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Title	Experimental and numerical investigation of towing operations for large floating offshore wind farms
Authors	Chitteth Ramachandran, Rahul
Publication date	2024
Original Citation	Chitteth Ramachandran, R. 2024. Experimental and numerical investigation of towing operations for large floating offshore wind farms. PhD Thesis, University College Cork.
Type of publication	Doctoral thesis
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Download date	2026-11-07 09:37:39
Item downloaded from	https://hdl.handle.net/10468/17004

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Experimental and Numerical Investigation of Towing Operations for Large Floating Offshore Wind Farms

Thesis presented by

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for the degree of

Doctor of Philosophy

University College Cork

School of Engineering

Head of School/Department: Prof. Jorge Oliveira

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2024

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Declaration Of Authorship

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism.

Signed: 

Date: 30 / 11 /2024

This work is dedicated to my beautiful wife Melanie, my parents Ramachandran, Bindhu and my brother Sunil.
Without them I wouldn't be here.

Acknowledgements

I extend my deepest gratitude and appreciation to all those who have contributed to the completion of this thesis.

First and foremost, I am profoundly thankful to my supervisors, Dr. Jimmy Murphy, Dr. Cian Desmond and Dr. Frances Judge for their invaluable guidance, unwavering support and insightful mentorship throughout this research journey.

A special shoutout to Dr. Cian Desmond for guiding me through the journey, helping me lay a strong foundation and roadmap for my work and taking the time to review and edit my publications amidst his busy schedules. Most importantly Dr. Cian was always available as a person of support, somebody to talk to and encouraging me to be confident and be there as a mentor and as a friend.

I am indebted to Mr. Jorrit-Jan Serraris and Erik-Jan de Ridder for their support during my stay at MARIN, for sharing their expertise and for providing me with the necessary tools and software for my work. A special thanks to Mr. Jorrit-Jan for taking an interest in my work taking initiative and supporting my plans for the experimental work carried out at MARIN and connecting me to the personnel who were experts in the domain.

I am thankful for the support of my PhD companions, Alder Otter (Ollie), Omar Ibrahim, Navid Belvasi and Omer Khalid and special thanks to Ollie for assisting me with experimental work and addressing related queries. My heartfelt appreciation goes to my STEP4WIND colleagues and friends—Felipe, Matteo, Likhitha, Deepali, Alejandro, Huzaifa and Ricardo—for the enjoyable times shared during project events and beyond.

My deepest and most heartfelt thanks to my wife Melanie Grohmann, for her unwavering love, boundless patience and unending support throughout this journey. Her encouragement, understanding and sacrifices have been the cornerstone of my perseverance and strength.

To my father, Ramachandran, mother, Bindhu, and brother, Sunil — thank you for your unwavering encouragement and support and being a consistent source of strength and motivation.

Lastly, my gratitude to the European Commission for funding my PhD, with special thanks to Dr. Axelle Viré and Oana Trifan for their coordination.

Abstract

Floating Offshore Wind Turbines (FOWTs) represent a pivotal advancement in renewable energy technology, extending the reach of wind power to previously inaccessible waters. Their importance lies in their ability to exploit the stronger and more consistent winds in deep waters. Installing these floating platforms in sites where the weather is harsh invites significant challenges. A major challenge lies in towing these platforms from the fabrication site to the farm location. The commercialisation of floating wind aims at farm-scale deployments and installation of large wind turbines. For planning fast, cost-effective and safe towing operations, the understanding of its physics is paramount. It is also important to develop numerical methods and simulation approaches to understand and predict the motions and towing loads while towing these significant floating structures. This thesis constitutes a deep exploration of the towing operations associated with floating wind turbines, integrating a multifaceted analysis encompassing case studies, experimental tests and numerical methodologies. Semi-submersible floaters, being one of the early movers, are the main focus of this thesis.

The presented thesis has followed an ‘industry-ready’ approach and aims at minimising the gap between academia and industry by attempting an equilibrium between them. The thesis is split into four research papers and starts with a literature review examining marine operations integral to floating wind turbines, identifying specific challenges and finding opportunities for synergy with other well-established and developed offshore industries such as Oil and Gas (O & G) and fixed-bottom wind industries.

Towing operations, being required for installation, major repairs and decommissioning are then analysed and two numerical approaches for the hydrodynamic analysis of semi-submersible floating wind turbines are developed and implemented in two different commercial hydrodynamic analysis tools. The first method is a potential flow-based forward speed approach with corrections for viscous effects implemented in the in-house tool SEACAL. The second method is a hybrid approach utilising a potential flow method combined with the Morison equation and implemented in the commercial tool Orcaflex. The hybrid approach is also implemented in a free open-source numerical tool OpenFAST for the further development of the research work.

To validate the numerical results, a detailed experimental campaign was conducted and validation data for towing in various sea conditions, towing configurations and towing speeds were generated. A comparative study of both approaches is presented and the advantages and disadvantages of the developed methods are summarised.

The findings indicate that both developed numerical models possess the capability to analyse and predict towing characteristics contingent upon towing speed and prevailing wave conditions. The first method is better suited to considering low speeds (0.514 m/s–1.542 m/s) and low wave heights (1m – 2m) whilst the second method is better suited for higher speeds (0.514 m/s – 3.084 m/s) and higher wave heights (1m – 6m). Depending on the weather conditions, towing requirements and availability of the numerical tools, the suitable analysis method can be chosen.

List Of Abbreviations

FOWT	Floating Offshore Wind Turbine
FOWF	Floating Offshore Wind Farm
O & G	Oil and Gas
O & M	Operation and Maintenance
DNV	Det Norkse Veritas
NREL	National Renewable Energy Laboratory
TLP	Tension Leg Platform
MW	Mega Watt
LCOE	Levelised Cost of Energy
MARIN	Maritime Research Institute Netherlands
HSE	Health Safety and Environment
CFD	Computational Fluid Dynamics
FIM	Fluid-Induced Motions

List Of Publications

This thesis is presented as a compilation of the following four papers presented as chapters. The author of this thesis (first author on all four papers) carried out the research work presented in the four publications and the co-authors supervised the work and collaborated in the reviewing process.

- **Chapter II** - Chitteth Ramachandran, R., Desmond, C., Judge, F., Serraris, J. J., & Murphy, J. (2022). Floating wind turbines: marine operations challenges and opportunities. Wind Energy Science, 7(2), 903-924.

- **Chapter III -** Chitteth Ramachandran, R., Otter, A., Serraris, J. J., de Ridder, E. J., Desmond, C., & Murphy, J. (2023, October). A study of the towing characteristics of a semi-submersible floating offshore wind platform. In Journal of Physics: Conference Series (Vol. 2626, No. 1, p. 012043). IOP Publishing.

- **Chapter IV** - Chitteth Ramachandran, R., Serraris, J. J., Hernandez Montfort, J., de Ridder, E. J., Desmond, C., & Murphy, J., Towing analysis and validation of a fully assembled floating offshore wind turbine based on experimental study, Journal of Marine Science and Engineering, 2024; 12(4):689

- **Chapter V** - Chitteth Ramachandran, R., Serraris, J. J., Hernandez Montfort, J., de Ridder, E. J., Desmond, C., & Murphy, J., An analysis of floating wind turbine towing operations using OpenFAST. Published in Journal of Physics: Conference Series (Vol. 2875, No. 1, p. 012035). IOP Publishing

Chapter 1

Introduction

1.1 Context

The global energy landscape is undergoing a seismic shift, marked by a profound transition from fossil fuels, towards renewable energy sources. The transition is driven by growing concerns over carbon-dioxide emissions which fuel global warming resulting in the catastrophic effects of climate change. It is paramount to develop renewable energy technologies as viable alternatives to support the growing energy needs around the world. Wind energy is considered one of the crucial energy sources as a means of generating clean electricity. Wind turbines are strategically positioned onshore or offshore to capture the kinetic energy of wind and convert it into electricity. In the offshore sector, fixed-bottom wind turbines were the early-movers and the technology has evolved over the years propelling the expansion of offshore energy production. While fixed-bottom wind turbines have been pivotal in establishing offshore wind farms in shallow waters, the pursuit of stronger, consistent winds and greater development opportunities has led to the emergence of Floating Offshore Wind Turbines (FOWTs). Unlike fixed-bottom wind turbines, FOWTs are structures installed in deep waters which are secured to the seabed through mooring lines, tethered using tendons (TLPs) or in some cases, using dynamic positioning systems for station-keeping.

While the technology for floating turbines is still evolving, significant progress has been made in the conceptual design of various types of floaters suitable for floating wind turbines, but the research in installation, operation, maintenance and decommissioning phases is lacking. A few floating wind farms are already operational in different parts of the world and large-scale deployments are on the horizon. FOWTs offer the unique opportunity for fully constructing the wind turbine system at the quayside or sheltered waters and towing them to farm locations using ocean-going tugs. The installation of FOWTs in exposed deep waters involves significant challenges due to

the harsh prevalent metocean conditions at the farm location and along the towing route from the port/quay to the farm. Similar challenges can be expected during operation and maintenance activities also, particularly if towing to port for major repairs. Decommissioning, which can be considered as a reverse-installation process, will also include significant marine operations, the viability of which will also depend on the prevailing metocean conditions (e.g., wind, waves and currents).

These marine operations largely depend on the type of floater used for supporting the wind turbine. Having a thorough understanding of the diverse marine operations pertinent to the entire lifecycle of the wind farm is essential. During the design phase, integrating and applying this knowledge is crucial for refining the process. In this pivotal scenario, characterised by the imminent scale-up of floating wind development around the world, it remains imperative to analyse and understand the role of marine operations. Towing operations are critical during the installation of a floating wind farm. There is a shortage of tug vessels with sufficient bollard pull for towing the floating wind turbines and this can affect the costs. During a major repair campaign of the Kincardine wind farm, tug vessels with a bollard pull higher than 200 tons were chartered at record-high rates in over a decade [1]. These elevated rates were due to the construction of the Hywind Tampen project which was taking place at the same period in Norway. This highlights the importance of carefully planning towing operations in the context of floating wind farms along with the extreme shortage of suitable vessels to carry out these operations for the pipeline of full-scale commercial developments currently under consideration.

Classification societies and regulatory bodies have defined general rules and limiting conditions while planning and executing various marine operations. Often marine operations need to wait for opportune weather windows when factors like wind speed, wave height and sea currents align within predetermined safety parameters, allowing for the safe and efficient execution of tasks. To calculate weather windows and limiting sea conditions a thorough understanding and accurate prediction is necessary. For example, motion limits are defined by classification societies during towing and it is necessary to check the weather conditions in which these limits will be exceeded. Accurate calculations of the dynamic response of FOWTs are required here to predict the weather windows. This thesis focuses on understanding towing operations and defining

methods for calculating the hydromechanical response of fully-constructed semi-submersible FOWT systems towed in various wave conditions.

The work presented in the thesis has been supported by the STEP4WIND project, a European Industrial Doctorate programme, granted under the H2020 Marie-Curie Innovative Training Network initiative (H2020-MSCA-ITN-2019, grant agreement 860737). The program runs between April 2020 and March 2024 and will deliver 10 PhD degrees, in joint supervision and training between the public and private sectors. The main objective is to address both technological and economic challenges related to the development of floating offshore wind farms. The thesis also presents the work carried out at the Maritime Research Institute Netherlands (MARIN), a leading maritime research and testing facility in the world, with over a century of expertise in the maritime domain. MARIN, as a beneficiary, has supported the work by providing the experimental facility, expertise and the necessary software for numerical simulations and for analysing the experimental results.

1.2 Research questions

As FOWTs get bigger in size to accommodate larger turbines and reduce the levelized cost of energy (LCOE), the complexity of marine operations, particularly towing, increases significantly. The construction of large FOWFs involves multiple towing voyages to transport fully assembled floating offshore wind turbines (FOWTs) from ports to installation sites. This critical stage of the project faces numerous challenges, including the need for precise planning and execution in often limited weather windows. The ability to tow these massive structures efficiently and safely can influence overall project timelines and costs, making towing optimization a key area for study.

The optimization of towing operations for FOWTs requires an in-depth understanding of several factors, such as towing speed, vessel requirements and the impact of varying sea states on the motion and stability of the platform. Figure 1 shows the scale of the various components involved in a long towing operation. The dimensions may vary depending on the size of the towed FOWT. Weather conditions, such as wind, waves and currents, directly affect the speed and safety of towing operations, while vessel bollard pull capacity and other operational limits also play a crucial role. By examining these elements, this research aims to identify the limiting factors that influence FOWT towing operations and propose methods to optimize the

process, ultimately contributing to more efficient and cost-effective wind farm deployment.

