profile geometry can significantly increase the lift coefficient, a mechanism that is also valid for sails. Atkinson (2019) performed three-dimensional CFD simulations to study a segment rigid sail. Nikmanesh (2021) proposed a type of crescent-shaped, cambered profile and predicted propulsive performance by performing unsteady RANS (uRANS) simulations based on the Spalart–Allmaras turbulence model, indicating that this type of profile provides a higher C_L, leading to larger thrust. Chen et al. (2022) introduced a set of arc-shaped wingsails and studied their aerodynamic characteristics by performing two-dimensional simulations. In October 2022, Japanese shipping company Mitsui O.S.K. Lines (MOL) delivered the world's first coal carrier equipped with crescent-shaped rigid wingsails (Prevljak, 2022).

1.2.2 Energy saving evaluation

The WASP system design is a type of systems engineering. The design parameters are coupled, which means that the relationship between them is one of mutual influence, condition, and transformation, presenting great complexity and considerable changeability. For example, if the area of the sail increases, the thrust force and side force will increase, as well as the yaw and heeling moments. Therefore, resistance also increases. The designer needs to judge and weigh since both the thrust and resistance increase (Viola et al., 2015).

Several studies have been carried out to analyze and evaluate the propulsive performance of WASP systems. Kijima et al. (1990) developed the Velocity Prediction Program (VPP), which is a computer program and a common approach used to solve the coupled equations of motion on high-performance sailing ships. The VPP is based on computational fluid dynamics, experimental fluid dynamics, or analytical formulations. Models of how the aero- or hydrodynamic forces and moments vary with key design parameters are used to solve the equations of motion for the ship (Larsson, 1990).

Tillig et al. (2017) developed a generic ship energy system model that Tillig and Ringsberg (2019) further developed. This model was later named ShipCLEAN (Tillig et al., 2019) and is aimed at predicting the fuel consumption of ships at sea while considering the external loads caused by wind, waves, currents, etc., and it is available for WASP components. By applying the model, Lu and Ringsberg (2020) compared three sail technologies (the Flettner rotor, the DynaRig, and a wingsail) in terms of the actual fuel savings for a specific ship sailing on specific voyage routes, showing that WASP technologies reduce fuel consumption by several percentage points but not as much as expected. One of the crucial factors found was the sail's performance with the wide range of α related to the ship's heading direction. A sail's performance also depends on the aerodynamic interactions among the multiple sails on the ship.

1.2.3 Structural response analysis

Sails must be strong and durable enough to withstand the forces that they will experience in use, including wind and wave loads, as well as other environmental factors. For application in large commercial ships, the wingsail is usually supported by an unstayed mast installed on the deck of the ship, so its structural response is similar to a cantilever that is subjected to a flow of air.

Today, numerical calculation methods based on the finite element method (FEM) are commonly utilized and have proven useful for structural analysis. Applicable mechanical solutions for a telescopic rig can also be found in existing mobile crane solutions. The shape, construction, and dimension of the sail panels can be derived using analytical, empirical, or modeling methods. However, to further optimize the construction for increased propulsion and sustainability, better calculation methods must be developed in parallel with the construction work. Therefore, a modern version of the FEM is used to analyze the structure and its performance.

In recent years, some researchers have performed structure analysis on WASP systems, though most of the studies that evaluated these systems focused on the fluid aspect. Ouchi et al. (2011, 2013) proposed a conceptual design for a telescopic rigid wingsail and used finite element analysis (FEA) to analyze deflection and stress distribution throughout the wingsail. Hu et al. (2015) investigated the structure design, dynamic performance, and control strategy of wingsails for large, ocean-going, sail-assisted ships.

As mentioned in Section 1.2.1, to achieve a higher C_L, the sectional profile of the wingsail can include significant camber. Nevertheless, because of camber, the wingsail is expected to induce strong flow separation, which results in vortex-induced vibration and fatigue that may lead to increased strength requirements (Storhaug et al., 2022). Due to strong flow separation, the structure of the wingsail will experience deformation, which can, in turn, affect the flow field. Therefore, it is necessary to analyze the fluid–structure interaction (FSI) of the wingsail (Bak et al., 2013). FSI models are an indispensable tool for calculations on large wind turbines and significantly increase calculation accuracy for large sail structures.

1.3 Objectives and goals

Recent studies on WASP have indicated that there are still several difficulties in developing WASP systems. In terms of technology, WASP systems require complex design and engineering integration, and there are many technical challenges associated with optimizing the performance of the sails and ensuring their stability and reliability.

1.3.1 Aerodynamic efficiency

One of the most important factors for aerodynamic efficiency is the design of the sail. The sail design must be optimized to ensure maximum performance and efficiency. This includes choosing the right materials, considering aerodynamic and hydrodynamic forces, and accounting for the effects of winds and waves. Take wingsails as an example: To contribute as much as possible to propulsion, the wingsail is expected to generate as great lift force and drag force as possible under sidewind and downwind conditions, respectively. In addition, for a given thrust force, a better performing aerodynamic profile will require less sail area, e.g., lower mast meaning, lower weight of the rig, and a lower heeling moment.

The first goal of this study is to introduce a novel telescopic wingsail design with a new crescent-shaped profile and establish high-fidelity numerical methods for predicting the wind loads. This profile is expected to be more aerodynamically efficient, i.e., generate higher C_L leading to higher C_T at relevant wind angles. To evaluate its performance, two- and three-dimensional CFD simulations are used, in addition to the uRANS and improved delayed detached-eddy simulation (IDDES) methods and the $k-\omega$ SST turbulence model. One of the sub-objectives of this study is to address suitable sail configurations with an advantageous C_L to maximize F_T for large sailing merchant ships and their ship operation profiles. This thesis compares the propulsive performance of two rigid wingsails with different sectional profiles (NACA 0015 and crescent-shaped). The analysis also focuses on exploring flow field properties, especially unsteady characteristics such as flow separation, wake flow, and tip vortices, as well as the impacts of external loading conditions on the wingsails.

1.3.2 Considerable fuel saving

WASP can be a good alternative for retrofitting existing vessels to reduce their dependence on fossil fuels, but sails are usually not the only solution, so WASP should be combined with other energy sources. Hence, studying how different sail technologies will be used and for which ship types and routes is useful.

The second goal of this study is to evaluate the level of relative fuel saving by applying the novel wingsail. In this thesis, the lift and drag coefficients from the CFD simulations are later used as input for the performance prediction model ShipCLEAN to perform studies with a real ship (a medium-sized tanker) using its operational data and hindcast weather. Further, the performance of the crescent-type sail is benchmarked against the performance of Flettner rotors.

1.3.3 Structural integrity

In practice, the structure of the wingsail is usually complex and includes panels, stiffeners, and horizontal section plates. To conduct FSI analysis, the structural model should, therefore, be simplified. Otherwise, the fluid mesh of the prism layers may need to be re-generated at every timestep to resolve the boundary layer flow and prevent the coupled simulation from diverging, which is computationally expensive. Therefore, the structural response of the full structure should be analyzed first to guide how the geometry of the structure can be simplified when performing FSI analysis. Moreover, since the wingsail is installed on the deck and is a considerable size, its weight must be kept as low as possible to ensure that it does not affect the cargo capacity and the stability of the hull.

The third goal of this study is to propose a lightweight design for telescopic wingsails and establish a numerical model to analyze its structural response. The present study uses quasistatic FEA to study the structural responses of a crescent-shaped wing sail rig. The objective of the structural analysis is to compare a few conceptual designs of telescopic rigs, ranging from a rig with a center mast to a mast-less rig. The rigs are compared against three criteria: the structural response (displacement), strength (ratio stress response/yield), and weight of the sail's rig. The external wind loads applied to the sails in the FEAs have been simulated and calculated using aerodynamic simulations in previous studies that the authors have conducted. The advantages and disadvantages of each concept are discussed, aiming to provide a good strategy for structural design and the arrangement of similar wind-assisted propulsion facilities. The results of the thesis will be used in future work as a guide for structural optimization and FSI analysis.

1.4 Assumptions and limitations

When comparing the newly introduced crescent-shaped profile with the NACA 0015, profiles with a flap are not considered. Even though the performance of the NACA 0015 profile can be improved with a flap, this is difficult to apply to a telescopic concept.

In the CFD simulations, the apparent wind, i.e., the inlet velocity, is assumed to be a uniformly distributed horizontal flow. Although real wind conditions are complex and variable, this assumption is considered reasonable because the Reynolds number of the wingsail profiles is normally in the range of 3×10^6 to 3×10^7, in which the force coefficients are not sensitive to the Reynolds number, as presented in Paper C. However, when analyzing fuel saving performance using ShipCLEAN, the wind profile is considered.

The geometry of the wingsail is simplified when performing CFD simulations. In the three-dimensional CFD simulations, the wingsail is simplified to uniformly extruded geometry, so the size differences among the different sections of the wingsail are not considered. The mast is not included since there is gap between the wingsail and the deck is only 5% of the entire height. Only one wingsail is considered at this stage, so the multi-wingsail interaction is neglected. The flow field induced by the hull of the ship is neglected in the CFD simulations.

The nonuniformity and instantaneity of the wind loads are not considered in FEA simulations. The wind loads are assumed to be uniformly distributed pressure on the pressure side and suction side, respectively. In addition, the structural analysis is based on quasi FEA simulations, so the dynamic response and FSI are not studied at this stage.

The material properties of the structure are assumed to be linear and elastic, which means that the nonlinear material properties are ignored. Since a factor of safety of 2 against the yield stress is introduced, the stress does not exceed the yield stress. The buckling analysis is limited only in terms of normal stress, and buckling due to shear stress is not studied. From the FEA results, the magnitude of shear stress is much lower than normal stress.

1.5 Outline of the thesis

The present thesis is divided into four parts. In Chapter 1, the background information and related studies are introduced, including an explanation of the research aims and motivations. In Chapter 2, the methodology used in this thesis is presented. The generated concept design and the established numerical model are also described and explained in this chapter. In Chapter 3, selected results from the three appended papers are summarized. In Chapter 4, a conclusion is provided, and possible future work is discussed.

2 Methodology

This section presents a brief summary of the methods and models used throughout Papers I, II, and III before examples of the key results are presented in Section 3. The workflow is shown in Figure 4. The red arrows in Figure 4 represent the methods and results that were transferred between papers. For example, the three-dimensional CFD simulations in Paper II were improved versions of those established in Paper I.

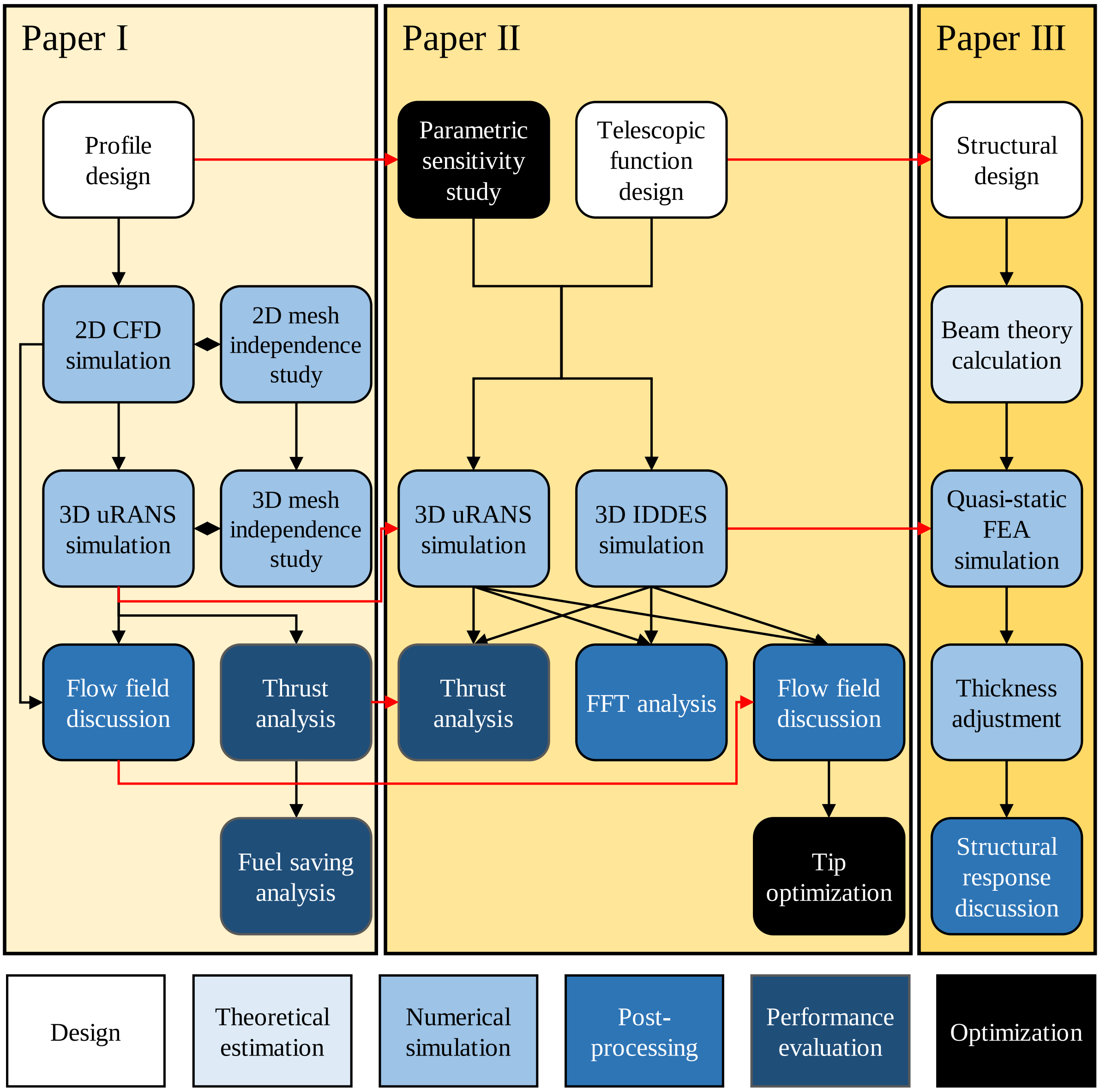


Figure 4. Workflow of the appended papers.

The main technology and methods that are developed in this thesis are outlined as follows:

- First, the design of a telescopic wingsail rig that can be adjusted for various wind conditions. This conceptual design is expected to provide notable thrust force. The concept design is discussed in detail in Sections 2.1.1 and 2.1.3.

- Second, the development of numerical models for predicting and evaluating the performance of the WASP system. This step includes developing a CFD model for predicting wind loads on the wingsail and an FEA model for analyzing the structural response of the wingsail structures. The CFD model is described in Section 2.2, and the FEA model is described in Section 2.3. The time-averaged CFD results are summarized in Section 3.1.1, and the unsteady characteristics are summarized in Section 3.2. The FEA results are summarized in Section 3.3.
- Third, performance analysis and evaluation of the conceptual sail at the system level. A model for the telescopic wingsail rig is entered into the ShipCLEAN model for estimating its fuel saving performance, and its performance is evaluated and compared with that of other sailing concepts. The method of the fuel saving analysis is shown in Section 2.4, and the results are summarized in Section 3.1.2.

2.1 Design and physical conditions

2.1.1 Crescent-shaped profile

In this thesis, a wingsail with a horizontal section profile is proposed, as illustrated in Figure 5: a simple crescent shape comprising arcs and circles. There are four main design parameters: the chord length, edge radius, suction-side arc radius, and mast diameter. The shape of the profile, including the pressure-side arc radius, is determined using these four parameters. The arcs of the pressure and suction sides are symmetric around the symmetric axis (the dashed blue line in Figure 5). The radius of the edges is chosen to make the profile structurally sound.

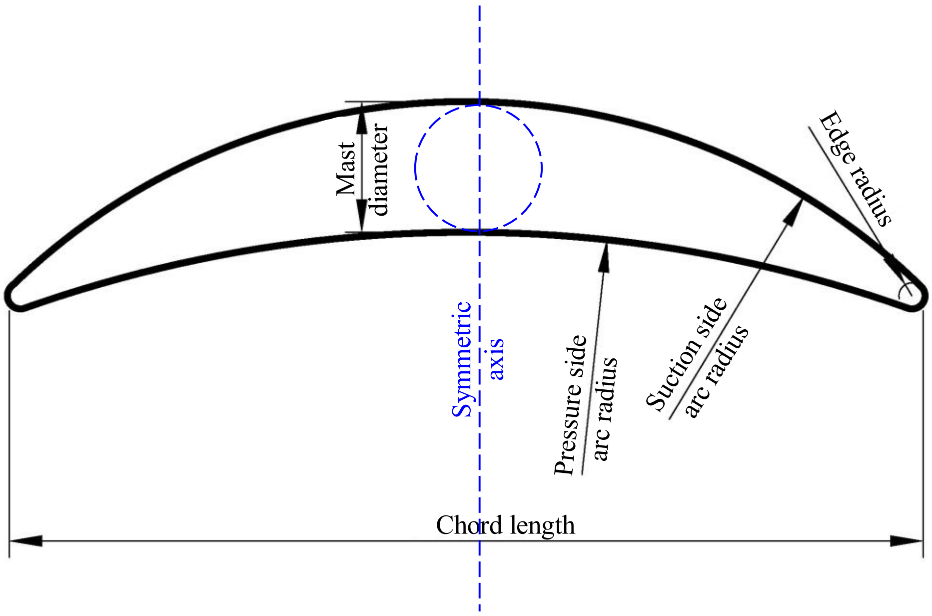


Figure 5. Design parameters of the crescent-shaped profile.

The mast diameter and suction-side arc radius are adjustable. The chord length is always set at 14 m, and the edge radius is always 0.2 m. The dimension parameters are suggested by ScandiNAOS AB according to their practice. A series of profiles are generated by varying the remaining two parameters and are labeled in the form "DxRy," where "x" represents the mast diameter and "y" represents the suction-side arc radius. For example, for the profile named "D2R8," the mast diameter is 2 m and the suction-side arc radius is 8 m, which results in an arc radius of 10.67 m on the pressure side.

2.1.2 Wind conditions

The sectional profiles, wind conditions (apparent wind speeds and angles of attack), and height of the wingsail that are studied in each paper are listed in Table 1. Detailed information about fluid properties can be found in Papers I and II.

Table 1. The wingsail geometry and wind conditions studied in each paper.

	Sectional profile	V_{AW}	H	α
Paper I	NACA 0015 D2R10	25 m/s	72 m	16° −2° ~95°
Paper II	D2R8	8 m/s 32 m/s	74 m 32 m	19°, 21°, 23°
Paper III	D2R8	16 m/s	74m	23°

In Paper I, to simulate a critical condition, i.e., a condition with high wind speeds, a uniformly distributed inlet flow velocity of 25 m/s is used to simulate wind speed, so the Re is 2.3×10^7, calculated based on the sail's sectional profile chord length. The height of the sail, H, is preliminarily defined as 72 m. According to wind tunnel tests (Sheldahl & Klimas, 1981), when the Reynolds number is 1×10^7, the critical angle of attack α_c of the NACA 0015 foil is approximately 16°. A previous study (Nikmanesh, 2021) indicated that for the newly introduced crescent-shaped profile, the α_c is around 20°. Therefore, the comparison between the two- and three-dimensional simulations, as well as the comparison between different boundary conditions, is based on α_c, with the angle of attack being 16° for the NACA 0015 foil and 20° for the crescent-shaped foil. Additionally, a wide range of α is also studied to predict propulsive performance. A series of two- and three-dimensional simulations with α from −2° to 95° are performed.

The D2R8 profile is studied in Paper II, and three sets of three-dimensional simulation cases with $\alpha = 19°, 21°, 23°$ are performed. In Paper II, the height of the wingsail can be adjusted according to the apparent wind speed. Two conditions are simulated, the fully expanded condition and the fully retracted condition, with Re of 6.78×10^6 for the fully expanded condition and 2.71×10^7 for the fully retracted condition. According to the structure arrangement, the height of the wingsail is adjusted to 74 m.

Following Paper II, in Paper III, which focuses on structural responses, the three-dimensional D2R8 profile is studied. The α with the highest C_L, i.e., 23°, is studied. A more critical fully expanded condition with $V_{AW} = 16$ m/s is applied.

2.1.3 Structural arrangement

The wingsail and its rig must have a lightweight design to reduce its influence on the ship's cargo capacity and fulfill any stability requirements. One challenge with this is that the wind loads acting on such a sail cause bending and torsion in its structure, which increase the required strength-to-weight ratio of the sail rig.

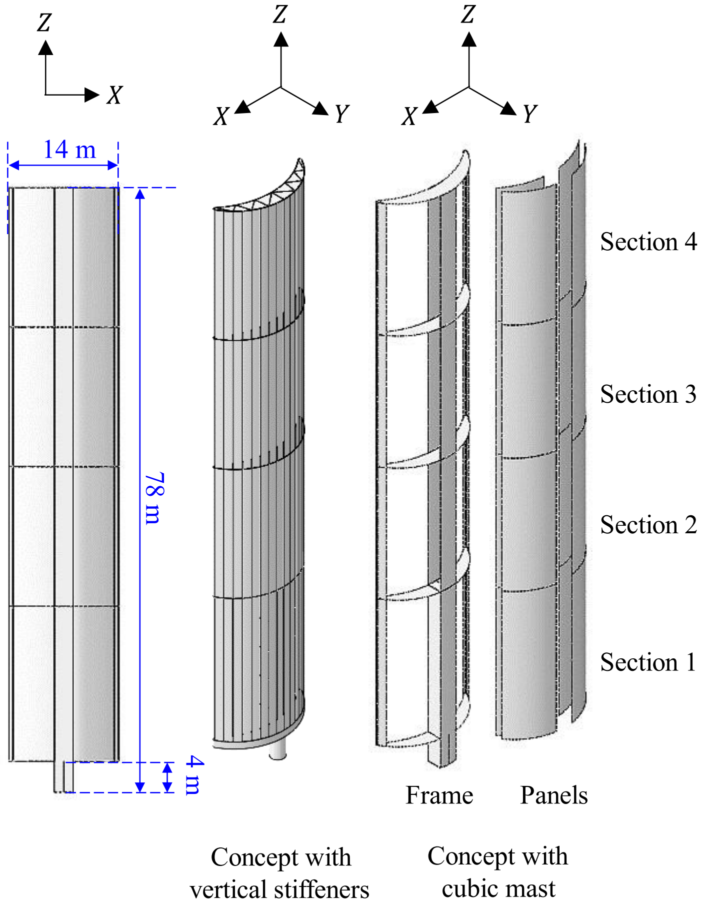


Figure 6. Size and structural designs of the wingsail.

In Paper III, the rigid wingsail is designed to be divided into four sections for the telescopic function, as shown in Figure 6. In this thesis, the lowest section is named "section 1," and the highest section is named "section 4." Two concept designs are presented. One of the concepts aims to use the global shell structure to bear global bending; several vertical stiffeners are used to increase the strength and rigidity of the wingsail structure. To release the stress concentration at the mast and lower part of section 1, some web structures are introduced. To prevent stress concentration in the mast and reduce the weight of the wingsail rig, another concept with a cubic mast is considered. The entire structure can be divided into two parts: the frame, which is expected to bear global bending and torsion, and the panels, which are assumed only to suffer under local wind pressure. The mast only extends to the lowest section.

For the concept utilizing vertical stiffeners, since the whole surface needs to be strong enough to withstand global bending, all parts of the wingsail are made of steel (S275) (BS EN, 2004). However, aluminum (6061-T4) (ASTM, 2004) is introduced for the concept utilizing a cubic mast to reduce the total weight of the structure. For the concept utilizing a cubic mast, two material arrangements are studied: “steel frame, aluminum panels” and “all in aluminum.”

2.2 Computational fluid dynamics simulation

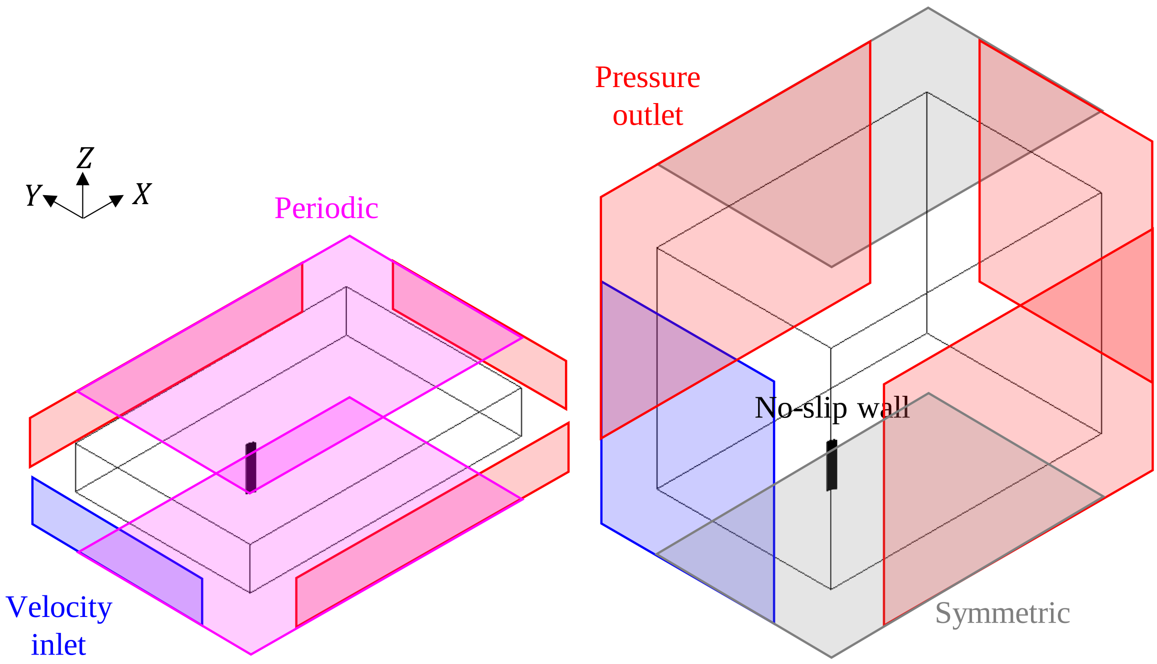
CFD simulations are applied for predicting the external load on the sail. The present study makes use of the mesh generators and solvers in the software STAR-CCM+ (Siemens PLM Software, 2021). In the CFD simulations, the wingsail is modeled as a uniformly extruded rigid body.

2.2.1 Domain and boundary conditions

Two-dimensional simulations are first performed to identify the α_c and provide a preliminary view of the flow field. Then, three-dimensional simulations with two types of boundary conditions are performed to study three-dimensional flow characteristics and the influence of tip vortices. One is a periodic top and bottom, and the other is a symmetric bottom and free tip, as Figure 7 shows.

A rectangular domain is used for the two-dimensional simulations, while a cuboid domain is used for the three-dimensional simulations. Full-scale simulations are performed in this thesis. For simulations with a periodic top and bottom, the spanwise size of the domain is the same as the spanwise length of the sail. For the two-dimensional simulations, the size of the domain follows the size of the bottom boundary of the three-dimensional simulations.

For both boundary conditions, the crossflow sides are set as pressure outlets to make the simulations as representative of real conditions as possible. For the two-dimensional simulations, the arrangement of the inlet and outlet boundaries follows the bottom boundary in Figure 7(b). The non-slip boundary condition is specified on the foil. The upstream boundary of the domain is assigned as a velocity inlet with a uniformly distributed inlet flow, representing apparent wind. A pressure outlet boundary condition with a zero-pressure loss coefficient is imposed on the downstream boundary of the domain with the crossflow sides. To prevent reversed flow from influencing the pressure outlet boundaries, the direction of the backflow is set to be extrapolated. The pressure loss at the pressure outlets is assumed to be 0, and the pressure jump under-relaxation factor is set as 0.5.