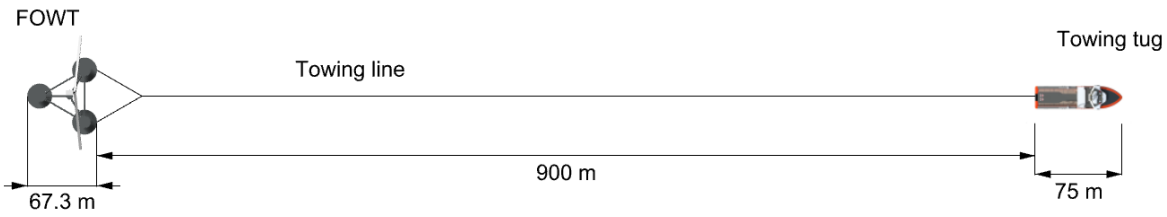


Figure 1: Scale of various components of a long towing operation

There is a significant knowledge gap here as usual towing analysis methods are derived from oil and gas platform towing operations, which do not fully address the unique dynamics of FOWTs, such as the presence of a delicate wind turbine structure, specific structural loads and the necessity of repeated towing operations. Furthermore, the lack of validated experimental data limits the accuracy of numerical models used for towing analysis, making it difficult to optimize towing operations in real-world conditions. This gap in understanding may lead to longer installation times, increased costs and safety concerns. Addressing this knowledge gap is vital for the future scalability and commercial success of large-scale floating wind farms. Based on these observations, this thesis attempts to answer the following research questions:

- What are the key challenges in marine operations faced throughout the lifecycle of a large wind farm?
- What is the essential marine operation that is relevant to all types of floaters?
- How can FOWT towing be optimised?
- How fast can FOWTs be towed?
- What are the limiting weather conditions?
- What are the vessel/bollard pull requirements?
- Are there other limiting factors affecting towing operations?
- What are the best numerical tools for analysis?
- How can these numerical tools be validated?

1.3 Objectives & Scope

The floating wind industry is entering the commercialisation stage where researchers, companies and governments are exploring methods for reducing the costs associated

with the deployment of large floating wind farms. Safe and cost-effective installation, operation and maintenance activities are crucial. Regardless of the type of floater, towing operations play an important role among the marine operations required throughout the life cycle of a floating wind farm. It has been shown that the size of the wind farm has a huge impact on the LCOE for floating wind farms [2]. The upsizing of the wind turbine and plant also has a substantial impact on the LCOE [3]. It is evident that the industry is headed toward large wind turbines and large wind farms for reducing the LCOE. Depending on the location of the wind farm, the towing vessels need to tow a large number of platforms in the available weather windows and this process requires a good understanding of the towing limits and vessel requirements. This thesis analyses the FOWT-related towing operations and presents methods to analyse them numerically. The main findings are presented as research papers. The primary objectives are:

1. **Analysis of various marine operations concerning FOWTs**: A comprehensive analysis of marine operations required during installation, O&M and decommissioning activities and identification of the various inherent challenges. Many marine operations are similar to O&G (Oil and Gas) and fixed-bottom wind industries, these synergies are identified and how they may be adopted for use in the floating wind industry is discussed.

2. **Development of a framework for analysing towing operations**: Given the significance of towing operations at each phase of a floating wind farm, it becomes imperative to adopt a systematic framework for the analysis of these operations numerically. The towing of a fully assembled FOWT is complex due to the presence of the delicate wind turbine structure and machinery onboard. Towing of an O & G floating platform is usually a one-off process compared to FOWTs which are usually planned for farm-scale deployments with multiple repeated towing operations. The objective is to develop a framework which provides a systematic approach to optimise the towing operations for developing a large floating wind farm.

3. **Experimental analysis of towing operations**: In order to achieve a full understanding of towing operations both physical and numerical modelling are

required. Due to the lack of experimental data, the objective is to conduct experimental studies and collect high-quality validation data.

4. **Numerical modelling of towing operations**: Prediction of hydrodynamic motions, accelerations and towing loads is imperative for assessing the limiting environmental conditions. The objective is to analyse the suitability of commercial numerical tools in predicting these towing characteristics.

5. **Assessment of a practical numerical tool for analysing towing operations**: To develop and advance further research it is important to use a free and open-source analysis tool. OpenFAST is a free open-source numerical tool used for the aero-servo-hydro-elastic simulations of offshore and onshore wind turbines. The objective is to explore the feasibility of adapting this numerical tool for the analysis of towing operations.

1.4 Methodology

The methodology adopted to realise the objectives mentioned in the previous section is presented here. A systematic approach was taken and the methodologies employed to understand the towing characteristics of FOWTS are explained. The steps taken are as follows:

1. Literature review and analysis
    a. Explore relevant literature sources and gather information from research articles, publications and reports on floating wind technology, marine operations and hydrodynamic analyses.
    b. Identify areas of overlap with other well-developed offshore industries and the gaps in the knowledge. Assess the existing numerical models, methodologies and experimental studies pertinent to FOWT-towing operations.

2. Analysis of the hydrodynamic aspects of towing
    a. Develop/adopt a framework for analysing towing operations by including the knowledge obtained from the literature review.

b. Analyse the hydrodynamic aspects of towing FOWTs within the framework.

c. Perform a basic hydrodynamic analysis and develop an understanding of the dynamic response of floaters while towing, the applicable limiting factors and metocean limits.

3. Experimental study

   a. Plan a detailed experimental campaign considering various towing configurations, wave conditions and platform responses.

   b. Conduct the towing experiments and gather quantitative data on the dynamic response of FOWTs, towing loads and wave interactions.

4. Numerical model assessment

   a. Assess existing numerical models and tools used for the hydrodynamic analysis of floating bodies.

   b. Investigate and develop analysis approaches for modelling the towing of a semi-submersible FOWT.

   c. Implement the developed analysis approaches in commercial as well as open-source tools.

   d. Perform numerical simulations using the adopted numerical models and derive platform responses and towing loads.

   e. Validate the numerical models using the data obtained from the experimental tests.

5. Comparative study

   a. Compare the results derived from the developed numerical models on the basis of the agreement with the experimental results. The advantages and shortcomings of these models are analysed in detail.

6. Conclusions and further work

   a. Synthesise and present findings from numerical simulations, experimental studies and their comparative analyses.

b. Conclude with insights on towing operations' behaviours, strengths and limitations of the developed numerical approaches and suggest recommendations for further research.

1.5 Outline

The thesis is organised as a compilation of four interconnected research papers, collectively contributing to an in-depth comprehension of towing operations within the life cycle of floating wind turbines. Figure 2 illustrates the thesis layout, demonstrating how the presented papers are connected to the research questions and how each question is addressed.

1. **Research paper A: Floating wind turbines: marine operations challenges and opportunities**

This paper is presented as Chapter 2 of the thesis. This is a review article analysing the various marine operations in the context of FOWTs. The construction of existing wind farms around the world is analysed based on the type of floater used in the farms. The important factors to be considered while planning floating wind farms are analysed and presented. The various innovations applicable to large-scale wind farms are analysed on the basis of the marine operations involved. The paper is aimed as a guideline for the industry while planning the construction of floating wind farms. The relevant considerations and recommendations have been identified and documented. It was found that towing operations are the most significant marine operations required for all floating wind farms irrespective of the floater type. This paper was published in the Wind Energy Science Journal.

2. **Research paper B: A study of the towing characteristics of a semi-submersible floating offshore wind platform**

The preceding paper highlights the significance of towing operations, necessitating a thorough analysis. This paper presents and analyses a framework for analysing and optimising towing operations. Various physical phenomena that should be considered while towing large floating platforms are also presented. An experimental study was conducted using an available FOWT platform model at installation draught, assessing its motion, dynamic response and towing loads while being towed in calm water and head waves. A numerical model was developed and the motions were analysed. Subsequently,

an analysis was performed to check the limiting factors and their effects on towing operations. This paper was presented at the Deepwind 2023 Conference and was subsequently published in the Journal of Physics. This paper constitutes the third chapter of the thesis.

3. **Research Paper C: Towing analysis and validation of a fully assembled floating offshore wind turbine based on experimental study.**

From the previous paper, the importance of calculating the motion response of FOWT platforms and the importance of identifying the limiting conditions were established. During the previous tests, since the platform draught was unable to be modified, the tests were performed in the installation draught. As this was not sufficient, another test campaign was conducted and this paper outlines the outcomes derived from this experimental campaign that tested the towing of a fully assembled semi-submersible platform in various towing configurations, speeds and wave conditions. The paper highlights significant observations drawn from the experiments. Additionally, two numerical analysis methodologies are presented along with simulations that were carried out to analyse the towing behaviour of the platform. The methodologies were implemented in a commercial tool Orcaflex [4] and an in-house developed tool SEACAL respectively and the results are discussed. The simulation results are compared against the experimental results and validated. This paper has been published in the Journal of Marine Science and Engineering. An uncertainty analysis of the experimental data has also been performed and added to the research paper.

4. **Research Paper D: An analysis of floating wind turbine towing operations using OpenFAST**

The two methodologies presented in the previous paper were implemented using commercial software suites which are usually closed-source and expensive. OpenFAST [5] is a free open-source numerical tool used for aero-hydro-servo-elastic simulations of floating wind turbines. A novel innovative method for modifying the OpenFAST input files and using it for analysing towing operations is presented in this paper. This paper was presented at the Deepwind 2024 conference in Norway and has been published in the Journal of Physics: Conference series. An exploratory analysis ascertaining the effect of wind on towing has also been performed and added to the paper.

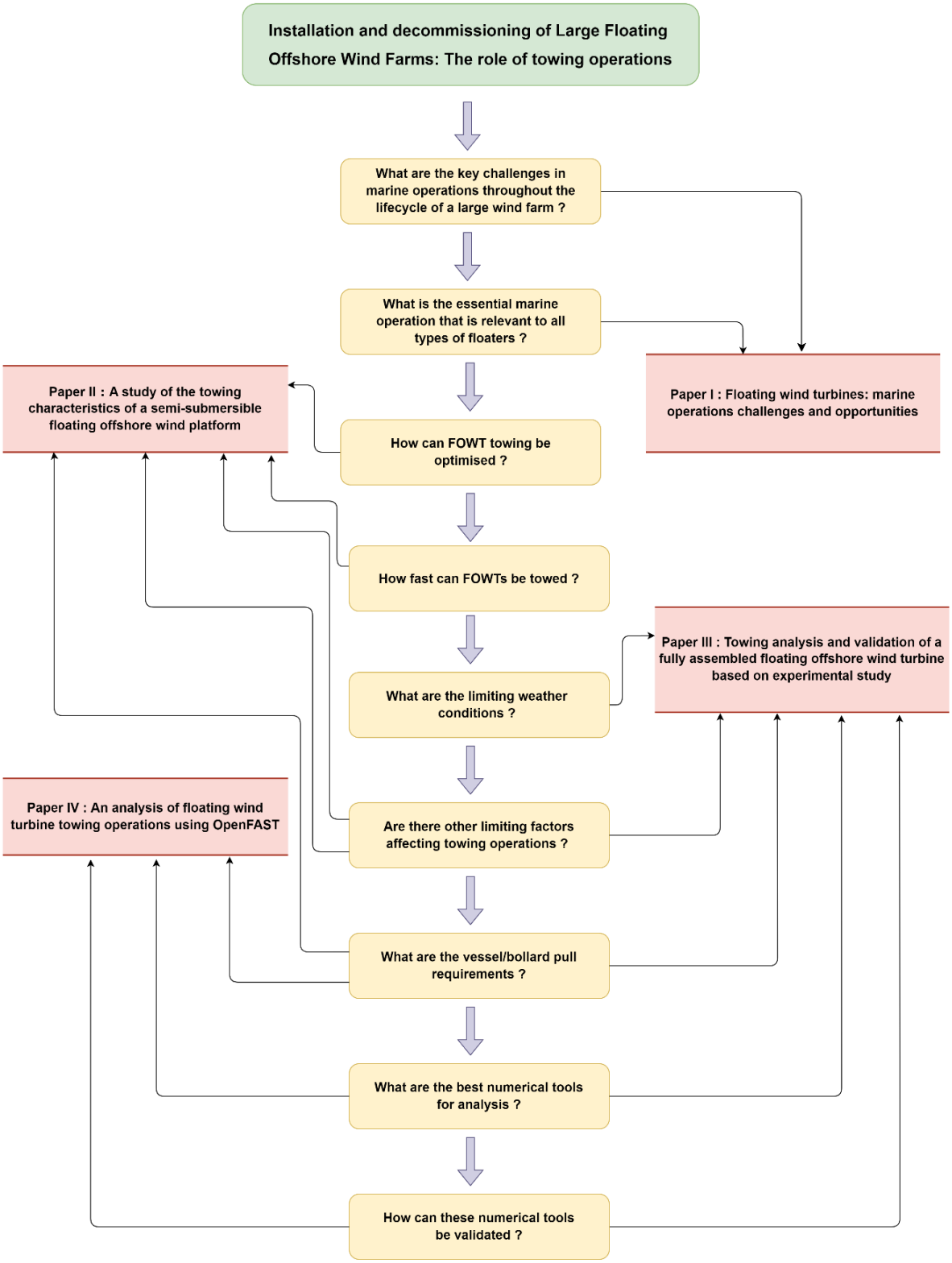


Figure 2: Thesis layout

Chapter 2

Marine operation challenges and opportunities: Paper A

2.1 Motivation and Aim

This review paper analyses the marine operations associated with the installation, O&M and decommissioning of FOWTs. Numerous marine operations are required during the whole lifecycle of floating wind farms and they vary according to the type of floater used for supporting the wind turbine. A critical initial step involves identifying the relevant marine operations corresponding to various floater designs utilised in existing floating wind farms. These floating wind farms were analysed and the installation, O&M and decommissioning strategies were investigated for reducing the costs associated with floating wind turbines and to enhance the safety and environmental sustainability of these marine operations.