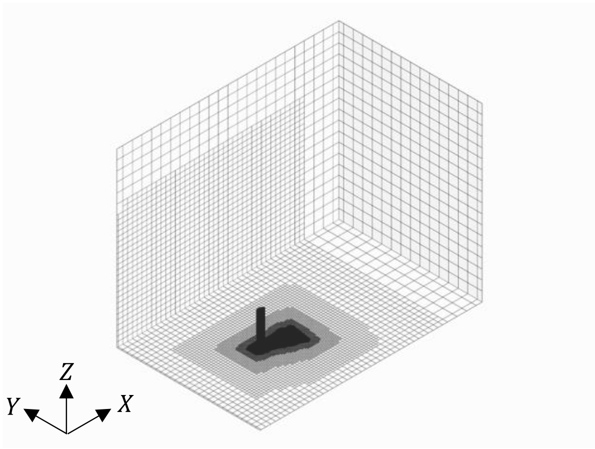
(a) Periodic top and bottom.

(b) Free-stream tip and symmetric bottom.

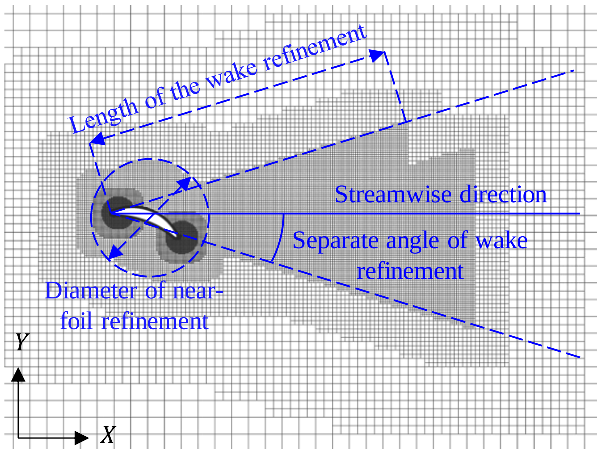
Figure 7. The two types of boundary conditions used in the three-dimensional simulations. Red panels: pressure outlets; blue panels: velocity inlets; purple panels: periodic boundaries; gray panels: symmetric boundaries; black panels: no-slip walls.

2.2.2 Numerical mesh

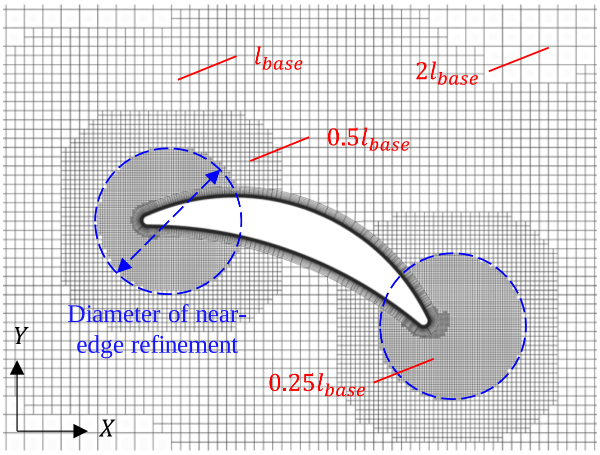
An unstructured mesh with trimmed cell topology is mainly used for the simulations. Figure 8 shows the mesh of the three-dimensional simulation with a freestream tip and symmetric bottom, with typical cell sizes. The cells have a uniform size in each region at each refinement level. The region near the foil and the wake region are both refined, which can be seen in the section plane of $Z = 0.5H$ in Figure 8(b). The mesh in the wake region is refined using two parameters, the length and separate angle of the wake refinement. A cylindrical volumetric mesh refinement with a length of $1.1H$ is introduced to refine the mesh near the foil. The diameter of the cylinder is $1.4L_c$. Flow separation points are expected to distribute around the two edges, so, similarly, a more refined set of mesh is applied to the region near the edges of the foil to capture the flow separation phenomena, as Figure 8(c) shows. The refinement, aside from that of the prism layer, is based on the base size, labeled l_{base} in Figure 8.



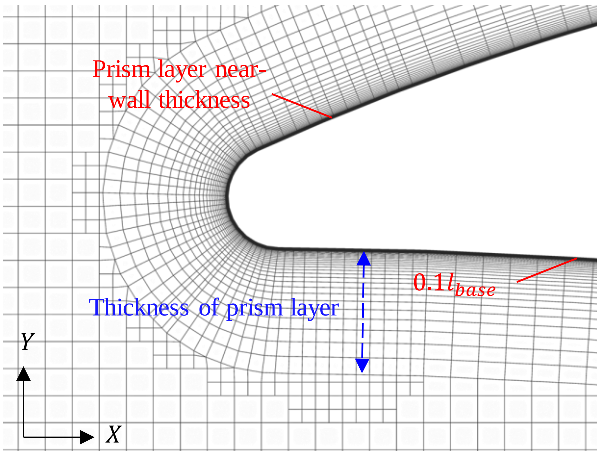
(a) Entire domain.



(b) Section plane at $Z = 0.5H$.



(c) Attached region near the foil, at the section plane of (b).



(d) Attached region near the leading edge, at the section plane of (b).

Figure 8. Three-dimensional trimmed mesh when $\alpha = 20°$ for the D2R10 profile.

Prism cells are generated near the wall of the foil to resolve flow in the boundary layers, as shown in Figure 8(d). The absolute total thickness of the prism layer is 0.5 m, and the number of prism layers is 55 for all simulation cases. Since the crescent-shaped profile has large camber, a strong flow separation phenomenon is expected. Therefore, it is desirable for the y^+ of the first-layer cells near the wall to be less than 1 to have a more detailed and accurate study of the boundary layer flow. In the simulation cases, the order of the magnitude of y^+ is around 10^{-1} on most areas of the wall. To obtain this low y^+ value, the near-wall thickness of the prism layer is set as the absolute value of 1×10^{-5} m, which does not change during global mesh refinement.

Under the deep-stall conditions, the von Kármán vortex street is expected to spread for a long distance in the downstream region, so extra downstream refinement of the downstream region is introduced when $\alpha \geq 40°$, as can be seen in Figure 9.

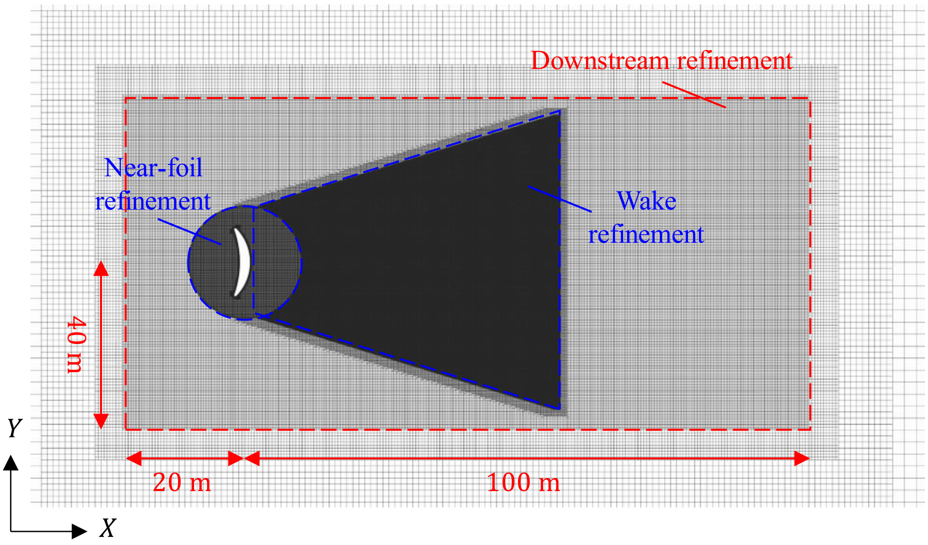


Figure 9. Two-dimensional trimmed mesh for the deep-stall conditions ($\alpha = 90°$).

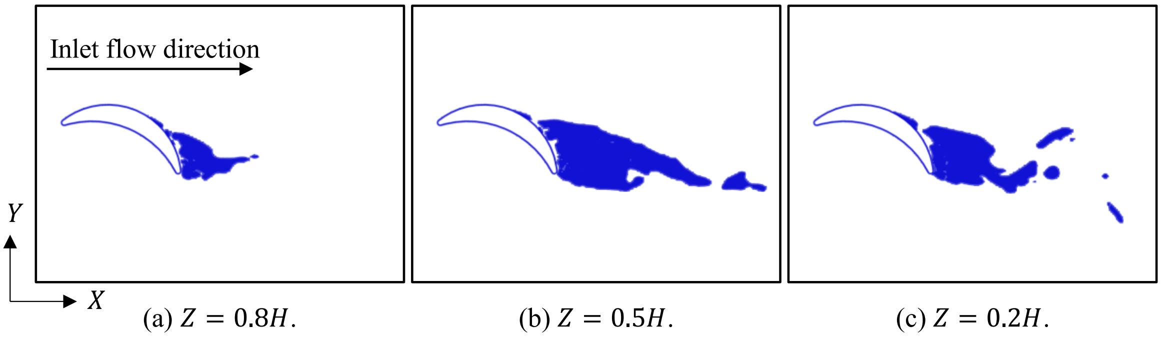
Two-dimensional mesh independence studies are conducted from two perspectives: the refinement strategy and the size of cells. For the refinement strategy, three factors, including the existence of near-foil refinement and the length and separate angle of the wake refinement, are studied to exclude any influences from the mesh. As a result, the mesh follows the strategy of having wake refinement with 0.3 rad at a separate angle and a length of 60 m, as well as near-foil refinement.

By following the certain refinement strategy, several two-dimensional simulations with different base sizes are performed. Variations in base size influence the entire mesh, except for the prism layer mesh, in the normal direction. Then, a series of three-dimensional mesh is generated based on the same refinement strategy.

2.2.3 Viscous regimes

To solve the high-*Re* problem, turbulence models need to be incorporated. In Paper I, a CFD model based on the uRANS method is developed, and the time-averaged loading conditions are well-solved since the boundary layer flow is resolved with a finely layered mesh. However, significant flow separation is found, leading to significant unsteady characteristics in the flow field. When studying the propulsive performance of a single sail, it is enough to only consider the time-averaged loads. However, unsteady characteristics should be considered when analyzing structural response. For example, a low-frequency oscillation of the external loads may cause a vortex-induced vibration of the whole sail, while a high-frequency oscillation may cause local vibrations on the shell panels, resulting in buckling. To simulate separating flow more accurately, the large eddy simulation (LES) method (Smagorinsky, 1963) needs to be introduced since all turbulent scales are modeled in uRANS, while only small, isotropic turbulent scales are modeled in LES (Davidson, 2019; Yao et al., 2008). By applying the LES method, both time-averaged properties and unsteady characteristics can be determined. On the other hand, the LES method imposes costly near-wall meshing requirements. To avoid these and keep the boundary layer flow well-resolved, the detached eddy simulation (DES) method, which combines uRANS and LES, is selected in this thesis. The k–ω SST model (Menter, 1993) is applied for both the uRANS and IDDES (Shur et al., 2008) simulations.

Take the fully expanded condition with $\alpha = 23°$ as an example. Figure 10 shows the distribution of regions calculated using the uRANS and LES methods. Most areas, especially the boundary flow regions, are calculated using the uRANS method, while the LES regions are mainly distributed in the downstream field. Due to the impact of the tip vortices, fewer areas are calculated by LES when approaching the tip (see Figure 10(a)).



(a) $Z = 0.8H$. (b) $Z = 0.5H$. (c) $Z = 0.2H$.

Figure 10. Distribution of the DES upwind blending factor at different spanwise positions, with a fully expanded condition of $\alpha = 23°$. Blue marks out the regions calculated with LES, while the remainder of the computation domain is calculated using uRANS.

The approach of blended wall treatment is applied to the RANS equations (Wilcox, 1989). This approach has the advantage of treating complex geometries with local flow characteristics. Since the velocity over complex walls varies widely, and the geometry of the wingsail profile has a curvature, it is difficult to ensure that y^+ in all cells adjacent to the walls are either above a high value or below a low value, which is required in a conventional wall treatment model. Contrastingly, blended wall treatment is considered a function of local y^+. Blended wall laws are employed to model smooth variable changes in the buffer layer between the viscous sublayer and the logarithmic region.

2.2.4 Solver and schemes

The CFD model is important in this thesis because there is a lack of research on wingsails with such a cambered profile. Hence, this thesis aims to establish and develop a high-fidelity CFD model for resolving the flow field that the wingsail with a crescent-shaped profile induces.

The finite volume method (FVM) is utilized to discretize the governing equations. This method employs a segregated flow solver that is accomplished with the semi-implicit method for pressure-linked equations (SIMPLE) algorithm (Patankar, 1980). It is worth noting that the flow is assumed to be incompressible in this thesis because of the low freestream Mach number.

The convection fluxes on cell faces are discretized by means of a hybrid second-order upwind and bounded-central scheme. The diffusion fluxes on both the internal and boundary cell faces are discretized with a second-order scheme. The second-order hybrid Gauss-LSQ method is used in gradient computation, which involves the reconstruction of field values in a cell face, such as the secondary gradients of the diffusion fluxes and pressure gradients, as well as the rate-of-strain tensors used in the turbulence models. A second-order implicit method is utilized to discretize the time derivative, while the Reichardt law (Reichardt, 1951) is utilized for the momentum equations.

The gamma transition model (Menter et al., 2015), which solves for turbulence intermittency to predict the onset of transition in the turbulence boundary layer, is also introduced to exclude the influence of transition flow. According to the results, the transition model mainly influences turbulence on the pressure side. It is found that the influence of the transition flow on propulsive performance can be ignored. Further, having the transition model significantly slows down the simulation speed since an extra equation needs to be solved, so the transition model is not applied in this thesis.

2.3 Structural analysis

2.3.1 Finite element analysis model

For the fully expanded wingsail, structure analysis is based on the apparent wind having $V_{AW} = 16\ \mathrm{m/s}$. According to the CFD results from Paper II, C_L is 2.10. The external load applied on the wingsail is divided into two parts: the pressure force on the pressure side and the suction force on the suction side, both of which are assumed to be uniformly distributed across the surface of the wingsail. Based on the CFD results, the magnitude of the total force on the suction side is approximately twice that on the pressure side.