Many of these floater designs have been already used in the O & G industry for floating platforms and the technology is relatively mature. In this regard, leveraging these established technologies for floating wind purposes proves advantageous. Existing knowledge within this domain can be readily adopted and applied to the floating wind sector. However, this adaptation also presents several challenges. This paper assesses both the opportunities and challenges involved in this technological transfer.

The paper commences with an examination of global existing wind farms, collating information from diverse sources, particularly focusing on their installation processes. Furthermore, it outlines and evaluates the relative merits and drawbacks linked to prevalent floater types.

The subsequent phase involves identifying both challenges and opportunities. Leveraging existing knowledge obtained from the O&G and fixed-bottom wind industries, an exploration into their applicability within the floating wind sector is undertaken. All maritime operations are contingent upon sea conditions for execution, emphasising the critical need to expand weather windows. Metocean assessment and prediction take precedence and are thoroughly explored. Various methodologies for this purpose are introduced and evaluated. Additionally, this study delves into examining and presenting metocean constraints applicable to diverse floaters and vessels utilised in these processes. An analysis of the assorted costs linked to floating wind farms and their Health, Safety, and Environment (HSE) considerations are also conducted and elucidated upon.

Since floating wind turbines enable farm-level deployments, many innovations can be tailored to suit their needs. This paper provides insights into the innovations suitable for floating wind farms, which, in turn, introduce challenges across diverse marine operations. The analysis herein is conducted within this specific context.

Conducting this literature review and study highlighted the significance of a single marine operation that is important for all types of floaters and throughout the lifecycle of any wind farm – towing. Developing large wind farms necessitates a comprehensive understanding of towing operations. Presently, towing operations primarily rely on experiential approaches during execution, with most decisions left to the tugboat captain. Introducing a science-based approach to towing operations is pivotal for enhancing their methodology.

Floating wind turbines: marine operations challenges and opportunities

Published in

Wind Energy Science Journal, eISSN: WES 2366-7451, WESD 2366-7621

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Abstract. The global floating offshore wind energy industry is rapidly maturing, with several technologies having been installed at pilot and demonstration scales. As the industry progresses to full array-scale deployments, the optimisation of marine activities related to installation, operation and maintenance, and decommissioning presents a significant opportunity for cost reduction. This paper reviews the various marine operations challenges towards the commercialisation of floating wind in the context of spar-type, semi-submersible and tension leg platform (TLP) technologies. Knowledge gaps and research trends are identified along with a review of innovations at various stages of development, which are intended to widen weather windows, reduce installation costs, and improve the health and safety of floating-wind-related marine operations.

A.1. Introduction

Wind turbines are moving further offshore to deeper waters and are exploiting higher wind speeds in harsher environments (McCann, 2016). This trend creates additional challenges in the design, installation, operation, maintenance and decommissioning phases of an offshore wind farm. Numerous investigations for developing efficient and optimum floating offshore wind turbine (FOWT) platforms and various innovative design concepts have been evolving in the last few years (Uzunoglu et al., 2016; EWEA, 2013). Several pilot- and demonstration-scale floating wind farms are now operational in different parts of the world (e.g., WindFloat Atlantic – Portugal (25 MW), Hywind Scotland (30 MW)), and there is a robust pipeline of projects which is expected to deliver 250 GW installed floating capacity by 2050 (DNV, 2020; James and Ros, 2015).

To realise this ambition, significant reductions in LCOE (levelised cost of energy) will be required across all key stages in the development of a floating wind farm. Numerous marine operations are required in the last three stages of the floating wind farm life cycle (see Figure 1). Marine operations represent a significant proportion of the offshore wind energy costs. Approximately 15.2 % of CAPEX (capital expenditure), 50 % of OPEX (operational expenditure) and 80 % of DECEX (decommissioning expenditure) are directly related to marine operations for a bottom-fixed wind farm (Judge et al., 2019). Comparative figures for the floating-wind-energy industry are unavailable due to a lack of projects; however, investigations by Castro-Santos (2016) show that approximately 36 % of the total floating project costs are

incurred during the installation, exploitation and dismantling activities. Castro-Santos et al. (2018a) have revealed that the size of the floating wind farms has a considerable impact on installation costs and LCOE. It was found that the LCOE reduces as the farm size increases.



Figure 1: Stages in the development of a wind farm.

Given the nascent nature of the floating-wind-energy industry and the lack of established best practices, these operations present a significant scope for optimisation and cost reduction. The FOWT industry has a significant second-mover advantage and can benefit from the technical expertise and innovations developed in the offshore oil and gas (O & G) and bottom-fixed wind turbine industries. However, the deployment of highly dynamic unmanned floating platforms is unprecedented and requires the development of bespoke solutions to reduce the cost and increase the safety of installation-, operation and maintenance (O & M) and decommissioning-related marine activities.

There is overlap across the life cycle for the various technologies and procedures for floating offshore wind turbines. For example, assessment and prediction of metocean conditions are always required for installation, O & M and decommissioning of floating wind farms. Towing vessels are also required in all these operational phases of a wind farm. So, it is beneficial to combine all the studies in those areas and investigate all of them together instead of treating them separately. The marine operations vary depending on the floater used; hence while selecting the floater, it is important to have a firm understanding of the marine operations required in each phase of its life cycle. Since marine operations represent a significant proportion of the total costs incurred for a wind farm, this knowledge aids the precise modelling of the costs. Many innovations have been recently introduced or adapted from other industries to take advantage of array-scale deployments possible for FOWTs. These innovations are also needed to be examined from a marine operation point of view. Since the floating-wind domain is new and maturing, there is a shortage of literature that focuses on marine operations. This

paper examines the various challenges and opportunities concerning marine operations during installation, O & M and decommissioning phases of a floating wind farm.

A.2. Installation, O & M and decommissioning of FOWT floater types

Floating wind platforms can be mainly classified into three broad categories according to the restoring mechanism for attaining hydrostatic equilibrium. They can be ballast-stabilised, buoyancy-stabilised, mooring-stabilised or combinations of these (Leimeister et al., 2018; Banister, 2017; Booij et al., 1999). Figure 2 demonstrates how the different FOWTs developed around the world fit into a stability triangle. Most floaters belong the inside region of the triangle as 100% stabilisation is not possible with one single stabilising mechanism. The stability of a platform depends on many factors and the stability triangle is a simplified representation. The stability of the platform is a result of a combination of buoyancy, gravity and mooring loads. If the centre of gravity of a platform is above the centre of buoyancy, the platform suffers from a loss of stability. In such situations, mooring lines or solid ballast provide the required stability.

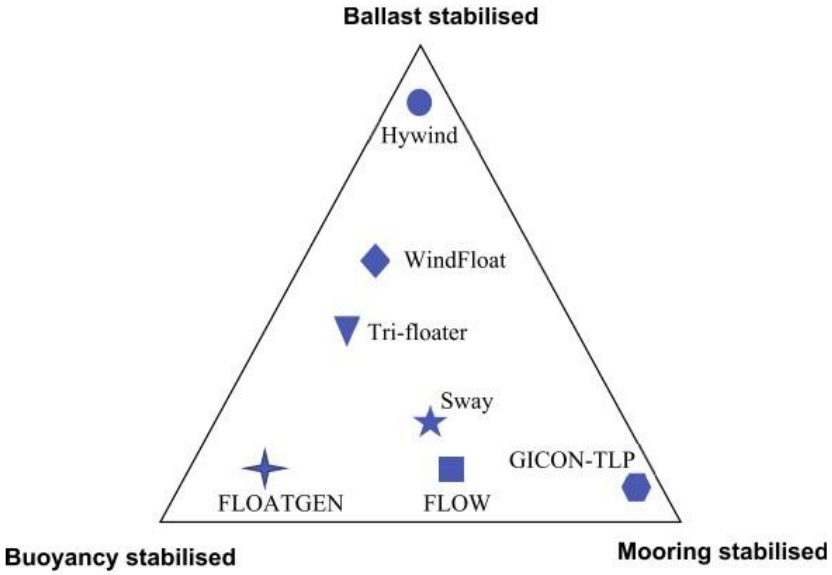


Figure 2: Stability triangle for floating structures (Jiang, 2021).

Generally, the installation of floating wind turbines requires a greater number of vessels compared to bottom-fixed wind turbines, but the vessels are cheaper to hire and easily available (Crowle and Thies, 2021). Even though many floating-wind concepts have been developed, only a few have been successfully deployed and commissioned at a commercial level. In the following sections, a review of the projects that have reached

the Technology Readiness Level 7 (TRL7) (EC, 2017) or above is provided with a focus on the marine operation strategies which they employed.

A.2.1 Spar type: Hywind Scotland project

Hywind Scotland is a floating offshore wind farm which has a rated capacity of 30 MW, produced from five 6 MW turbines, and has been functioning since 2017 (Equinor, 2022b). The spar-type floater, namely the Hywind concept, was developed by Equinor ASA (Equinor, 2022b; Skaare, 2017). A 2.3 MW demo (TRL 8) (OREC, 2015) was deployed on the west coast of Norway in 2009 for a test run of 2 years (Butterfield et al., 2007; Equinor, 2022b). Following the demonstration, a wind farm was installed 30 km off the coast of Aberdeenshire, Scotland. The farm has an area of approximately 4 km^2 and an annual average significant wave height of 1.8 m (Mathiesen et al., 2014).

The spar-type substructures have high draughts which require the use of offshore assembly. The installation phase also requires sheltered coastal waters (maximum significant wave heights are up to 0.5 m and a Beaufort wind force 4; (DNV, 2015)) for some operations. This is a challenge as sheltered waters with high depths are required near the construction sites due to the high draught of the floaters. They should either be available near the ports or be made by dredging. The first marine operation was the installation of the suction anchors and the mooring lines. The floaters were first wet-towed out into a sheltered area using tugboats. Then they were upended using water ballast. Later, the water was pumped out and solid ballast (magnetite) was filled using a rock installation vessel. The tower-and-rotor assembly was mated with the floater later (Jiang, 2021). This was done using the heavy-lift vessel, Saipem 7000 (Saipem, 2017). A notable feature of the Hywind installation was the use of this expensive heavy-lift vessel. Figure 3 shows the various stages of the installation of this wind farm. Significant cost cuts may be achieved by innovative installation methods in the future by avoiding the use of such vessels. After the mating, the wind turbines were towed to the location of the wind farm. They were then connected to the pre-installed mooring lines and final ballast corrections were performed.

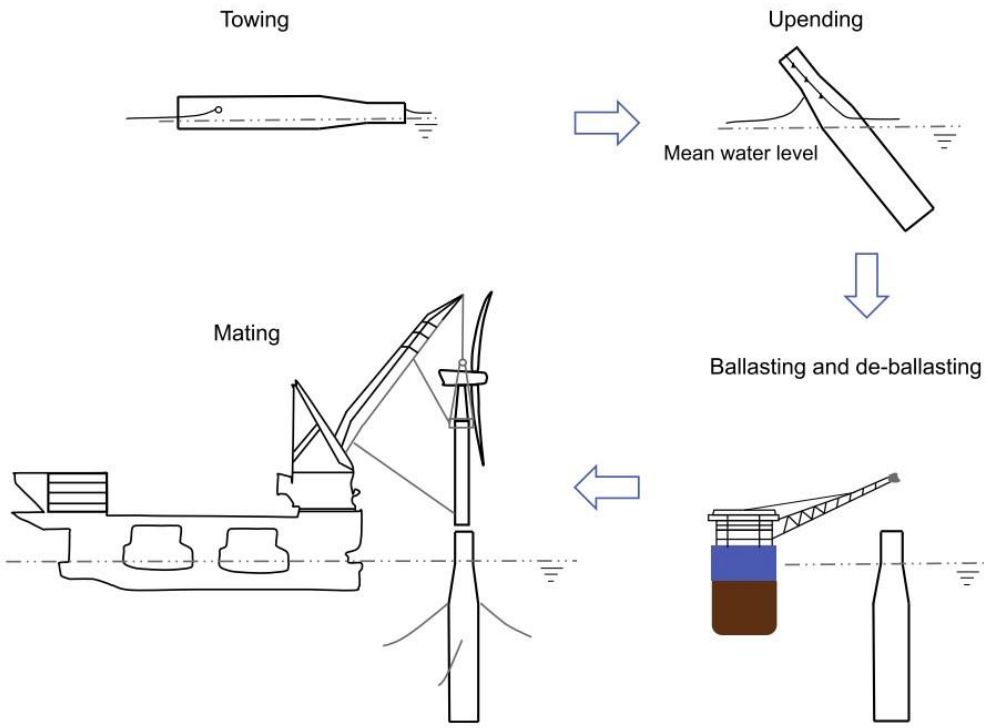


Figure 3: Stages in the installation of the Hywind Scotland spar-type platforms (Jiang, 2021).

Metocean assessments were performed before the commencement of the project to check for suitable weather windows for marine operations. The duration characteristics of marine operations were predicted for various limiting conditions of wind and waves for a full year (Mathiesen et al., 2014). The months from April to September were found to have the widest operational time windows. The inshore assembly (upending, solid ballasting, heavy lift) and offshore installation operations (anchor and mooring, transfer and installation of wind turbine generators, cables) were scheduled and carried out in this period.

The operation and maintenance of the wind turbine mounted on the spar-type substructure are similar to that of a bottom-fixed offshore wind turbine. A campaign-based inspection and monitoring scheme is planned for the FOWTs. Maintenance and repairs of the sub-sea systems (foundation, mooring system, cables) will follow a different approach. Periodic sub-sea inspections and maintenance will be performed using ROVs (remotely operated underwater vehicles). Scour might also be an issue concerning the Hywind spar-type platforms as they employ suction anchors. Heavy component exchanges up to 2 t will be performed using the platform crane and a crew transfer vessel (CTV). Heavier components like the transformer can be exchanged using

a dynamically positioned offshore service vessel. In the case of even larger components, the turbines have to be towed to a sheltered region, and exchange will be carried out using heavy-lift vessels (H. H. Hersleth, 2016).

The decommissioning of the spar-type platforms could be more expensive compared to other types of platforms. The platform has to be partially decommissioned in deep water due to the high draughts before getting towed to the quayside. The blades, nacelle and tower can be dismantled using a heavy-lift vessel; this incurs additional costs. The mooring lines and anchors also must be retrieved. Easily recoverable anchors can reduce decommissioning costs and time. There is scope for further investigations to develop cheaper and easy decommissioning strategies of spar-type FOWTs.

A.2.2. Semi-submersible type: WindFloat Atlantic and Kincardine projects

In 2011, Principle Power installed a prototype semi-submersible FOWT, namely WindFloat, 5 km off the west coast of Portugal (Roddier et al., 2010). This was followed by the installation of a 25 MW floating wind farm on the west coast of Portugal. The wind farm consists of three MHI Vestas 8.4 MW turbines mounted on Principle Power's semi-submersibles (Banister, 2017). The installation operations were carried out with the help of tugs, AHTS (anchor handling tug supply) vessels and ROV-support cable-lay vessels supplied by Bourbon Offshore (Ocean-Energy-Resources, 2020). The towing operation took 3 days, taking the completely assembled FOWT from the port of Ferrol, Spain, to the farm located 20 km off the coast of Viana do Castelo, Portugal. The AHTS, Bourbon Orca (Ulstein, 2022), was used for the operations, which is an advanced vessel with a bollard pull of 180 t and a maximum speed of 17.1 kn. Most AHTSs were constructed to serve the O & G industry, but they make a good choice for floating wind farm installation since there is good availability, and they can be used for the installation of anchors and for towing purposes. One of the floaters was loaded out and floated off using a semi-submersible barge, Boskalis Fjord. Compared to the Hywind project, specialised expensive heavy-lift crane vessels were not employed here. Castro-Santos et al. (2013) has observed that the installation of anchoring and mooring systems is less expensive using an AHTS compared to a combination of barges and tugboats.

The Kincardine offshore floating wind farm is another project which employs semi-submersible floaters for the wind turbines (offshorewind.biz, 2021). The wind farm is located 15 km off the coast of Aberdeen, Scotland. It features a wind farm with a

nameplate capacity of 50 MW. All of the floaters were constructed in Fene, Spain, and transported to Rotterdam for mounting the 9.6 MW wind turbines (Umoh and Lemon, 2020).

Semi-submersibles are buoyancy-stabilised floaters. The stabilising righting moment is contributed either by the large water-plane area of the hull or small cross-sectional areas at some distances from the central axis (Leimeister et al., 2018). They can be fully constructed and assembled onshore. The installation of mooring systems is less expensive compared to other types of floaters, which makes semi-submersibles one of the most cost-effective solutions from an installation point of view (Liu et al., 2016). However, the construction costs are higher compared to other types of floaters since they are larger and heavier structures (James and Ros, 2015). The semi-submersible wind turbines are completely constructed onshore and towed to the wind farm location and connected to the pre-installed mooring lines. Light drag-embedded anchors can be used for semi-submersibles. The main challenge in the installation process is finding the right weather window for the marine operations as they are more sensitive to wave heights during towing (Banister, 2017).

The installation of the three FOWTs in the WindFloat project took place in October 2019, December 2019 and May 2020, respectively (EDP, 2019, 2020). It is very important to assess the weather windows and downtime before commencing marine operations. Another important aspect to be considered is the safe havens. Towing of FOWTs is a continuous operation, and it is difficult to halt the operation during the process. Safe havens should be identified along the route of the towing operation to avoid difficulties in case of harsh weather. Some of the floaters in the WindFloat and Kincardine projects were constructed at a different location and transported to the assembly port using specialised heavy-transport vessels. This can be avoided by carefully choosing the right port with shipyard facilities where the complete construction and assembly of the FOWT can be carried out.

Operation and maintenance activities can be carried out either offshore or onshore (Banister, 2017). The periodic inspections, preventive maintenance and repair activities will be performed in situ (i.e. at the platform location). In case of large corrective maintenance or repair activities, the platform can be towed to a sheltered location or port. No heavy-lift vessels are required and local vessels can be used for

towing. This is beneficial in terms of promoting the use of local content and adhering to regulations such as the Jones Act (B.Cheater, 2017), which requires the usage of US-built ships for marine operations in the US waters. Due to the large size of the floater, helipads can be constructed aboard, which make access by helicopters possible. During decommissioning, the platform can be towed to shallow water or taken out of the water completely inside a dry dock and dismantled.

A.2.3. Other upcoming projects

The Floatgen project by Ideol (France) is another project that employs barge-type substructures (Alexandre et al., 2018; Ideol, 2021). They can be fabricated using steel and concrete, which can help promote the use of local content and employment. The damping pool technology developed by Ideol is designed to stabilise the floater in harsh sea conditions. Two demonstration projects have been in operation since 2018, and pre-commercial and commercial projects are expected to be launched in the coming years (Ideol, 2021).

Another floater concept is the tension leg platform (TLP), which is widely used in the offshore O & G industry. This concept has also been adapted from the O & G industry for the FOWTs. Tension-leg-platform wind turbines (TLPWTs) are well suited for intermediate water depths. The depth varies from 70 m, which is an approximate upper limit for fixed wind turbines, to 200 m, beyond which the spar-type platforms are considered to be the most economical option (Bachynski and Moan, 2012).

In 2008, Blue H Technologies successfully installed a prototype in Italy as a predecessor of commercial-scale TLPWTs (Adam et al., 2014). Even though many concepts have been developed and a few prototypes have been reported, commercial-scale TLPWTs are still not a reality. The installation of a conventional TLP system is a complex process. The tendons, which hold the platform in place, are usually installed before the platform. The TLP floater is constructed onshore and towed to the location using tugboats or transported using a bespoke barge. The platform is ballasted and connected to the pre-installed tendons. Finally, the platform is de-ballasted to a draught where the tendons attain the optimum tension, and the TLP is secured. The nacelle acceleration and the dynamic tension on the mooring lines are the critical operational parameters here. Low nacelle accelerations are required for the reliable operation of the wind turbine, and low mooring line tensions ensure low weights of gravity anchors and

longer fatigue lives. Sclavounos et al. (2010) investigated the hydrodynamic performance of the TLP in various significant wave height and water depth conditions. It was found that the TLP is safe to be installed in waters deeper than 50 m and significant wave heights up to 14 m. Figure 4 illustrates the main components involved in the installation.

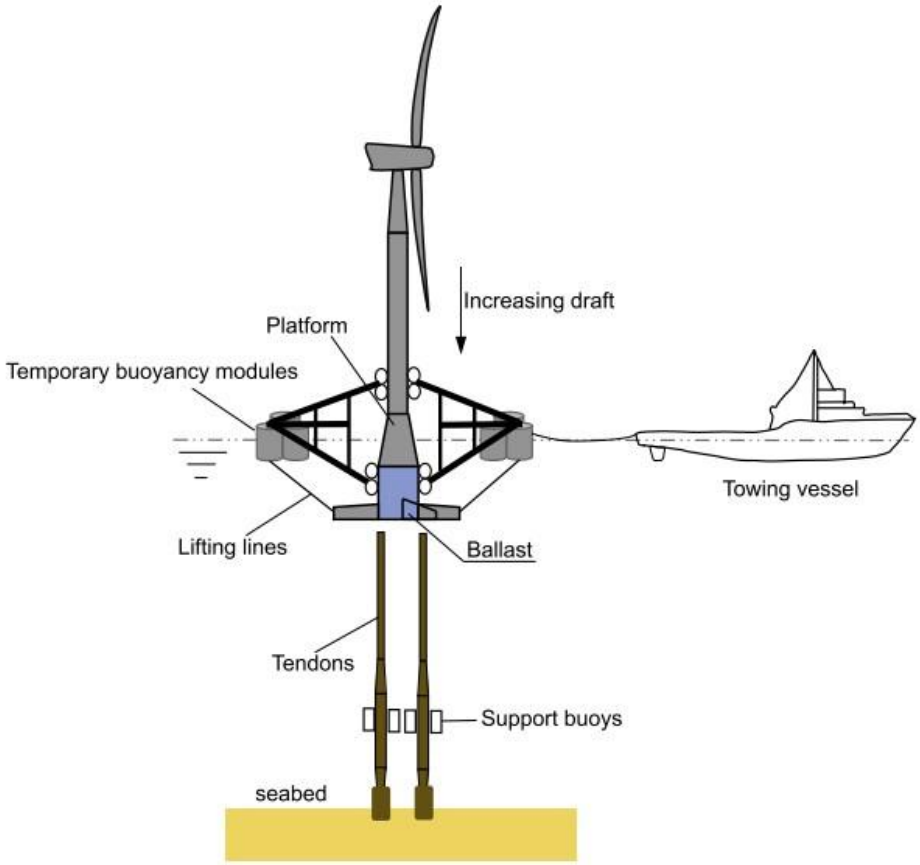


Figure 4: Representative diagram (not to scale) showing the installation method of an MIT and Enel TLP (Jiang, 2021).