For the boundary condition, the bottom of the mast, where it is fixed to the deck of the ship, is a fixed boundary, so no translation or rotation is allowed.

For the concept utilizing a cubic mast, each pair of sub-parts that contact each other is tied together at the contact surface to ensure that there is no relative motion between them. The panels can have small relative tangential displacement in the vertical direction because the panels do not need to bear global bending.

Quasistatic FEA is used to predict and evaluate the structural response. The commercial software ABAQUS (Dassault Systemes, 2020) is used to perform the FEA simulations. The analysis product is ABAQUS/Standard. The geometrical nonlinearities are considered in ABAQUS using the NLGEOM option, which considers large deformations and displacements but not large rotations.

The structure of the wingsail is considered a group of shell elements in the FEA simulations. Five thickness integration points are set, and Simpson’s Rule is applied for integration.

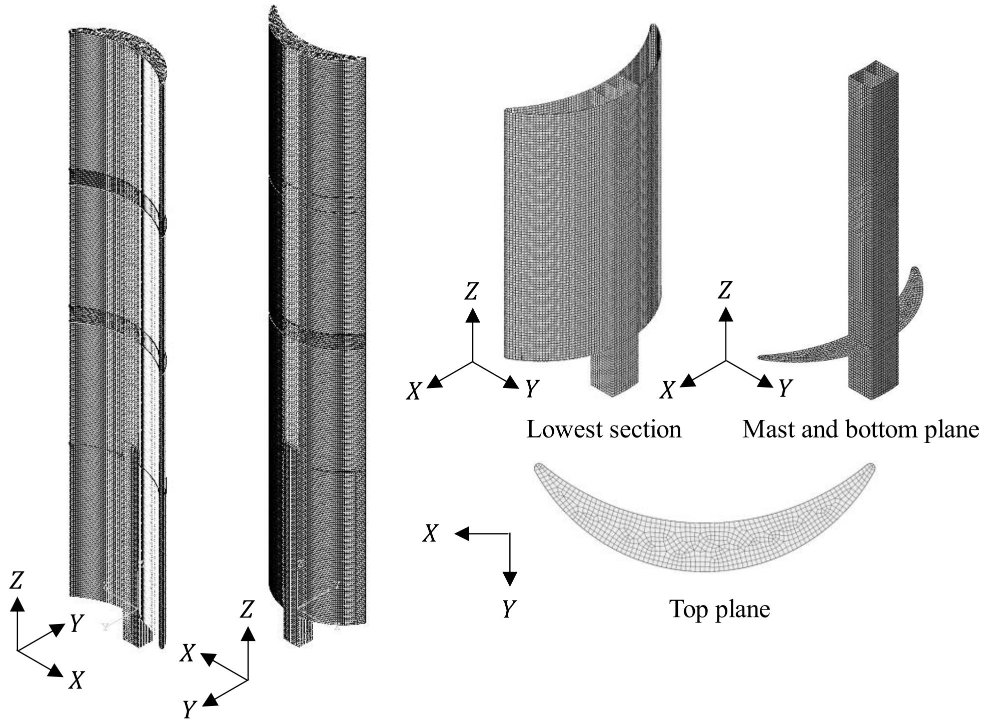


Figure 11. The numerical mesh of the concept utilizing a cubic mast.

A set of quad-dominated mesh is applied to the FEA model, as shown in Figure 11. The quadrilateral mesh elements are assigned the S4R element type, while the triangular mesh elements, which are mainly distributed on the horizontal section plates, are assigned the S3 element type. The typical element size is 0.2 m, selected based on mesh independence studies. According to the stress distribution, more refined mesh is applied to the edges. Since the section profile of the wingsail has some arcs and circles, curvature control is applied to the mesh generator. The maximum deviation factor is set to 0.1 so that the approximate number of elements per circle at the edges of the crescent-shaped profile is 8.

The gravity of the wingsail structure, i.e., the inertia loads from the self-weight, is ignored since it does not have a noticeable influence on stress distribution.

2.3.2 Evaluation criteria

In this thesis, three properties of each structure are evaluated: its weight, strength, and rigidity. Since there is no guidance for this crescent-shaped structure, the authors of Paper III formulate a series of conservative criteria:

- The total weight of the wingsail must be as low as possible.
- The maximum von Mises stress (σ_{Mises}) should not exceed the yield stress. Including a factor of safety of 2, the allowable von Mises stress for steel (S275) (ASTM, 2004) is 140 MPa, while the allowable stress for aluminum (6061-T4) (BS EN, 2004) is 105 MPa. The maximum normal stress in compression should not exceed the buckling stress. The maximum shear stress should be less than 50% of the allowable von Mises stress; that is,

the allowable shear stress is 70 MPa for steel and 53 MPa for aluminum.

- Rigidity or flexibility is also relevant because if the structure is not rigid enough, the telescopic function will not work. The maximum deflection, which usually occurs at the tip, should not be larger than 5% of the fully expanded height. In the fully expanded state, the maximum allowable tip deflection is 3.7 m. The relative displacement of the panels should not exceed half of the mast diameter (i.e., 1 m).

Because only quasistatic condition is considered in the present study, while the inertia loads from dynamic forces, wind gusts and other loads are ignored, these criteria listed above are set to be stricter than those recommended by DNV (DNV, 2022).

2.4 Fuel saving evaluation

Predicting the performance of a WASP system requires the inclusion of the full system, i.e., the sails and the ship, especially due to the F_S that the sails create. The F_S and yaw moments that WASP systems introduce must be compensated for by a drift of the ship and the rudder angle, both of which introduce an added resistance that causes both a lower net thrust (i.e., the thrust of the sail minus the added resistance caused by the sail) and the need for sail trim optimization to achieve the best performance and respect any given constraints on the rudder or heel angle, for instance. Therefore, a model respecting at least four degrees of freedom, i.e., surge, drift, yaw, and heel, must be used. Further, the performance of a WASP system also depends on the ship upon which it is installed, which means that any performance or comparison study must incorporate a case study ship. In this thesis, a tanker with a deadweight of approximately 100,000 tons is used. The sail is positioned 5 m behind the forward perpendicular, at the centerline of the ship.

ShipCLEAN, a generic model developed to provide accurate predictions with little input data that respects the minimum four degrees of freedom, is used as a performance prediction tool in this thesis. Polar plots for fuel saving are first created for different wind strengths and true wind angles. Then, to predict long-term fuel savings, the automatic identification system (AIS) data of the ship are used to derive the position and speed of the ship during 2018. Environmental conditions are retrieved from the Copernicus Marine Environment Monitoring Service (CMEMS) and are updated every 3 hours. Detailed information of the route and weather conditions of the case study can be found in Paper I.

3 Results

This chapter presents a summary of the results of the appended papers. It highlights the main achievements of and presents a selection of important results from the papers.

3.1 Summary of Paper I

Paper I introduces the concept design of a telescopic wingsail with a new crescent-shaped profile. To evaluate its performance, two- and three-dimensional CFD simulations with uRANS and the k–ω SST turbulence model are used. One objective of the study in Paper I is to address suitable sail configurations with an advantageous C_L to maximize F_T for large sailing merchant ships and their ship operation profiles. Paper I compares the propulsive performance of two rigid wingsails with different sectional profiles (NACA 0015 and crescent-shaped). The analysis also focuses on exploring flow field properties, including flow separation points and tip vortices, as well as the impacts of external loading conditions on the wingsails. A case study in which the new sail is applied to a fossil fuel-free ship is included, and the ship modeling platform, ShipCLEAN, is used to evaluate its propulsive performance.

3.1.1 Force coefficients

Based on the results of Paper I, which are derived from a comparison of the two- and three-dimensional simulations with a periodic top and bottom, the differences for the crescent-shaped foil, D2R10, are 7.5% for C_L and 58.1% for C_D, as Figure 12 presents. Therefore, two-dimensional simulations significantly overestimate force coefficients, even under low α conditions, and C_D is more sensitive than C_L. In the two-dimensional simulations, due to the limitation of spanwise flow, the vortices are constrained and not well-developed (Park et al., 2017). An overestimation of force coefficients, especially C_D, was also found in similar research performing high-Reynolds-number CFD simulations for airfoils with strong flow separation (Zhu, 2020). Comparing the results from the different boundary conditions, these two cases provide force coefficients with obvious differences, indicating that the tip vortices, which are discussed in Section 3.2, have significant impacts. Specifically, when there is a freestream tip, the lift force on the foil decreases by 5.7%, and the drag force increases by 35.0%.

As Figure 12 shows, the crescent-shaped profile, D2R10, has significantly higher force coefficients and is expected to provide better propulsive performance. Furthermore, the impacts of tip vortices on the crescent-shaped concept are not as significant as those on the NACA 0015 wingsail. On the other hand, because of flow separation, the crescent-shaped wingsail shows a remarkable oscillation amplitude with the force coefficients. Therefore, the crescent-shaped sail may suffer from more serious flutter, which makes higher requirements on the structure of the sails.

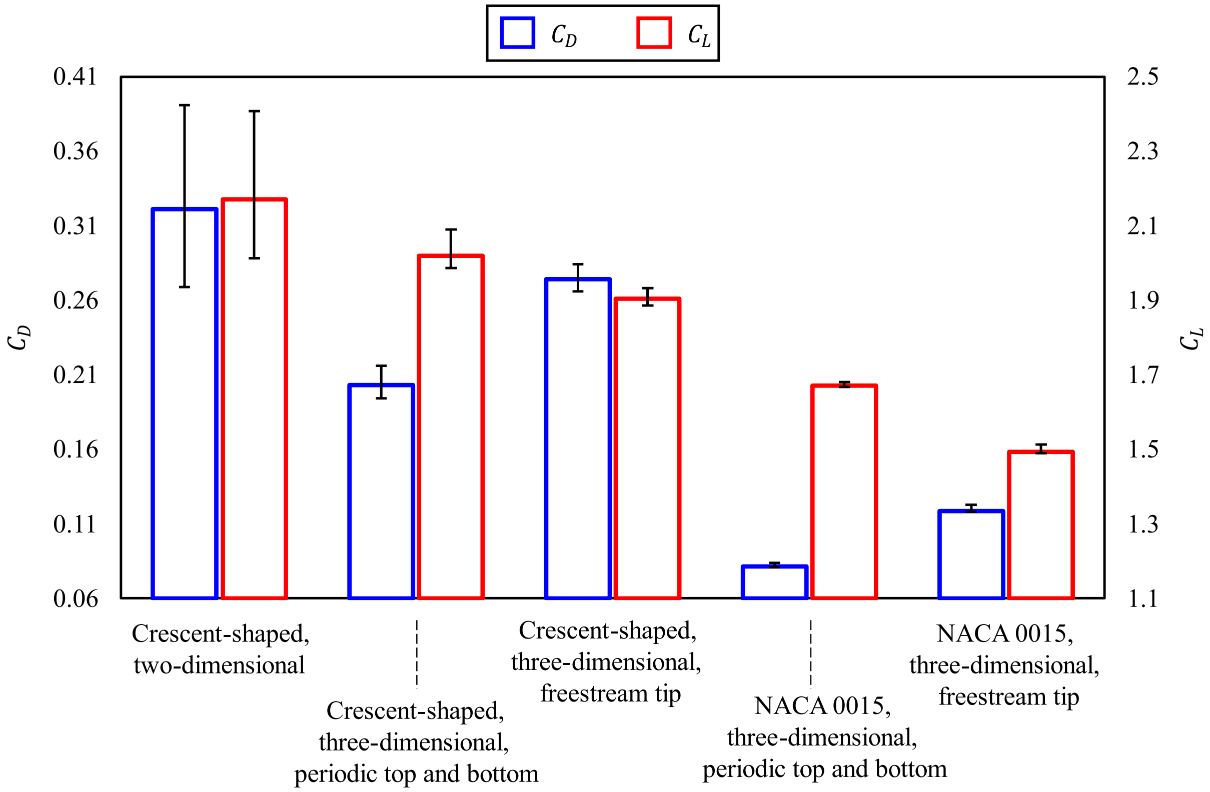


Figure 12. The force coefficients of the NACA 0015 and D2R10 crescent-shaped foils from the two- and three-dimensional simulations with different boundary conditions. The error bars represent the amplitude of oscillation.

The plots of the force coefficients within a wider range of α can be found in Figure 13, with the blue lines and symbols representing the two-dimensional results and the red lines and symbols representing the three-dimensional results. In Figure 13(a), it can be seen that there is no clear α_c for this type of profile, and two peaks of C_L occur when $\alpha = 20°$ and $\alpha = 35°$. The highest C_L is approximately 2.7 when $\alpha = 35°$ based on the two-dimensional simulations and 1.9 when $\alpha = 20°$ based on the three-dimensional simulations. As for C_D, as shown in Figure 13(b), both the two-dimensional and three-dimensional simulations show that when $\alpha \leq 80°$, C_D increases as α increases. The two-dimensional simulations also predict much higher C_D than the three-dimensional simulations, and other researchers have detected a similar phenomenon (Najjar & Vanka, 1995). According to the two-dimensional simulations, the highest C_D is around 3.7 when $\alpha = 80°$. For the high-Re conditions, C_D for a flat plate is approximately 1.98, and for a semicircle opening upstream, it is approximately 2.30 (Hoerner, 1976). The C_D of the crescent-shaped profile should probably be between these. Additionally, due to the tip vortices, C_D is expected to be even lower, so the predicted C_D is unreasonably high. In addition, C_D suddenly decreases when α increases from 80° to 90° in two-dimensional simulations. As the findings from the two-dimensional simulations do not agree with the basic physics that are addressed in the three-dimensional simulations, it is believed that the two-dimensional simulations cannot provide reasonable predictions of the force coefficients when $\alpha > 20°$ due to the strong flow separation, which is explained in Section 3.2.