The main challenge involved in the installation of a conventional TLP is its unstable behaviour before connecting to the tendons. For the installation of an O & G TLP, bespoke barges are often used for transportation and positioning of the system, which incurs additional expenditure (James and Ros, 2015). The anchors and mooring line system used in TLPs are designed to handle high tensions and are thereby more complex than the semi-submersible and spar-type platform systems. The tendons are susceptible to fatigue failure, which makes TLPs expensive from an O & M point of view also. Decommissioning of a TLP system is also expected to pose some challenges due to the complexity of the mooring system. The platform has to be carefully released

from the tendons and towed back to the shore. The mooring lines and anchors are removed later.

The GICON TLP (Adam et al., 2014; Kausche et al., 2018) is another innovative concept. The TLP system is placed on a floating slab and dry-towed to the location. The slab is then ballasted, which submerges the TLP into the required final draught. Figure 5 shows this installation method proposed by GICON. Analyses by Hartmann et al. (2017) found that the transportation of the GICON TLP should be performed only at a wind speed below 12 m/s and a maximum towing speed of 5 kn.

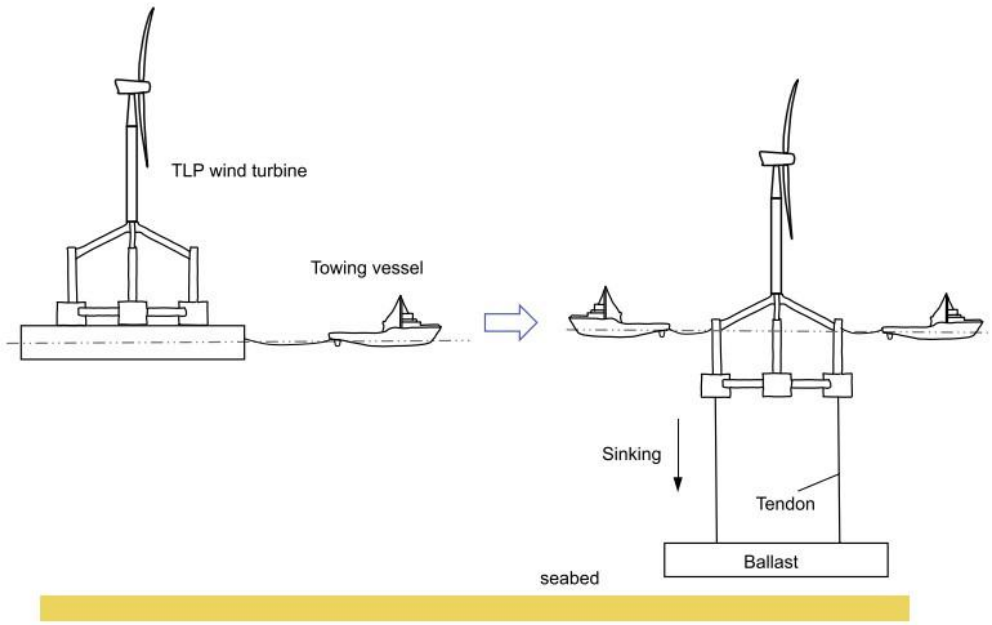


Figure 5: Installation of a GICON TLP (Jiang, 2021).

There are many upcoming concepts that are designed to allow alternative installation methods. An example is the TetraSpar concept (Borg et al., 2020), which features a tetrahedral floating structure equipped with a keel, which can be ballasted and lowered into a certain depth on-site. The keel can be air-ballasted and towed to the offshore location. Once the mooring lines are hooked, the keel is lowered, and the system starts acting like a spar-type platform. The TetraSpar has been developed with the aim to implement large-scale industrial production as it consists only of cylindrical tubes bolted together. These platforms do not require specialised vessels for installation since they can be towed using low-cost and widely available tugs (Andersen et al., 2018). The towing vessels and the FOWT must satisfy the stability criteria set by a classification society (Hartmann et al., 2017; DNV, 2021). Even though small tugs can be used for

towing, this might not always be feasible for installation in deeper seas, where higher waves may be encountered. It is advisable to use larger towing vessels for such installations. During the sinking operation of the ballast, the structure will be susceptible to current loads also. Detailed analysis is required to ascertain the motion and the loads on the tendons during this operation.

As mentioned above, different types of FOWTs have advantages and disadvantages when it comes to installation, O & M and decommissioning. Table 1 summarises them according to the type of floater. Significant wave height, current and wind speed restrictions apply to all marine activities. Some are more sensitive to this, but generally, it is important to overcome this restriction by precise weather monitoring and forecasting (Emmanouil et al., 2020) or using innovative ships and technologies.

Table 1: Advantages and disadvantages concerning installation, O & M and decommissioning of different floater types of FOWTs (Leimeister et al., 2018; James and Ros, 2015; Liu et al., 2016).

Platform Type	**Installation**	**Operation & Maintenance**	**Decommissioning**
Spar type	− High draught makes towing difficult - Requires heavy-lift vessels − Unstable motion of floater during mating − High installation cost − Tighter weather constraints −Requires deepwater ports and sheltered areas	+ Similar to bottom-fixed wind turbines − Heavy-lift vessels might be required for major repairs − Needs deepwater ports and sheltered areas for repairs	- Partially decommissioned in deepwater − Requires heavy-lift vessels
Semi-submersible type	+ Easy installation + Fully assembled at quayside. + Cheaper mooring and anchoring system + Short installation time + Low installation	+ Simple unhook from mooring system. + Can be towed back to quayside for major repairs. + No heavy-lift vessels required. + Helicopter access possible	+ Can be completely towed back to shore for dismantling. + Uses easily recoverable drag-embedded anchors. + No heavy-lift vessels required

	cost − More sensitive to wave height limits during towing		
Tension leg platforms	+ Can be completely constructed onshore. − Complex mooring and anchoring system − Slow and lengthy installation process − High installation cost − Bespoke barge required	− Difficult to unhook, more on-site repairs − Mooring system highly susceptible to fatigue damage	− Difficult process due to complex mooring system − Difficult or non-recoverable pile-driven anchors

+ : relative advantage - : relative disadvantage

A.3. Challenges and opportunities

Marine operation is defined as "a generic term covering, but not limited to the following activities, which are subjected to the hazards of the marine environment: Load-out/ load-in, Transportation/ towage, Lift/Lowering (Offshore/Inshore), Tow-out/tow-in, Float-over/float-off, Jacket launch/jacket upend, Pipeline installation, Construction afloat" (DNV, 2011a). Clearly, many of the operations listed here are applicable for floating wind farms.

DNV (Det Norske Veritas) (DNV, 2011a, b) classifies marine operations into weather-restricted and weather-unrestricted. The operation period TR is defined as:

$$T_R = T_{POP} + T_C$$

T_R is the operation reference period, T_{POP} is the planned operation period, and T_C is the estimated maximum contingency time for the marine operation. Weather-restricted operations are marine operations with T_R less than 96 h and T_{POP} less than 72 h. This is the maximum period for which the weather forecast is sufficiently reliable. Precise weather forecasts and continuous monitoring are required for weather-restricted operations. Towing operations must be analysed based on this (DNV, 2011a). For the Kincardine project, the towing took approximately 9–10 days (Bridget Randall-Smith, 2021). This can be considered to be a weather-unrestricted operation (DNV, 2011a).

Statistical extremes of metocean conditions must be considered for planning such an operation according to Table 2.

Table 2: Acceptable return period for unrestricted operations (Berg, 2017; DNV, 2011a).

Duration of towing	Return period of metocean parameters
Up to 3 d	Specific weather window to be defined
3 d to 1 week	1 year, seasonal
1 week to 1 month	10 years, seasonal
1 month to 1 year	100 years, seasonal
More than 1 year	100 years, all year

As mentioned before, the marine operations vary according to the type of floater used. The challenge here is the optimisation of the unavoidable marine operations throughout the life cycle of the wind farm. The installation locations of FOWTs present considerable challenges in terms of harsh weather conditions and catastrophic events such as tsunamis. There is a significant opportunity to transfer knowledge and technology from the mature O & G industry, for example, the optimised marine operations, resource assessment and the prediction of offshore weather conditions. The general approach for planning a marine operation is described in Figure. 6.

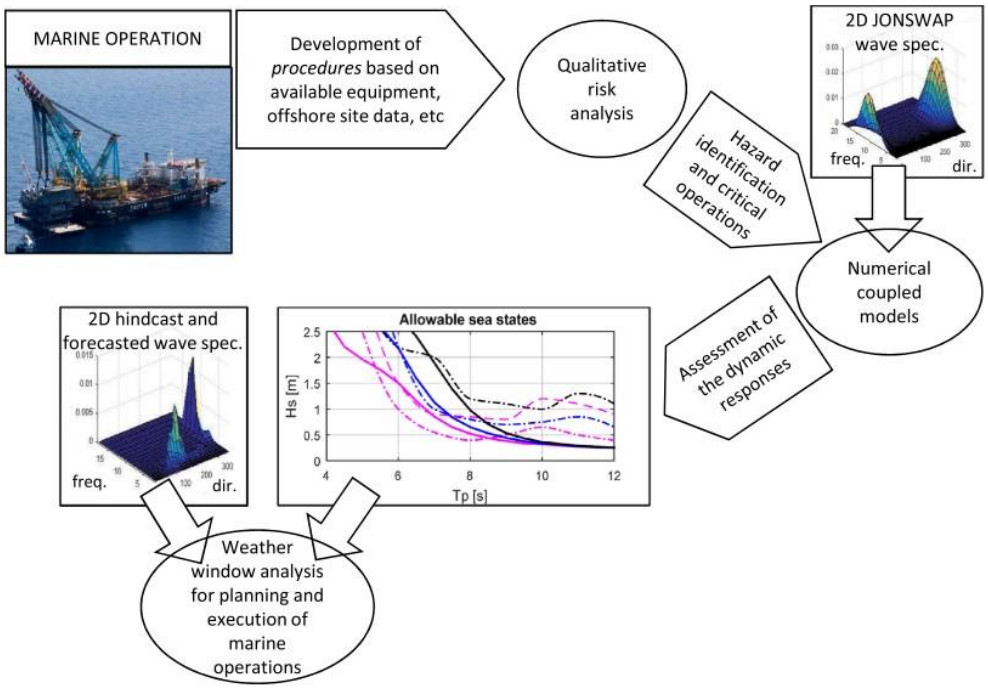


Figure 6: General procedure of assessing operational limits for an offshore marine operation (Acero et al., 2016).

There is a lack of consensus on installation approaches, costs and time for each task for floating offshore wind farms. Multiple installation, O & M and decommissioning approaches have been suggested for bottom-fixed wind turbines and many of them can be adopted for floating wind farms but FOWTs also present additional challenges, for example dynamic cables, mooring lines and longer real-world operational windows. The most significant challenges and the opportunities for addressing them are discussed in the following sections.

A.3.1. Metocean assessment and analysis

One significant challenge associated with FOWTs is predicting the optimum meteorological and ocean conditions for design as well as operation of FOWTs. In general, metocean data are required for planning installation, operation, maintenance and decommissioning activities by predicting the suitable weather window and associated costs based on wind, wave and current data (Jacobsen and Rugbjerg, 2005). Moreover, metocean conditions play an important role in site selection, calculation of design loads for floaters and mooring systems also. Wave and wind conditions also present safety concerns during the transfer of the crew to the floating platforms. The uncertainty associated with various environmental variables is of interest to all offshore operations concerning renewables as well as the O & G industry. The high complexity of the ocean environment makes it even harder to predict the operating conditions due to the presence of numerous variables. Also, the availability of metocean data for a particular location and period affects calculations. It is very important to have a general understanding of the metocean conditions of a particular geographical area to plan the construction of wind farms. There are four main sources of metocean data:

1. in situ measurements
2. numerical modelling
3. satellite measurements
4. pre-existing statistics and reports.

Among these, the in situ measurements provide the most reliable metocean data. Even though in situ measurements cannot provide long-term data and incur costs, it is advisable to start taking in situ measurements once the location is decided for a wind farm. Predictions using numerical models can be validated and augmented using in situ measurement data or satellite measurements. Long-term metocean data can also be

generated using hindcast data for a particular region. A careful combination of all these will serve as a reliable data set for planning installation, O & M and decommissioning activities. Wind, waves and current are the most important metocean parameters to be monitored and analysed for offshore wind installations. Wind, being the primary source of power, can be measured using lidar or a satellite scatterometer (Ahsbahs et al., 2018; Remmers et al., 2019); the former has proved to be more accurate and continuous for a particular region of interest. Waves can be measured using multiple buoys deployed at a particular location, microwave radar systems (Teleki et al., 1978) or satellites. Current measurements are made using current meters mounted below buoys or using microwave radars. Large-scale geostrophic currents can be measured using satellites (Dohan and Maximenko, 2010). Shore-mounted HF (high-frequency) radars can measure winds, waves and currents in coastal waters over a range of 120 km from the shore (Wyatt, 2021). Various numerical models exist for the precise calculation of metocean conditions. SWAN (Booij et al., 1999) is a third-generation wave model that can calculate random, short-crested waves in shallow waters and ambient current.