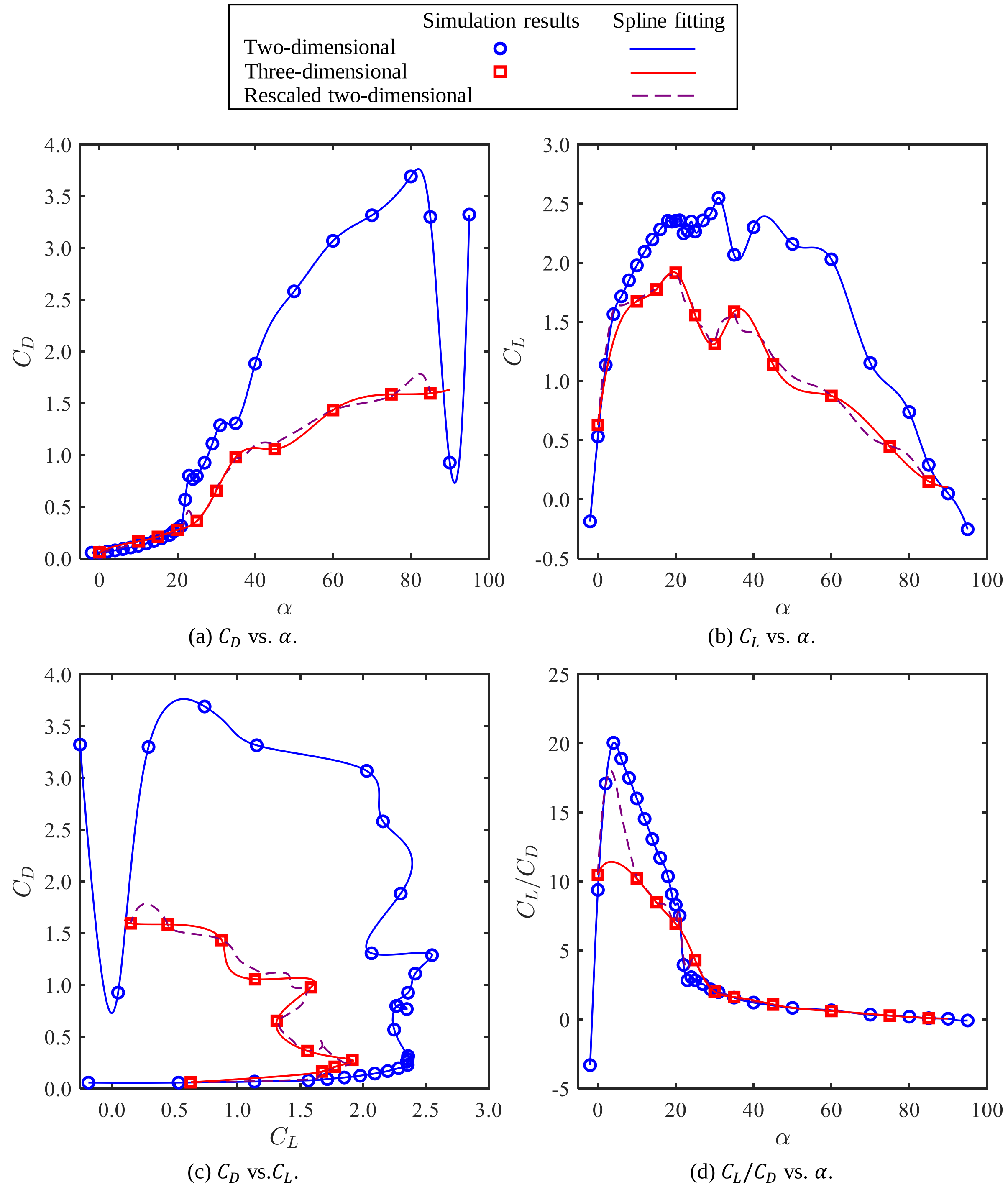


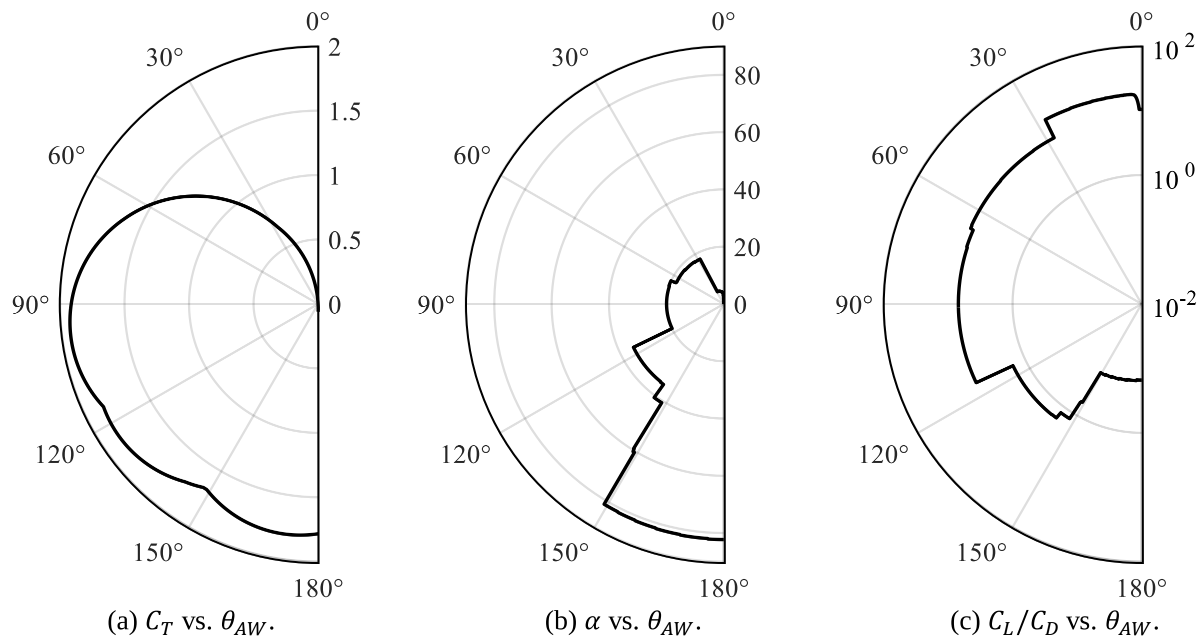
Figure 13. Time-averaged C_L and C_D curves.

However, the assumption that the two-dimensional simulations correctly show the trend of the force coefficients is still held. Based on this assumption, a hybrid two- and three-dimensional simulation method is proposed. First, a series of two-dimensional simulation cases with various α are performed to get the time-averaged force coefficients. Second, a limited number of three-dimensional simulations with distinctive α, e.g., α that have a peak or valley force coefficient value, are performed. Third, the ratio of C_L and C_D between the two- and three-dimensional simulations is calculated. Finally, C_L and C_D are rescaled based on this ratio. In this way, the computational capacity can be reduced because the three-dimensional simulations are much heavier than the two-dimensional simulations. In Figure 13, the purple dashed line represents the rescaled two-dimensional results. From Figure 13(a) and Figure 13(b), it can be seen that the rescaled two-dimensional results are closer to the three-dimensional results, so the rescaling method is feasible.

3.1.2 Propulsive performance

Based on the force coefficients from the CFD simulations with the freestream tip setup, propulsive performance is executed with the assumption that the force coefficients will remain the same when the apparent wind speed changes following the direction of navigation since the force coefficients are believed to be less sensitive to Re.

Notably, when the point of sail is luffing, close-hauled, or beam reach, i.e., θ_{AW} is from 30° to around 90°, F_L is the main source of thrust. However, under other conditions, the wingsail may be operated to use F_D. Therefore, to predict the propulsive performance for all the directions of apparent wind, an enumeration method is used to ensure that C_T with θ_{AW} is in the 0° to 180° range and α is in the 0° to 90° range. The results for the level of propulsion (the highest C_T at different θ_{AW}) and how the wingsail is operated (α that is applied to get the highest C_T) are plotted in Figure 14. Since the polar diagram is always symmetric, only half of the polar plot, i.e., $0° \leq \theta_{AW} \leq 180°$, is presented.



(a) C_T vs. θ_{AW}. (b) α vs. θ_{AW}. (c) C_L/C_D vs. θ_{AW}.

Figure 14. Polar diagram of C_T, α, and L/D versus θ_{AW} for the crescent-shaped profile at $V_{AW} = 25$ m/s.

When the ship is navigating against the wind, i.e., the luffing point of sail, C_T is rather low or even less than 0. Here, the wingsail is operated with a very low α to reduce the extra resistance. As θ_{AW} increases, e.g., to $\theta_{AW} = 60°$, C_T increases, and the wingsail is operated with α_c to have the maximum C_L. For θ_{AW} in the 60° to 180° range, the wingsail can provide notable propulsion. However, the wingsail is not operated in the same way. For instance, when $30° < \theta_{AW} < 120°$, α should be around 20° to get the maximum C_L, and F_L is the main source of thrust. When $120° < \theta_{AW} < 150°$, i.e., the point of sail is board reach, the optimum α is around 40° with $C_L \approx C_D$, and the wingsail uses both F_D and F_L for propulsion. When the point of sail is running, which means θ_{AW} is around 180°, F_D is mainly used, and the wingsail is operated with $\alpha \approx 80°$.

The polar diagram is applied to the inhouse program, ShipCLEAN (Tillig & Ringsberg, 2019). Figure 15 presents a polar plot of the fuel savings for the case study tanker with one crescent sail in 10 kn and 20 kn of wind.

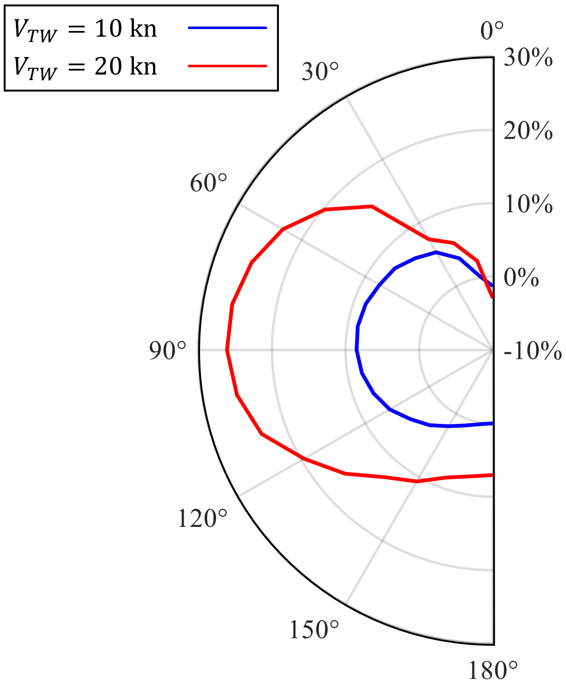


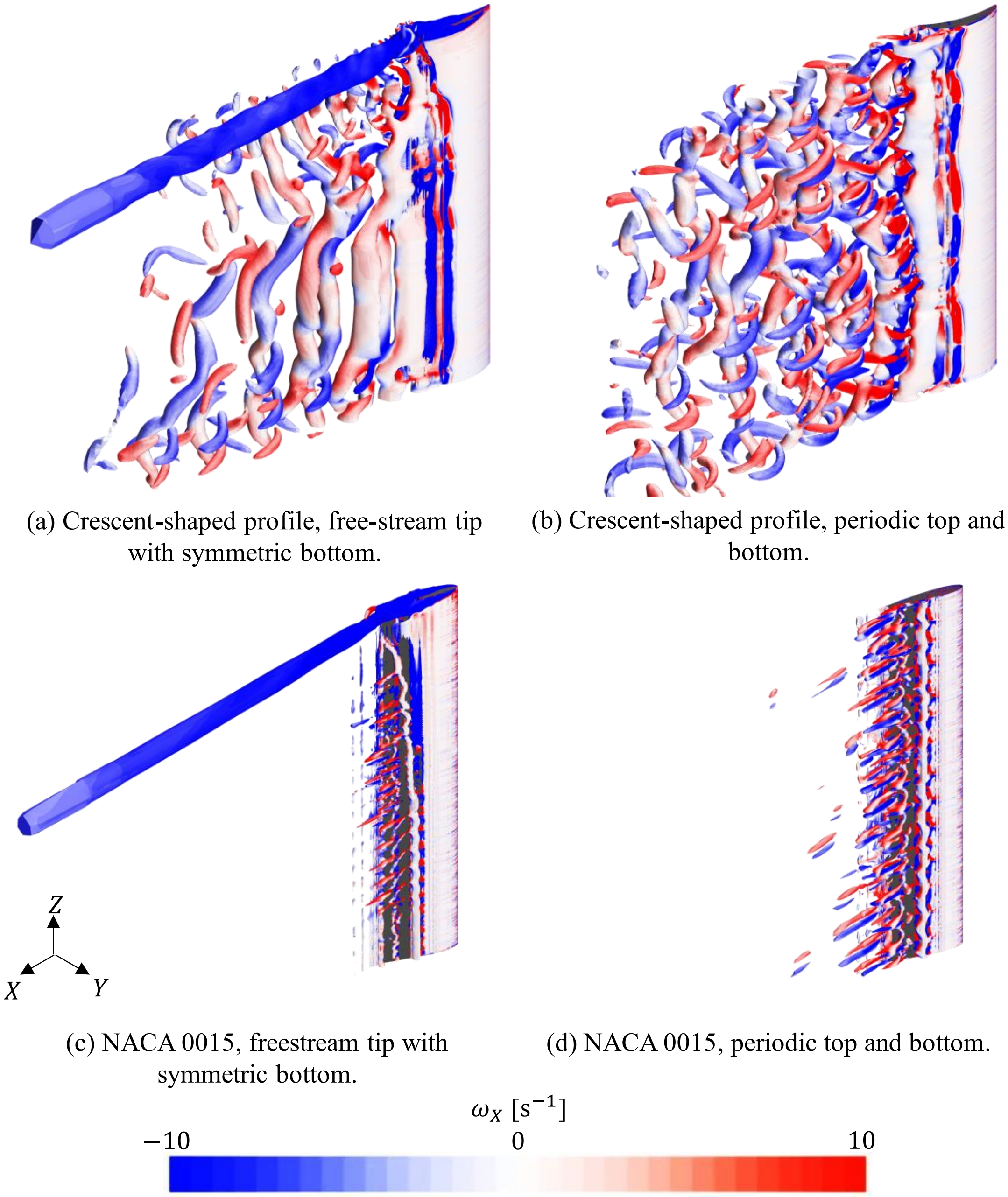
Figure 15. Polar plot of relative fuel consumption savings vs. θ_{TW} at two V_{TW}.