A.3.2. Environmental limits for installation, O & M and decommissioning

The installation, O & M and decommissioning activities require precise monitoring and assessment of metocean conditions in the planning phase itself. FOWTs are installed far offshore to utilise the higher wind speeds. Wind speed and wave height are generally related, as stronger winds tend to generate higher waves over time. However, wave height also depends on factors such as fetch, wind duration, and water depth. Additionally, swell waves, which originate from distant wind systems, can result in high wave heights even in calm local wind conditions. Hence, the installation and O & M of a floating wind turbine can be more challenging compared to a bottom-fixed wind turbine. Many pre-hook-up activities like site inspection surveys, installation of anchors, cable laying etc. are possible only during calm sea states. Periodic maintenance and repairs also depend on the weather conditions for safe crew transfer. Special operations, such as the mating of a spar-type platform with a wind turbine, are difficult when the platform is unstable. The installation of TLPs also poses similar challenges as the platform itself is relatively unstable before the connection to the tendons. Waiting for suitable weather conditions can raise the costs, so a precise weather forecast is essential. Figure 7 shows

the metocean limitations during assembly, transit and installation of different kinds of platforms.

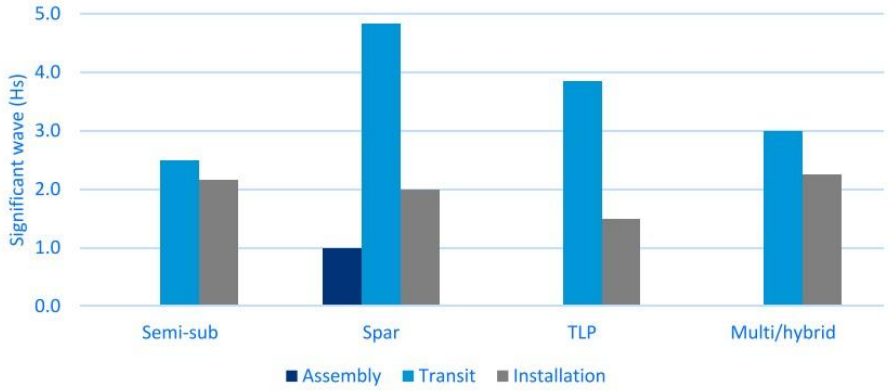


Figure 7: Significant wave height limitation during assembly, transit and installation (James and Ros, 2015).

DNV (2021) has defined the motion criteria for various marine operations. Anchor handling operations can be considered hazardous due to the high unexpected mooring loads in adverse sea conditions. For safe performance, it is important to define detailed operation and suspension criteria for anchor handling operations. For example, the 3 h maximum roll angle criterion can be used to compute the probability of exceeding a limiting roll angle of 15^{o}, which should remain below 10^{-4}. This criterion will ensure that the vessel will not capsize during anchor handling operations (Wu and Moan, 2017).

The operational limits and operability of marine operations are largely dependent on the critical events and the corresponding response parameters (Acero et al., 2016). For example, for the lifting of the fully assembled wind turbine for mating with a spar-type floater using a heavy-lift vessel, the critical event is the failure of the lifting wire. The tension on the wire varies according to the prevailing environmental conditions. The tension on the wire has to be determined and care should be taken to keep it below the breaking load (including a factor of safety). Using numerical analyses, the allowable environmental conditions that lead to the breaking load should be determined and they should be avoided. This operation is similar to the mating of the transition piece on a monopile foundation in the case of a bottom-fixed wind turbine (Acero et al., 2017). The only difference is the relative motion between the floating foundation and the wind turbine. The motions of the foundation should also be considered in the analyses. The installation of a wind turbine on a floating substructure using a floating crane vessel is a complex procedure. Cozijn et al. (2008) determined the operational limits of a similar

installation operation. The lifting and lowering of two topside modules onto an FSU (floating storage unit) were analysed, and the critical parameters were identified. Impact loads during the lowering phase were also calculated. The impact loads acting on the floater tip during the mating procedure can also be a critical factor depending on the structural design of the floater tip.

Towing is another marine operation that is significant during the installation, operation and maintenance, and decommissioning of FOWTs. Here the critical response parameter is the tension on the towing line, which has to be kept below the breaking load during the operation. During the towing of fully assembled FOWTs, one large towing vessel provides the required bollard pull for towing and two or three smaller tugs stabilise the motion of the floater and maintain a straight-line course. DNV (2021) has provided the allowable motion and acceleration limits for these vessels used in the operation. In all these cases, it is important to ascertain the environmental conditions corresponding to the limiting value of the response parameter. These conditions should be compared with the metocean forecasts and the decision of whether the operation can be executed or not should be taken. For long-duration projects a weather window analysis is performed to predict the periods when the weather parameters that affect the operations are below the threshold limits. Using hindcast data of a particular location, the weather downtime (WDT) can be predicted, and decisions on important marine operations can be made (Lambkin et al., 2019).

Significant wave height and wind speed are two major factors that affect workability. Depending on the marine operation, multiple environmental factors need to be considered. For example, wind speed is important for lifting operations, and wind and current speeds are important for towing operations (Acero et al., 2016). Transfer of the crew for maintenance activities becomes difficult in high wave heights. Beyond a significant wave height of 1 m, marine operations become difficult, and most operations halt at a swell of 1.5 m (Lange et al., 2012). Raising this limit is essential for all marine activities concerning offshore structures. Table 3 shows the significant wave height and wind speed limits for various vessels used for marine operations involving FOWTs. Another significant factor that affects the workability of a vessel is its response behaviour to these environmental limits. This is a design-related aspect of the vessel. The RAOs (Response Amplitude Operators) determine the response of the vessels in

various weather conditions. These limits can be raised by developing innovative ship designs that have better hydrodynamic performance in rough seas; walk-to-work vessels are one example. The possibility of outfitting existing vessels with motion-compensated gangways should also be investigated. At the same time, specialised vessels are expensive to hire, which would raise the costs.

Table 3: Operability of various vessels used in the FOW domain (Paterson et al., 2018; Ahn et al., 2017).

Vessel type	**Purpose**	**Max. significant wave height (m)**	**Max. wind speed (m/s)**
AHTS	Installation of anchors and moorings	2	20
Tugboats	Towing	1-1.65	14
Cable laying	Installation of cables	3.5	15
Heavy-lift vessel	Mating of spar-type platforms	1.8	15
Offshore supply	O & M	2	11
Monohull	Crew transfer, O & M	1	-
Catamaran	Crew transfer, O & M	1.2	10
SWATH (small-waterplane-area twin hull)	Crew transfer, O & M	1.5	-
Jack-up barge	O & M	1.65	16

A.3.3. Cost modelling of floating-wind marine operations

Installation, O & M and decommissioning costs depend on a variety of factors and stakeholder engagements. It is very important to model the costs accurately over the whole life cycle of wind farms. Figure 8 shows the important factors and inputs to be considered while modelling the costs of a floating wind farm.

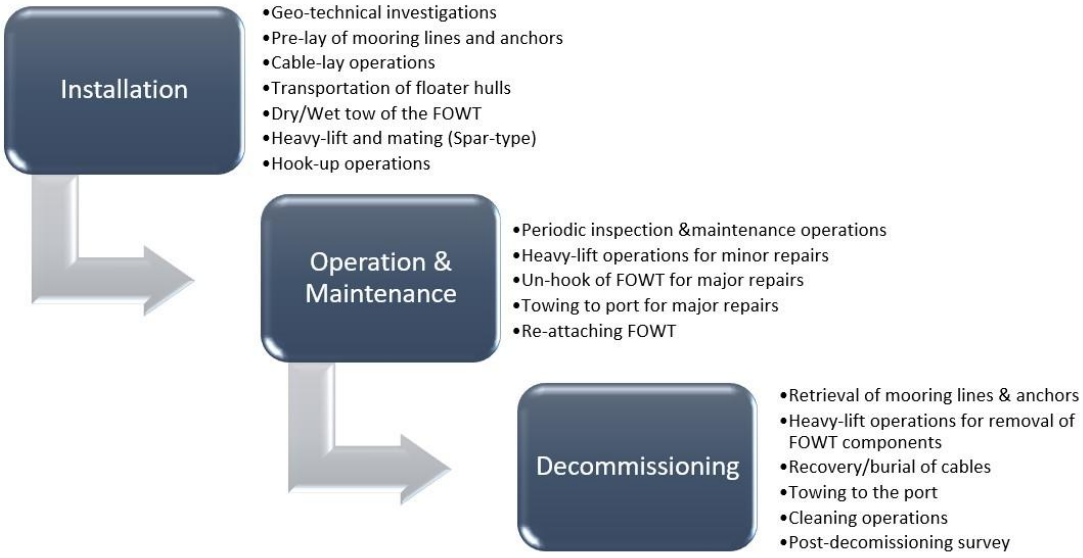


Figure 8: Important factors to be considered for the financial modelling of FOW (floating offshore wind) marine operations (Judge et al., 2019).

To optimise marine operations, precise modelling of the associated costs is required. The cost modelling of marine operations concerning FOWTs requires a detailed analysis of each phase of the life cycle and the vessels involved in the processes. For array-scale deployments, innovations like shared mooring and anchor systems can be implemented, which would bring down costs. For O & M purposes, modern vessels like service operation vessels (SOVs) and walk-to-work vessels fitted with motion-compensated gangways should be used considering the harsh sea conditions in the deep seas where the FOWTs will be installed. Many good models exist for bottom-fixed wind turbines. Figure 9 shows the breakdown of costs associated with a floating wind farm compared to a bottom-fixed wind farm. They can be extended into floating wind farms depending on the type of floater and the methodology of the various operations. The floating-wind costs are less developed at the moment; hence new and improved models are required for precise calculation of the costs.

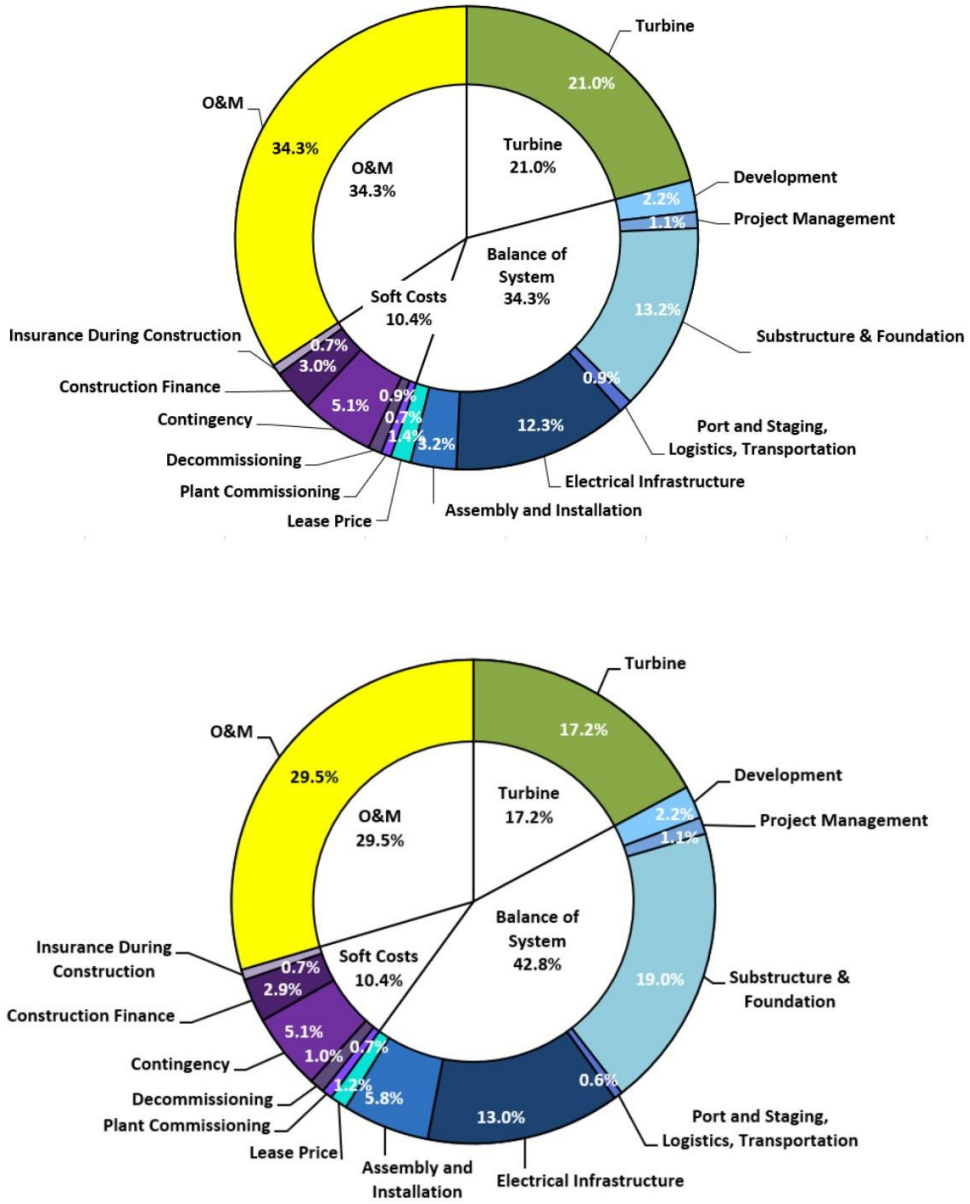


Figure 9: Comparison of component-level LCOE contribution for fixed-bottom (top panel) vs. floating wind (bottom panel) farms operating for 25 years (Stehly et al., 2020).

The installation costs consist of costs incurred for the installation of the wind turbine, floating platform, electric system, mooring and anchoring systems, and the start-up cost (Castro-Santos et al., 2016). The installation costs of the floating offshore wind platform depend on the port and shipyard costs, transportation and towing costs, and site installation costs. Draught restriction applies to many ports depending on the type of floater used. The spar-type platforms and TLPs have higher draughts compared to semi-submersibles. In such cases they have to be stored in a special storage area (Castro-

Santos et al., 2018b), or the port needs to be dredged, which incurs additional costs. The electric system installation costs are composed of cable installation costs and sub-station installation costs. For the installation of mooring and anchoring systems, it is economical to use an anchor handling vessel (AHV) compared to using barges and tugs (Wayman et al., 2006). The costs vary according to the number of anchors used in the wind farm. By the end of the installation of all the systems, the wind farm is commissioned, and start-up costs are also incurred during its connection to the electrical grid.

Installation costs strongly depend on the site location of the wind farm. Maienza et al. (2020) investigated how the factors like distance from the coast, distance from the nearest port and sea depth influence the total cost of a wind farm in Italian waters. A cost map for Italian national waters was produced, indicating the total costs for a wind farm consisting of 12 TLP FOWTs. Preliminary analysis showed that the number of wind turbines has a considerable effect on the total cost. Doubling the number of turbines increased the cost by 35 %, but quadrupling or increasing eightfold increased the costs by 60 % and 80 %, showing a decrease in the rate at which the total costs increase. The LCOE was found to decrease with an increase in the farm size (Castro-Santos et al., 2018a; Myhr et al., 2014). According to Castro-Santos and Diaz-Casas (2015), the distance from the shore has a 36.3 % influence on installation cost and 14.2 % on dismantling cost. As the wind turbines move further into the sea, it is expected that they will grow in size too to fully utilise the higher wind speeds; 15 MW wind turbines are predicted to be used from around 2030 and 20 MW turbines from 2037 in the UK floating offshore wind sector (OREC, 2015). The wind turbine diameter is found to have a 15.9 % influence on the dismantling cost (Castro-Santos and Diaz-Casas, 2015).

O & M costs mainly consist of the corrective and preventive maintenance costs throughout the whole life cycle of the wind farm (Castro-Santos, 2016; Sperstad et al., 2016). To minimise these costs, it is important to design reliable systems and efficiently monitor the health conditions of the turbine system, floater, electrical installation, and mooring and anchoring system. This is of high importance as the failure of main components could result in considerable downtime as the FOWT might not be accessible due to a lack of suitable weather windows. A preliminary analysis by Dewan and Asgarpour (2016) considered using SOVs and towing vessels for O & M of a floating offshore wind farm consisting of fifty 8 MW semi-submersible wind turbines and

investigated the costs and downtime. The availability was found to be 91.4 %, which was lower than fixed-bottom wind turbines, because of the towing of the platform to the shore for major repairs. A detailed investigation is pending in this area to improve the downtime by using better vessels (e.g. walk-to-work vessels), helicopters (Maples et al., 2013) etc. for different types of floaters. Easy-coupling-and-decoupling systems should be developed to facilitate easy attachment and detachment of FOWTs during major repairs. Advancements in robotics have paved the way for the usage of robots for inspection and maintenance; iFROG (Offshore-Engineer, 2020) is an amphibious robot developed by InnoTecUK, ORE Catapult, TWI Ltd. and Brunel University London which can clean corrosion and bio-fouling from monopile surfaces. Using remote condition-monitoring systems, crack initiation and propagation, corrosion, pitting, rubbing etc. can be detected (Tchakoua et al., 2014). Remote visual inspection devices and acoustic emission detectors can record and transmit data to the shore and the data can be analysed using machine learning models to enable accurate prediction of developing hazards (Stetco et al., 2019).

Decommissioning is an environment-sensitive activity. It is better to incorporate decommissioning studies in the design phase to avoid complications in the final years of the wind farm life cycle (20 years or more) (James and Ros, 2015; Castro-Santos, 2016). A reverse-installation approach can be used for calculating the decommissioning costs of a wind farm (Topham and McMillan, 2017). The main components are the dismantling costs of the wind turbine, floating platform, electric system, mooring and anchors. Some anchors, e.g. drag-embedded anchors, are easily recoverable, which would save costs and time (González and Diaz-Casas, 2016). There is an additional cost due to the cleaning of the wind farm site which is of environmental concern (Castro-Santos et al., 2016). Some materials can be sold as scrap, e.g. steel from the floater and copper from the electric cables, which would result in a negative cost (income) (Castro-Santos et al., 2016).

Various stakeholders are involved in the construction of an offshore wind farm. Proper planning and optimum utilisation of resources are very important in bringing down costs. Weather restrictions during the marine operations would cause the logistic costs to increase exponentially (Lange et al., 2012). Often hiring offshore support vessels from abroad invites large hiring costs. Specialised vessels also raise costs; see Table 4.

Depending on the location, optimised use of local vessels and port facilities would help bring down the associated costs.

Table 4: Day rates of different types of vessels used in the FOW industry (Jiang, 2021; Sperstad et al., 2017; Foxwell, 2019).

Vessel Type	Approximate typical day rate (EUR)
Tug	1000-4500
AHTS	20000-50000
Cable lay vessel	70 000–115 000
Barge	80 000–180 000
Jack-up	72 000–130 000
DP (dynamic positioning) vessel	50 000–200 000
Bespoke vessel	200 000
Crew transfer vessel	1750
Service operation vessel – large (W2W)	52 000
Service operation vessel – medium (W2W)	35 000
Semi-submersible crane vessel	200 000–360 000

A.3.4. Health, safety and environment (HSE)

One of the non-technical challenges that needs to be addressed is improving the HSE conditions during the complete life cycle of floating offshore wind farms. HSE factors must be considered during all phases of the development of the wind farm, but only the installation, O & M and decommissioning phases are considered in this section. Since the floating-wind technology is in its infancy, there is a shortage of dedicated applicable rules and standards. Until the development of such standards, it is advisable to follow component- and process-specific standards used in the bottom-fixed-wind-turbine industry or O & G industry (Hutton et al., 2016). Marine operations in general can follow the various safety standards, codes and classification society rules accordingly.

Theoretically, the installation of FOWTs is less environment-sensitive compared to fixed offshore wind turbines as most of them are constructed completely onshore and towed to the offshore sites. Again, the type of floater is a deciding factor here. The installation of anchors and mooring lines can have a negative impact on the environment. Spar-type platforms and semi-submersibles employ catenary moorings

with long mooring lines that have a larger footprint on the seabed, while TLPs do not, because they employ taut mooring lines (James and Ros, 2015). Heavy-lift vessels are used during the installation of spar-type platforms, which invites additional safety issues, but there are well-defined guidelines and standards available for this operation. The installation of drag-embedded anchors has less of an environmental impact compared to suction or pile-driven anchors. The noise impact during hammer piling is also an issue. However, the underwater noise during the installation of FOWTs is less compared to bottom-fixed wind turbines (Koschinski and Lüdemann, 2013). The noise during hammer piling can be mitigated by carefully engineering the piling process. By using the right specification of piles and drivers the noise can be reduced. Bubble curtains can be created using underwater bubble pipes to attenuate the blast and piling noise. Vibropiling is another technique employing vibratory pile drive machines that drive the pile by applying rapidly alternating forces, which are quieter than impact piling machines (Nedwell et al., 2003). Long-term post-installation noise measurements are required to understand the effects of operational noises of large wind turbines fitted on floating foundations (Farr et al., 2021; Koschinski and Lüdemann, 2013). The effects on fish populations and marine mammals need to be studied separately. Protected marine areas, migratory birds' paths and migratory marine life paths should be avoided while selecting sites for offshore wind farms (Díaz et al., 2019).

The most challenging safety concern is access and egress of personnel to and from FOWTs during repair and maintenance activities. The FOWT and the vessel form a floating–floating couple which makes access and egress challenging. Bump and jump can only be safely accomplished in low wave heights, whereas walk-to-work systems increase this wave height limit while providing safer means of access and egress. For crew transfer onto FOWTs, SOVs with relative-motion compensation are preferred over CTVs due to higher operability limits and established practices. A precise weather forecast is also required for planning O & M operations to avoid difficulties during the operations. Aboard a FOWT, even the small motions of the floater get amplified into large displacements at the nacelles and blades. This contributes to severe motion sickness or reduced efficiency of the personnel working on such structures. In the long-term, these factors have to be considered in the design phase of the FOWT itself to reduce the dynamic response in waves. Remote O & M can also be considered to reduce

the O & M visits. FOWTs can be towed back to shore for O & M, which makes them attractive from an HSE point of view.

After decommissioning, it is important to leave the site in a similar condition as it was before the deployment of the wind turbines. After the wind turbines are transported to the shore, the mooring lines and anchors have to be removed. Certain types of anchors offer easy removal, while others are difficult or impossible to remove. Extreme care should be taken while removing cables from the sea. The complete removal of cables can cause severe damage and disruption to the seabed and in most cases, they are left buried on-site (Topham and McMillan, 2017). Following decommissioning, it is important that equipment is well below the seabed and does not pose a risk to fishing or other marine activities. Where this is not possible, these locations must be recorded and reported to relevant local authorities. Post-decommissioning surveys are conducted to ensure that no debris is left behind, and the buried remnants are not causing obstructions.

A.4. Innovations applicable to floating offshore wind turbines

Significant research is currently being conducted in the development of efficient and optimal floating wind turbines. To decrease the costs associated with installation, O & M and decommissioning operations, many innovative designs, procedures and technologies along with established best practices are required. Some aspects can be adopted from the O & G industry; however, the unique nature of FOWTs requires dedicated research and development. Some of the innovations applicable in this domain are discussed in this section. These innovations are targeted at improving the operability of vessels, widening weather windows, improving HSE factors and reducing the need for complex marine operations.

A.4.1. Shared-mooring and shared-anchoring systems

For large floating offshore wind farms, the mooring lines and anchors can be shared with multiple FOWTs, reducing total mooring line length, saving construction material for anchors and reducing the need for marine operations by optimising utilisation of the installed infrastructure. In a shared-mooring system, the FOWTs are interconnected using mooring lines, reducing the frequent connections to the seabed using anchors. In a shared-anchor system (Figure. 10), a single anchor takes multiple mooring lines, and the

number of anchors can be reduced. Both these systems are practical for large wind farms and significant cost reductions are achievable due to the savings in material and installation costs.