The polar plot shows that a maximum fuel saving of about 9% at $\theta_{TW} = 90°$ in $V_{TW} = 10$ kn, and 25% in $\theta_{TW} = 90°$ in $V_{TW} = 20$ kn can be expected. However, the fuel savings vary over the true wind angle; thus, the performance must be predicted using actual routes with realistic weather, as presented in the following section.

As a result of long-term fuel savings, total savings of 9.5% are achieved with the crescent sail. For comparison purposes, the simulations are repeated with a Flettner rotor (5 m in diameter and 30 m in height) positioned similarly. The Flettner rotor has resulted in 9.8% savings on the same route. About 34% of the time the fuel savings are larger than 5%. The maximum additional fuel consumption is less than 1%. The maximum fuel saving is 97.5%. See Paper I for more detailed results.

3.1.3 Flow field characteristics

The flow field that the crescent-shaped profile induces has a remarkable flow separation phenomenon at the suction side close to the trailing edge, which results in unsteady characteristics.



(a) Crescent-shaped profile, free-stream tip with symmetric bottom.

(b) Crescent-shaped profile, periodic top and bottom.

(c) NACA 0015, freestream tip with symmetric bottom.

(d) NACA 0015, periodic top and bottom.

Figure 16. The iso-surfaces of $Q = 5\ s^{-2}$, colored with ω_X. $\alpha = 20°$ for the crescent-shaped profile and $\alpha = 16°$ for NACA 0015. The inlet flow velocity is in the positive X direction.

For the NACA 0015, there is usually no or one flow separation point depending on the α. The characteristic of flow separation does not appear if α is lower than the critical angle of attack. However, when looking at the flow field that the crescent-shaped foil generated, flow separation always occurs. From the iso-surface plot in Figure 16, where the colorful contours represent the streamwise vorticity, the circular patterns of rotating air left behind the tip of the foil, which are the tip vortices, can be easily recognized (see Figure 16(a) and Figure 16(c)). Tip vortices cause a reduction in C_L . Wingsails with different section profiles also show different wake characteristics. For the crescent-shaped profile, vortex shedding is much more significant. As shown in Figure 16(a) and Figure 16(b), numerous vortex tubes can be seen in the wake region. However, for the NACA 0015 profile (see Figure 16(c) and Figure 16(d)), only limited vortex tubes can be seen developing on the suction side. The oscillation in force coefficients of the crescent-shaped wingsail is much stronger than those of the wingsail with the NACA 0015 profile.

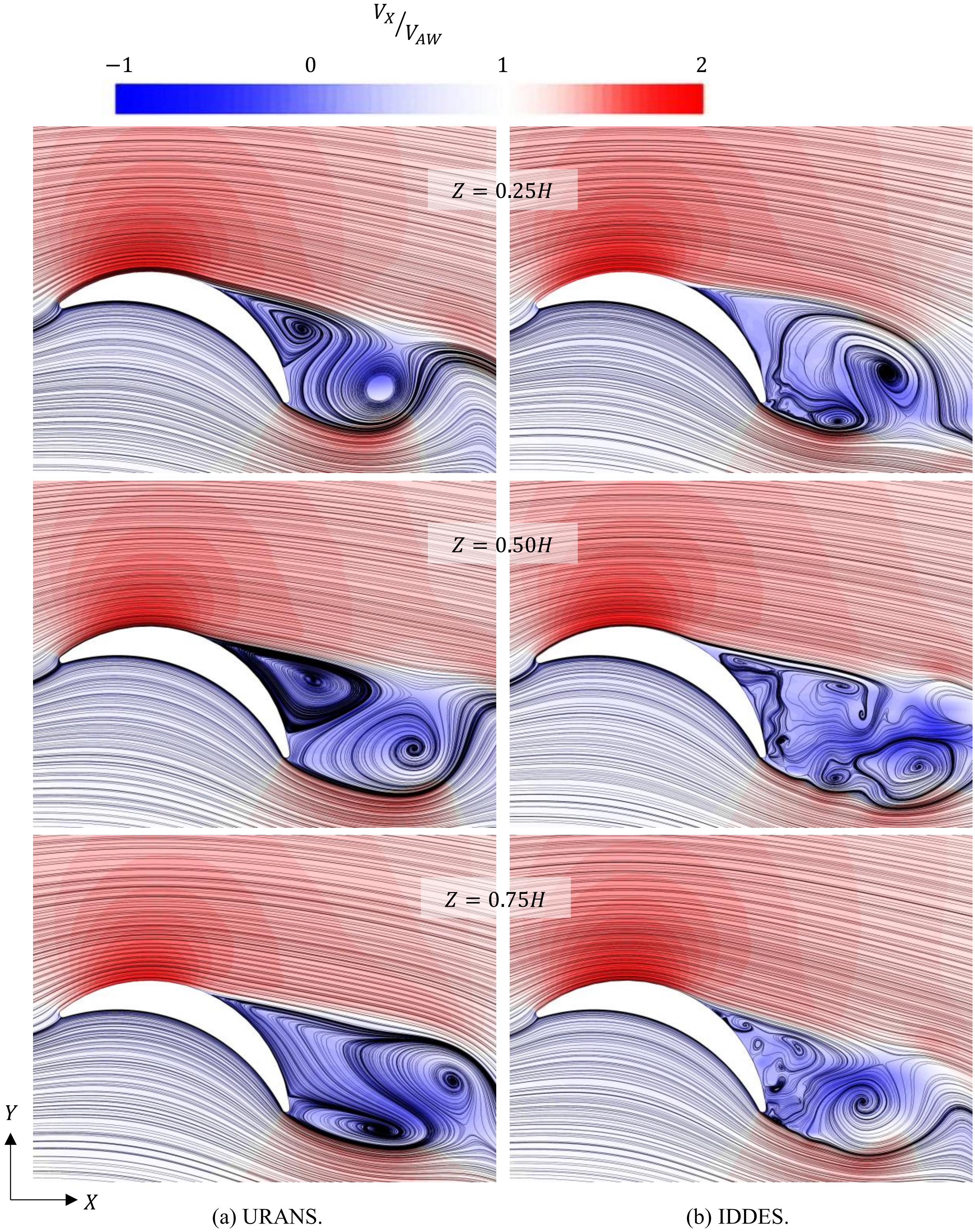
The characteristics of the flow field that the crescent-shaped wingsail induces are more deeply examined and discussed in Paper II.

3.2 Summary of Paper II

In Paper II, full-scale simulations, utilizing both the uRANS and IDDES methods, are performed to analyze the flow field around a wingsail. The paper's analysis includes flow separation and vortex shedding, the development and dissipation of wake vortices, and lift reduction due to tip vortices. It also studies the telescopic function of the wingsail by analyzing sails with different heights and under different wind conditions. The paper concludes that the uRANS and IDDES simulations make similar predictions for time-averaged loads but disagree on the unsteady characteristics of the flow field. The IDDES simulations also indicate more complex vortex shedding phenomena.

3.2.1 Flow separation

The flow field that the crescent-shaped profile induces has a remarkable flow separation phenomenon at the suction side close to the trailing edge, resulting in unsteady characteristics. To reduce the influence of the tip vortices, analysis of the flow separation and vortex shedding is based on the fully expanded condition. For a clearer presentation and discussion of the flow separation phenomenon, the simulation case with the largest α, i.e., $\alpha = 23°$, is taken as an example. Figure 17, which presents streamwise velocity distribution and the streamline at the sectional plane with different spanwise positions, shows that the results from the uRANS and IDDES methods share some similarities. For upstream areas of the half chord, i.e., on the left of the half chord in the sub-figures of Figure 17, the flow is resolved by applying the k–ω SST turbulence model when using both the uRANS and IDDES methods. Therefore, the characteristics of the flow field that the two methods predict are almost the same. There is a high-velocity region where the streamwise velocity is approximately twice the inlet flow velocity on the suction side upward of the half chord, which causes a reduction in pressure and finally leads to lift force. There is also a pronounced low-velocity region on the suction side of the profile that extends to the downstream areas. The observed phenomena support the hypothesis that the IDDES method provides more detailed information on separating flow since eddies smaller than the integral scale but larger than sub-grid scales are directly resolved instead of being modeled (H. Yao et al., 2018).



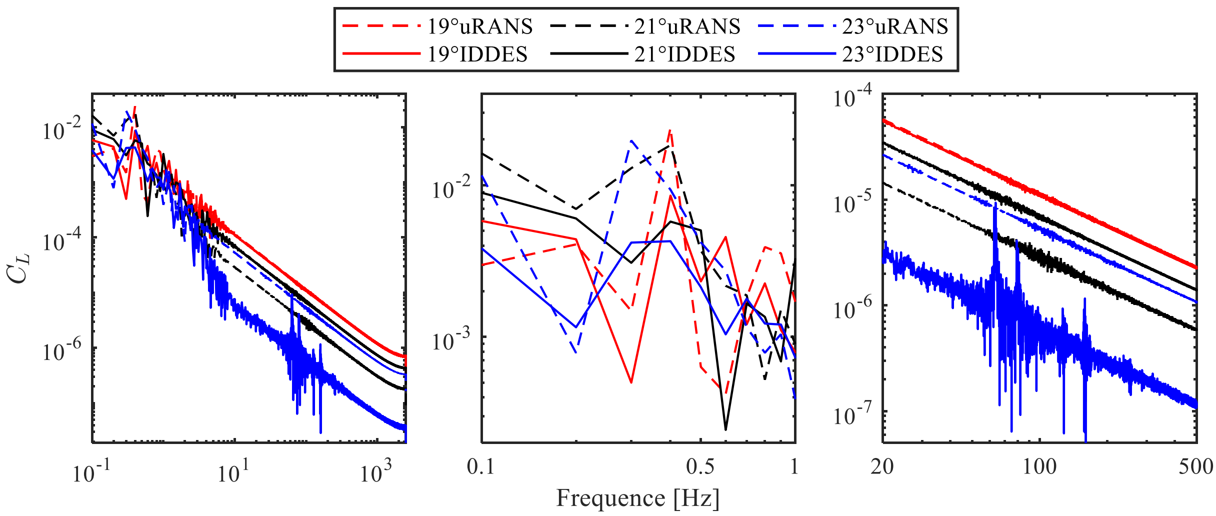
(a) URANS. (b) IDDES.

Figure 17. V_X distribution and streamlines at different spanwise sections under the fully expanded condition of $V_{AW} = 8$ m/s, $\alpha = 23°$.

As shown in Figure 10, the low-velocity region is mainly calculated using a LES when applying the IDDES method. Therefore, the flow field in this area is different for the two methods. The results from the uRANS method show two main vortices (see Figure 17(a)). At the lower part of the sail, e.g., $Z = 0.25H$, the IDDES results also show the main vortices because the bottom panel with the symmetric boundary condition constrains vortex development in the spanwise direction. However, at the higher part of the sail, e.g., $Z = 0.50H$ and $Z = 0.75H$, the flow shows more complex characteristics according to the IDDES results (see Figure 17(b)).

Periodic oscillations are evident from the time history of the C_L values in the uRANS simulations. Contrastingly, the oscillations are quite random, without a clear period, in the IDDES simulations. Referring to the FSI simulations in Paper II, these irregular oscillations explain the high-frequency damping found in the IDDES results.

Therefore, to study the unsteady properties of force coefficients, fast Fourier transform (FFT) analysis is conducted. Figure 18 presents the FFT analysis results for C_L under the fully expanded condition. The length of physical time of the selected data is 10 s, so the first peak with a frequency of 0.1 Hz is spurious and can be ignored. When looking at the dashed lines, a second set of peaks is evident, with frequencies around 0.4 Hz, so the uRANS simulations indicate that C_L has a clear oscillating period of 2.5 s and an amplitude of approximately 0.02. The C_L values that the IDDES simulations predict do not show periodic oscillations. In Figure 18(b), in which the FFT plot is zoomed in on the low-frequency region, the second set of solid-line peaks is unclear. Some small oscillations can also be found in the solid lines in the high-frequency region of the FFT results, shown in Figure 18(c). The time history and FFT results of C_D and C_M, as well as those under the fully retracted condition, show similar characteristics.



(a) All frequency range. (b) Low frequency range. (c) High frequency range.

Figure 18. FFT results of C_L, fully expanded condition.

3.2.2 Wake flow

Normally, more than one wingsail is installed and operated on a ship. Analysis of the wake flow is expected to provide some guidance for future studies on ships with multiple sails. The wake flow that the two methods resolve shows many differences. Taking the results under the fully expanded condition as examples, the IDDES simulations predict a flow field with much more complex vortex structures. From the uRANS simulations, the spanwise vortex tubes can be easily observed, so the vortex shedding phenomena do not show significant spanwise characteristics, except for the tip vortices. However, the vortices have numerous streamwise and crossflow structures when applying the IDDES method.

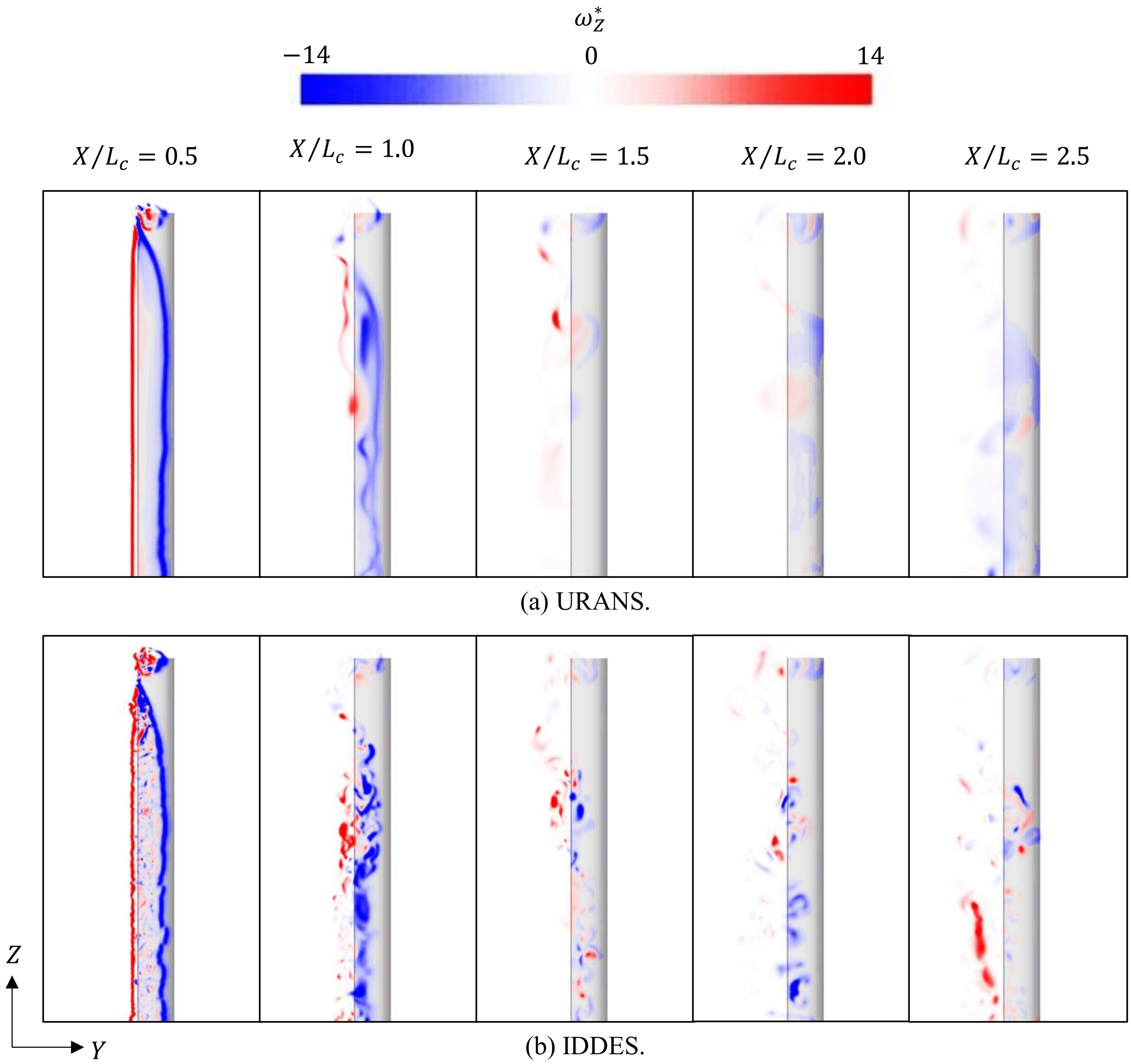


Figure 19. Non-dimensional ω_Z distribution at different streamwise positions in the wake field under the fully expanded condition of $V_{AW} = 8\ \mathrm{m/s}$, $\alpha = 23°$. The inlet flow orients in the direction perpendicular to the paper/screen, pointing outwards.

When looking at the ω_Z distribution at section planes with different streamwise positions, as shown in Figure 19, the differences between the results that the two methods simulate are more apparent. The uRANS results show some vertical vortex tubes. For example, in Figure 19(a), when $X/L_C = 0.5$, i.e., it is just behind the trailing edge, a strong vortex tube can be found. However, when using the IDDES method (see Figure 19(b)), there are small vortices on the decimeter scale at the section plane of $X/L_C = 0.5$. When looking at the position $X/L_C = 1.0$, the distribution of ω_Z is preserved, as shown in Figure 19(a), while for the IDDES results, it can only be found in the lower part close to the bottom panel. Moreover, the vortices dissipate quickly in the wake region when applying the uRANS method, which indicates that there is more energy loss. The turbulent kinematic energy in the wake region is also much lower when applying the IDDES method. When looking at the streamwise position of $X/L_C = 2.0$, the vortices that the IDDES method predicts are still noticeable, while those that the uRANS method predicts are almost dissipated.

3.2.3 Tip vortices

Another important characteristic of the flow field is the phenomenon of tip vortices, which is believed to be the main reason for lift reduction when changing the boundary conditions from periodic top and bottom to free tip and symmetric bottom. Notably, when the top and bottom have periodic boundary conditions, the pressure distribution along the foil is similar at the different Z positions. However, if the boundary condition is a free tip and symmetric bottom, the pressure difference between the pressure and suction sides becomes smaller when approaching the tip of the wingsail, leading to lift reduction.

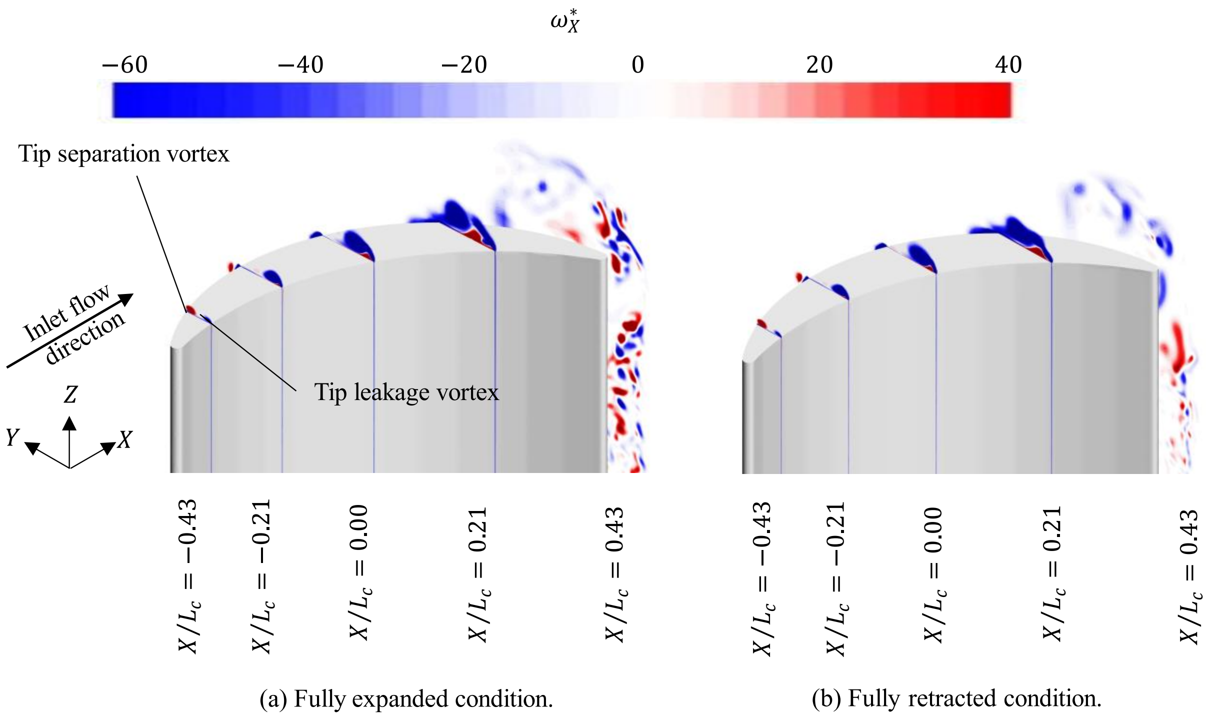


Figure 20. The non-dimensional ω_X distribution at different streamwise positions around the tip, based on the IDDES simulations, $\alpha = 23°$. For the fully expanded condition, $V_{AW} = 8$ m/s, while for the fully retracted condition, $V_{AW} = 32$ m/s.

By plotting ω_X^* at several different streamwise positions around the tip (Figure 20), two tip vortices, the tip separation vortex and the tip leakage vortex, develop at the suction and pressure sides, respectively. According to the uRANS simulations, the two vortices combine at around the half chord into a single vortex with a more complex internal flow structure. Nevertheless, in the IDDES results, the two vortices do not combine. The tip leakage vortex is also much stronger than the tip separation vortex, which dissipates quickly at around the half chord. Due to the higher apparent wind speed, the tip vortices are stronger under the fully retracted condition. However, when comparing the dimensionless value of ω_X, the distribution is similar between the two conditions.

It is believed that tip vortices have notable negative effects on propulsive performance. That is, the pressure on the pressure side is lower when it is close to the tip, leading to a reduction in lift force. Therefore, some actions are suggested to release the phenomenon of tip vortices, e.g., a top-mounted disk installed on the tip would likely improve propulsive performance.

3.3 Summary of Paper III

In Paper III, quasistatic FEA is performed to study the structural responses of a crescent-shaped wingsail rig. A few conceptual designs of telescopic rigs, including different structural designs and material arrangements, are analyzed and compared by considering three criteria: rigidity, strength, and weight. The external wind loads applied to the sails in the structure analysis are obtained from the aerodynamic simulations performed in Paper II. The advantages and disadvantages of each concept are discussed, aiming to provide a good strategy for the structural design and arrangement of WASP systems. The results of the study can also be used in future work as a basis for structural optimization and FSI analysis.

3.3.1 Thickness and weight

A series of FEA simulations are performed to determine the thickness of different parts of the structure. The thicknesses of the different parts are then adjusted several times to satisfy the strength requirement and minimize the weight.

Table 2. Weight, maximum von Mises stress, and maximum deflection of different structural designs.

		Concept utilizing vertical stiffeners	Concept utilizing a cubic mast	
			Steel frame, aluminum panels	All in aluminum
Total weight	[t]	130	116	74
Weight excluding the panels	[t]		75	33
Max. von Mises stress	[MPa]	158 [a]	141 [b]	103 [b]
Max. deflection	[m]	0.32	0.59	1.14

[a] The Max. σ_{Mises} happens at horizontal section plate of section 2, close to the edges (see Figure 21).
[b] The Max. σ_{Mises} happens at bottom plate, close to the mast (see Figure 22).

By comparing the two concepts, the total weight can be reduced by approximately 11% by dividing the wingsail structure into a strong frame and light panels (see Table 2). For the all-aluminum concept utilizing a cubic mast, the weight can be significantly reduced, but this results in a much larger tip displacement. Therefore, the "steel frame and aluminum panels" design shows better rigidity, while the "all in aluminum" design is lighter.

3.3.2 Strength

In the concept utilizing vertical stiffeners, at the section plate of section 2 approaching the edges, stress concentration is found, although web structures have been added to avoid stress concentration at the bottom. However, for the remaining parts of the wingsail, the von Mises stress (σ_{Mises}) is much lower than the threshold value, as shown in Figure 21, so there is no need to continue adjusting the thickness.

In Figure 21 and Figure 22, the counterplots follow the visualization rule that if the values for elements are within 75% of each other, they will be averaged and then displayed.

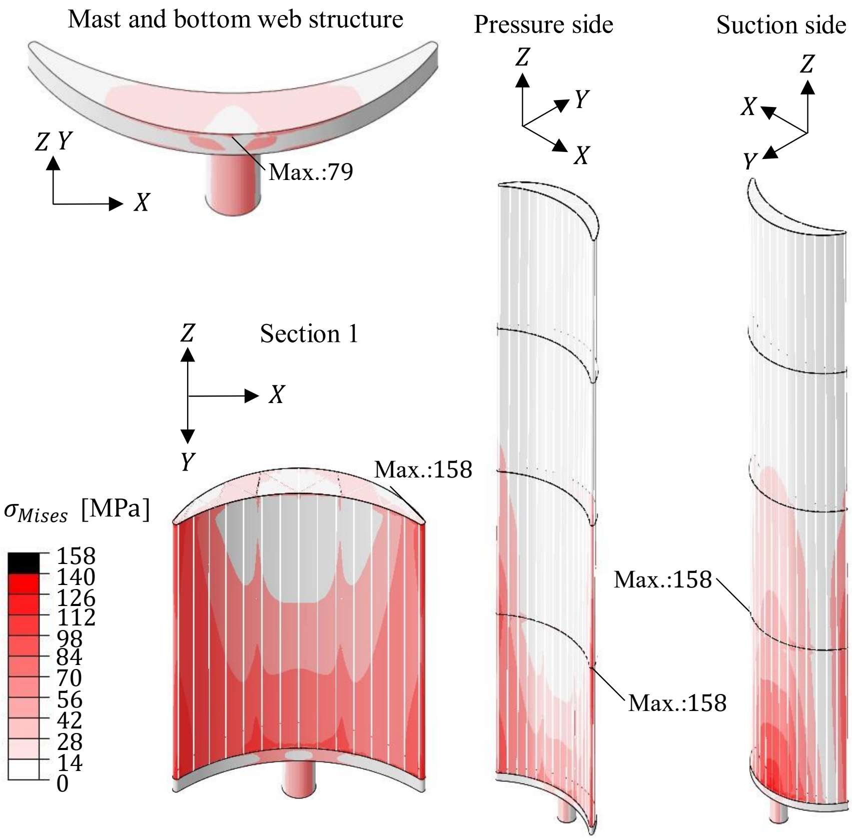
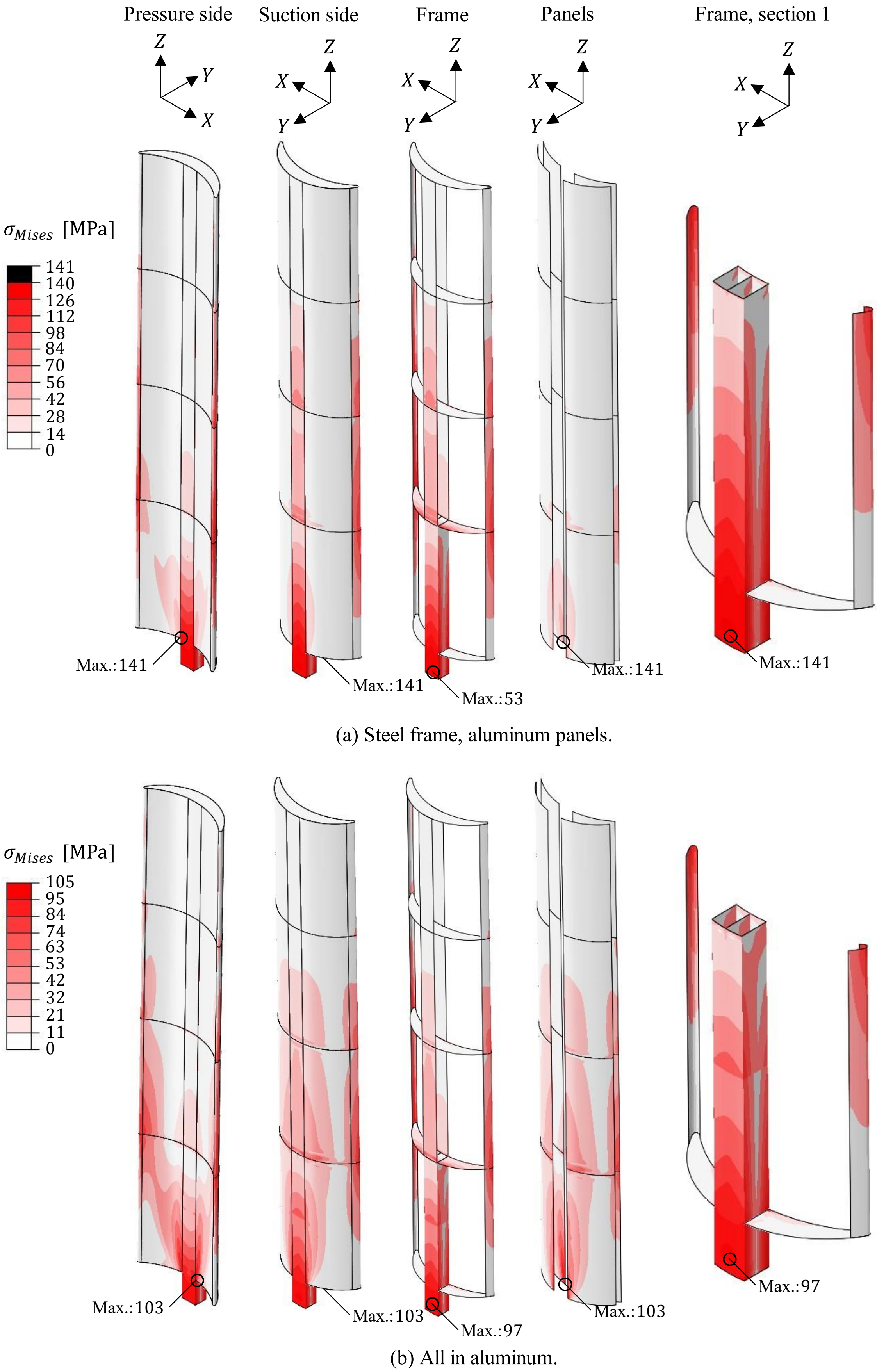


Figure 21. Von Mises stress distribution for the concept utilizing vertical stiffeners.



(a) Steel frame, aluminum panels.

(b) All in aluminum.

Figure 22. Von Mises stress distribution for the concept utilizing a cubic mast.

Figure 22 shows the von Mises stress distributions for the two material arrangements. When the wingsail has a steel frame, as shown in Figure 22(a), the maximum von Mises stress occurs at the bottom of the mast. The stress distributed throughout the panels is much lower than in the frame, so the frame bears global bending. On the other hand, for the "all in aluminum" concept shown in Figure 22(b), the stress in the panels is comparatively larger, although the distribution of von Mises stress throughout the frame shows similar characteristics. The maximum von Mises stress is found at the contact area of the mast and the bottom plate. The stress concentration is reduced by introducing the cubic mast, but stress still occurs. The maximum von Mises stress occurs at the contact area of the mast and the bottom for both material arrangements.

The risk of buckling due to compressive normal stress is assessed in this thesis by calculating the buckling stress of the mast according to Euler's formula for buckling and comparing it with the maximum compressive normal stress from the FEA results. Shear buckling is not studied here since the shear stress throughout the wingsail structure is lower than normal stress. Additionally, shear stress mainly occurs at horizontal section plates, which are unaffected by global bending and are much thicker and stronger than the other parts of the structure.

Compressive normal stress mainly occurs in the mast and central plates. The riskiest part with the highest compressive normal stress is the bottom of the mast on the suction side of the wingsail, which is the compressed side in the structural response. For the all-aluminum arrangement, the normal stress distribution shows similar characteristics. High compressive normal stress brings the risk of buckling at the mast. To reduce the compressive normal stress at the bottom of the mast, several solutions can be considered, such as making the lower part of the mast thicker or adding stiffeners inside the mast.

3.3.3 Rigidity

The characteristics of the distribution of the deformation displacement in the Y direction (γ_y) are similar for the two material arrangements, as shown in Figure 23. In the all-aluminum structure, the displacement is around twice as large as in the structure with a steel frame and aluminum panels. For the steel frame structure, maximum displacement occurs at the edges of the top plate, while for the all-aluminum structure, it occurs at the middle of the top plate. Hence, the rigidity of the center plates is higher than that of the edges when applying a steel frame, but for the all-aluminum arrangement, the edges show higher rigidity. In addition, the deformation of section 1 is small due to the strong mast, especially with the steel frame arrangement. A possible solution to increase the rigidity of the higher sections would be to add a vertical plate expanding in the Y direction between the center plates for each section, but it may affect the telescopic function of the wingsail.

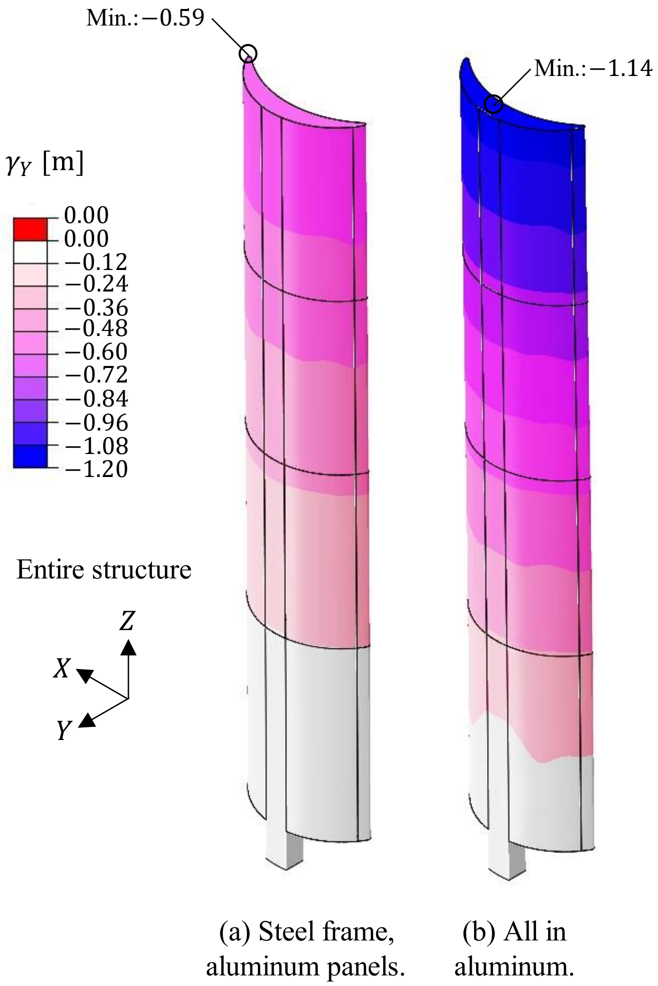


Figure 23. The deflection magnitude distribution for the concept utilizing a cubic mast.

It is also found that the center plates of section 2 experience significant rotation at their bottom, increasing the displacement of the upper sections (i.e., sections 2, 3, and 4). Therefore, compressive normal stress also occurs there, so the lower part of each center plate can be made thicker, or some extra stiffeners can be added for reinforcement.

4 Conclusions and future work

4.1 Conclusions

4.1.1 Practical significance

In conclusion, this thesis demonstrates the significant potential of wingsails in augmenting ship propulsion and reducing fuel consumption. The introduction of the novel crescent-shaped sail profile proves to be more effective in generating thrust force compared to the NACA 0015 profile, as evidenced by high-fidelity CFD simulations, as the potential thrust force coefficient is approximately 30% higher. Although the lift-to-drag ratio of the crescent-shaped wingsail is much lower than that of NACA 0015, F_D is seldom negative for propulsion, except under headwind conditions.

The implementation of crescent-shaped wingsails presents a promising avenue for enhancing the efficiency and sustainability of maritime transportation since the case study highlights the considerable fuel savings that can be achieved by installing a single crescent-shaped wingsail, with anticipated savings ranging from 9% in $V_{TW} = 10\,\mathrm{kn}$ to 25% in $V_{TW} = 20\,\mathrm{kn}$. Furthermore, the long-term fuel saving prediction indicates that the overall savings attributed to the crescent-shaped wingsail amount to 9.5%. One drawback of the new profile is the increased resistance experienced when sailing against the wind; however, such occurrences are infrequent.

4.1.2 Aerodynamic characteristics

The present study identifies certain challenges associated with the newly proposed wingsail profile, particularly regarding flow separation. The strong flow separation observed in this profile exacerbates flow unsteadiness and consequently imposes more unsteady surface loads on the sail, which may potentially compromise the strength and stability of the wingsail structure. The CFD results, especially those utilizing the IDDES method, reveal the presence of vortex tubes extending in the spanwise direction. These results also suggest less dissipation and energy loss in the wake region, which allows for discernible vortex structures to persist further downstream of the sail. Therefore, the wake flow may lead to interactions among sails in a ship equipped with multiple wingsails.

To investigate the effects of tip vortices on aerodynamics, this thesis employs two computational domain and spanwise side boundary condition setups: periodic boundary conditions and symmetry boundary conditions, with the top-side boundary positioned far from the sail's top-side edge to minimize boundary influence on flow. The sail configuration is affixed to the bottom side boundary, which is the water-free surface and is, therefore, subject to symmetry boundary conditions. The second case reproduces the vortices induced from the tip of the wingsail. Moreover, as side-edge vortices exist, this effect alleviates the breaking of the spanwise coherence in the vortex shedding that evolves downstream of the sail trailing edge.

4.1.3 Modeling experience

Two-dimensional simulations generally overestimate the force coefficients for the crescent-shaped profile. This discrepancy can be attributed to the exclusion of vortex evolution and coherence in the spanwise direction in two-dimensional simulations, as well as lift reduction caused by tip vortices due to the freestream tip. Despite these differences, both the two- and three-dimensional simulations exhibit similar trends in force changes concerning the angles of attack. Consequently, by rescaling the two-dimensional results to a limited number of three-dimensional simulation cases, propulsive performance can be effectively predicted.

For the time-averaged force coefficients, which are crucial to propulsive performance, both uRANS and IDDES methods yield similar predictions. However, the external loads that these methods predict exhibit distinct unsteady characteristics, which are expected to significantly impact the structural response. FFT analysis reveals that the uRANS-based results display more pronounced low-frequency oscillations, while the IDDES-based results capture the high-frequency characteristics of external loads. These high-frequency oscillations may contribute to local vibrations or buckling of the structures, warranting further investigation in future FSI analyses. Being able to provide more detailed information about the flow field, particularly in terms of vortex shedding in the wake region, is likely responsible for this difference, as large-scale eddies are resolved without modeling in the IDDES method.

4.1.4 Structural design and evaluation

In conclusion, the structural analysis demonstrates that the wingsail concept featuring a strong frame with a cuboid mast and lightweight panels offers superior performance in terms of weight, strength, and rigidity. Among the assessment criteria considered, strength—specifically, von Mises yield and compressive normal stress—emerges as the most critical factor when evaluating wingsail structures. The cuboid mast design has the advantage of mitigating stress concentration in the lower sections, particularly at the interface between the mast and the bottom plate. Extending the mast throughout section 1 also alleviates stress concentration on section 2's horizontal plate. In comparison to the previous concept utilizing vertical stiffeners, the "frame and panels" concept achieves the necessary strength at a significantly reduced weight. Substituting steel with aluminum can further decrease the frame's weight by approximately 50%, although the flexibility, as indicated by the tip displacement, increases.

To summarize, this thesis predicts the propulsive performance and structural response of a single crescent-shaped wingsail. This thesis also provides insights into the potential causes of structural instability or fatigue in relation to fluid dynamics, which will occur due to multi-wingsail interaction problems. This can be extended to guide the design of wingsail geometries and installation.

4.2 Future work

Three main areas of future work are identified, namely multiple wingsail interaction, FSI analysis, and hull–wingsail interaction.

Usually, two or more wingsails are installed on a ship to increase its propulsive power. In addition, a wingsail with a crescent-shaped profile affects the wake flow over a relatively long distance. Therefore, when more than one wingsail is installed on a ship, the interactions among these wingsails can be important. The first main area, multiple wingsail interaction, entails using numerical and experimental methods to study the aerodynamic interactions among multiple wingsails. This area can include how multi-wingsail interaction affects the wind loads on the wingsail, what the characteristics of the flow field that multiple wingsails induce are, and which arrangement of the wingsails provides better propulsive performance.

Wind loads on the wingsail are unsteady, and they experience oscillations with both low and high frequencies, which cause vortex-induced vibrations. Hence, dynamic structural responses need to be studied. In addition, the deformation and vibration of the structure may influence the flow field, and the affected flow field may also influence wind loads, so the second area of study, FSI analysis, is proposed to solve these problems. FSI analysis can be fully coupled simulations, i.e., coupled FEA and CFD at each time step, or aeroelastic simulations with the assumption that the geometry deformation of the section profile can be ignored.

The third area of study, the interaction between wingsails and the hull, is vital for WASP, as it influences overall performance. Aerodynamic and hydrodynamic interactions affect lift, drag, and resistance, while structural considerations ensure integrity and stability. The wingsails' position and size can impact balance and maneuverability, necessitating careful integration with the hull. Hence, analyzing and optimizing this interaction is essential for efficient propulsion and vessel performance. This methodology may involve coupling aerodynamic and hydrodynamic simulations, i.e., two-phase flow simulations.

Other ideas for future work can be the optimization of wingsail geometry for improved aerodynamic efficiency and life cycle assessment to evaluate the sustainability of the wingsail, among others.

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