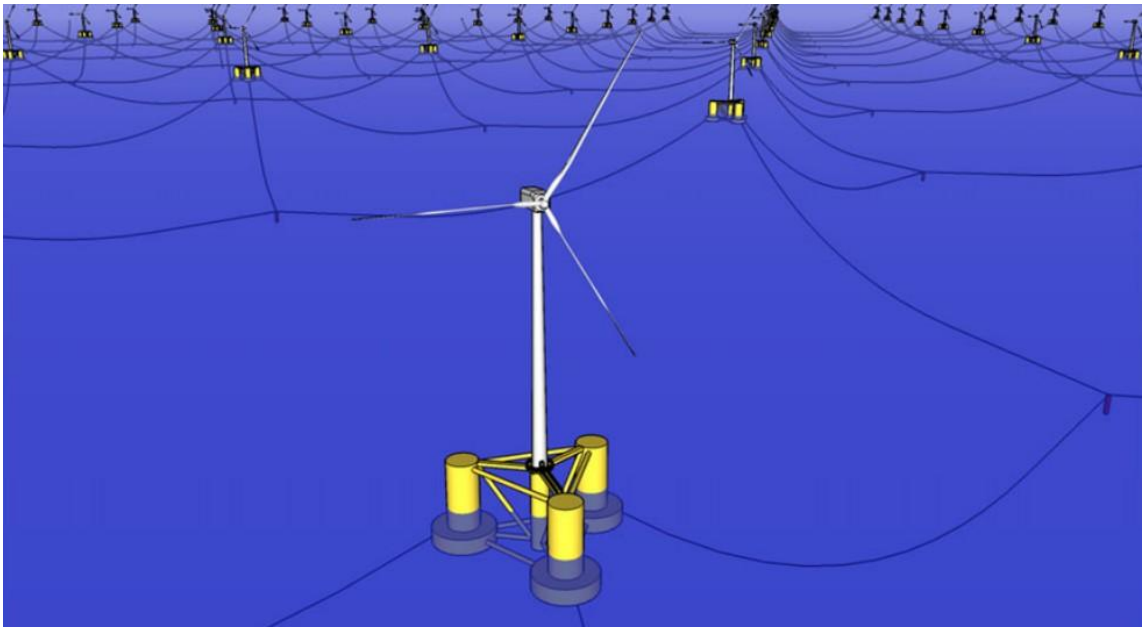


Figure 10: Shared-anchor system (Fontana et al., 2018).

Many researchers have worked on these concepts for application in the floating offshore wind domain. The technical know-how of integrated mooring systems can be transferred from the O & G industry. They have been employed in the floating O & G platforms, and the technology is relatively mature. Musial et al. (2004) have observed that individual mooring and anchor costs are significant for single-turbine systems compared to a shared system.

Fontana et al. (2016) investigated the hydrodynamic performance and loading analysis of shared anchors for various FOWT configurations and found that shared anchors must be structurally strong enough to handle loading from unexpected directions. Anchors with a directional preference in their holding position and capacity are generally not suited for multi-line moorings, but they can be adapted by extra structural outfitting for handling mooring loads in various directions (Diaz et al., 2016). The type of floater is also found to have a significant influence on the anchor forces. Balakrishnan et al. (2020) analysed and compared the anchor forces on a semi-submersible floater system and a spar-type floater system and found that the anchor forces on the latter were less. This is because spar-type platforms have less surface area interacting with waves compared to that of a semi-submersible.

Goldschmidt and Muskulus (2015) investigated the performance of coupled-mooring systems involving 1, 5 and 10 floaters in various configurations. Semi-submersible floaters were arranged in a row and triangular and rectangular configurations separately, and the system dynamics were studied. It was found that mooring system cost reductions up to 60 % and total system cost reductions up to 8 % were achievable using shared moorings. However, it was noted that the displacements of the floaters were higher when the number of floaters in the system increased, which would be a problem for large wind farms. Further investigation is required to improve the behaviour of floaters in larger wind farms. One of the main challenges in adopting a multi-line system for FOWTs is the reduction in system reliability. Failure of the multi-line system components can cause a large number of FOWTs to detach and stay adrift. Hallowell et al. (2018) investigated the reliability of a multi-line system (100 wind turbines in a configuration of 10 rows and 10 columns) compared to a conventional single-line system. It was found that the reliability of a multi-line system reduced considerably in extreme load conditions due to progressive failures. Further research is required in this area to increase the reliability of multi-line systems for FOWTs.

Geotechnical investigations are carried out at the anchor site prior to the installation of anchors. Dedicated geotechnical investigation vessels are used for this. The cost of geotechnical investigations is a function of water depth, site conditions, pre-existing survey data and method of investigation. The geotechnical site investigation costs are also dependent on the number of anchors (Fontana, 2019). In a wind farm with shared anchors, there is a significant reduction in the number of anchors. This would help to bring down geotechnical site investigation costs. Fontana (2019) compared the costs of installation and geotechnical site investigation for different farm sizes. It was found that a multi-line configuration reduces the installation cost for wind farms with 36 or more wind turbines. The geotechnical site investigation costs also get reduced with an increase in the size of the wind farm but taper due to the diminishing of the perimeter effect (anchors in the perimeter share fewer FOWTs). In a shared-mooring system, mooring lines can be interconnected instead of connecting to the seabed. The critical parameters are the tensions in the mooring lines and the loads acting on the anchors. As mentioned before, the system is susceptible to loading from multiple directions, and the reliability of the system is dependent on the line taking the maximum tension. The tension on the mooring line must be below the breaking load in all environmental

conditions as well as extreme events. The pad eye on the anchor is also subjected to loads in various directions (Hallowell et al., 2018). Shared mooring can also make access by large vessels difficult. When FOWTs are interconnected, it can cause hindrance for such vessels with high draughts to approach the platform and transfer the crew. The mooring architecture has to be designed in such a way that vessels can safely pass between the FOWTs. Available depth at the farm location and the point at which the mooring line is connected to the floater are deciding factors here.

Detailed analyses are required to ascertain the dynamic performance of a shared-mooring system and estimate the increase in extreme and fatigue loads (Hall et al., 2014). The feasibility of using shared-mooring systems for pilot-scale floating wind farms was investigated by Connolly and Hall (2019). It was found that significant cost reductions can be achieved by proper selection of wind farm layouts, mooring line properties and platform displacements. The Hywind Tampen is an upcoming floating wind farm that employs shared anchors (Reuters, 2020). The optimised array-scale installation procedure for the shared-mooring and shared-anchoring systems and its effect on costs and time are yet to be investigated.

A.4.2. Dynamic positioning for FOWTs

The FOWTs are generally positioned in the deep sea using mooring lines. They have to be pre-installed using offshore support vessels, which are expensive and the process is time-consuming. Precise engineering calculations are required to design the mooring lines and anchors for offshore structures.

The water depth is a decisive factor that determines the length of mooring lines and the costs associated with them. In many cases, the seabed has to be analysed and prepared depending on the type of anchors used for installation. Semi-submersibles and spar-type floaters are moored using a longer but simpler mooring system compared to TLPs, but the TLPs employ complex anchors and vertically loaded tendons with high load-bearing capacity. The conventional steel tendons are heavy and thereby costly and impractical for ultra-deep installations (Cummins and McKeogh, 2020). Large expensive vessels will be required for transporting and installing them in an array-scale wind farm, which would increase the costs. A mooring system is considered impractical and uneconomical for water depths greater than 1000 m (Yamamoto and Morooka, 2005). At the moment, researchers agree that the practical water depth limit for floating wind

turbines should be between 700 and 1300 m (Musial et al., 2016). Developing a cable system for transferring electricity from such depths is difficult and impractical. But with the development of better electricity storage technology, e.g. efficient hydrogen production and storage (Cummins and McKeogh, 2020), FOWTs can be deployed in deeper waters. Mooring systems will be less effective for station-keeping in such cases.

Dynamic positioning has been often used for station-keeping of ships and offshore structures in the O & G industry for years. Offshore support vessels actively employ dynamic positioning systems (DPSs) for a variety of offshore activities. Employing DPSs can be considered for FOWTs in deeper waters. The water depth and sea-bottom conditions do not affect the DPS; hence it can save mooring line, seabed preparation and anchoring costs. The disadvantage of the DPS is that it consumes a considerable amount of energy the turbine produces. Xu et al. (2021) proposed the feasibility of a dynamically positioned semi-submersible 5 MW floating wind turbine in their paper. It was found that the DPS utilised approximately 1/2 of the total generated energy when the current forces are not considered, and the ratio becomes 4/5 when current forces are taken into account (Xu et al., 2021). The concept has not been experimentally evaluated and the economics of the DP system have not been optimised.

Another scenario where the DPS can be useful is during the crew transfer from an offshore support vessel to the FOWT during operation and maintenance activities. Even with the mooring lines attached, the platform is subject to motions which make the transfer of personnel difficult. In such cases, the DPS would help to stabilise the FOWT and help the safe transfer of the crew. Heavy-lift vessels can also employ the DPS during heavy-lift operations in the deep sea (e.g. mating of spar-type platforms, O & M). The economics of using such systems for FOWTs are yet to be investigated.

A.4.3. Walk-to-work for FOWTs

Operation and maintenance of offshore platforms are often challenging due to the difficulty in accessing the platforms. Safe transfer of the crew is essential for all kinds of maintenance activities concerning offshore structures. Access to O & G platforms and bottom-fixed wind platforms has always been challenging. In the case of floating platforms, it is even more challenging as the platform and the crew transfer vessel are in relative motion during transfer. Since floating wind technology is relatively new, it is

necessary to use the knowledge acquired in the O & G and fixed-wind domain for floating platforms (Santos et al., 2016).

Walk-to-work (W2W) vessels are equipped with motion-compensated gangways (MCGs) that enable crew transfer in higher wave heights. They help to widen operational weather windows and eliminate the waiting time, which saves time and expenses. They can also be employed during installation activities for the transfer of the crew. The MCGs employ a technology known as active motion compensation (Chung, 2016). Accurate motion sensors detect vessel motions and counteract them using a sophisticated hydraulic hexapod on which the gangway is mounted. Motion detection and hydraulics are governed by an automated control system. MCGs allow crew transfer in significant wave heights up to 3.5 m and wind speed up to 20 m s−1 (Salzmann et al., 2015).

Guanche et al. (2016) investigated the hydrodynamic performance of a catamaran crew transfer vessel (CTV24) with a fender and a platform support vessel (PSV80) with an MCG, and the operating significant wave height conditions were compared. It was found that access was theoretically possible with wave heights up to 2 m using the catamaran and 5 m using the PSV in head-seas (Guanche et al., 2016). In a separate study, accessibility was calculated for a semi-submersible located off the coast of Portugal using hindcast data from 1980–2013. Safe access was possible up to 20 % and 76 % of the time using the catamaran and PSV, respectively (Martini et al., 2016). Li (2021) further investigated the operability of such systems by also taking second-order drift motions into consideration. It was noticed that the general wave height limit reduces to 2–3 m when nonlinear drift forces were involved. Both investigations revealed that beam seas are to be avoided in all cases when employing W2W vessels for access. However, all these studies indicate that W2W vessels equipped with MCGs are considerably advantageous over conventional access systems for floating-wind-platform access. The complex motion of the multi-body system requires further studies to ensure the safety of the crew during such operations.

A.4.4. Specialised ships for FOWT-related marine operations

Even though many FOWTs do not need specialised installation vessels, innovative vessel designs that could simplify the installation processes are worth investigating. Many of the floater types can be constructed onshore and towed to the location by using

tugs. An exception to this is the spar-type platforms. They need heavy-lift vessels for the platform–turbine mating process. There is potential for developing innovative ship designs that can facilitate cheaper and safer marine operations compared to the existing methods. One public competition we can examine to give insight into this happened in 2014, when Statoil (now Equinor ASA) presented the “Hywind Installation Challenge” (Equinor, 2022a) that sought out innovative installation technologies and methods for the installation of the Hywind wind turbines.

Stavanger-based Windflip AS proposed an innovative vessel design that can be used for the installation of floating offshore wind platforms (Maritime-Journal, 2012). The proposal was based on a specialised barge that can transport a fully assembled spar-type platform to the location and unload by flipping. The turbine is loaded in an almost-horizontal position, and the barge is towed to the offshore location. The aft side of the barge is then ballasted, taking the whole barge–turbine system into a vertical position. The turbine is then connected to the mooring lines, and the barge is towed back to the quayside for reloading. Windflip AS claims that the vessel can operate in shallow waters, which is an advantage when it comes to the installation of spar-type platforms.

Another concept was proposed by Jiang et al. (2020) to aid the installation of spar-type platforms. A floating dock (Figure. 11) was specifically designed for shielding a wind turbine during the installation of the tower, nacelle and rotor onto a spar-type platform. Hydrodynamic evaluation showed that the floating dock was able to reduce the pitch and heave response of the spar-type platform, which aids mating of the blades.

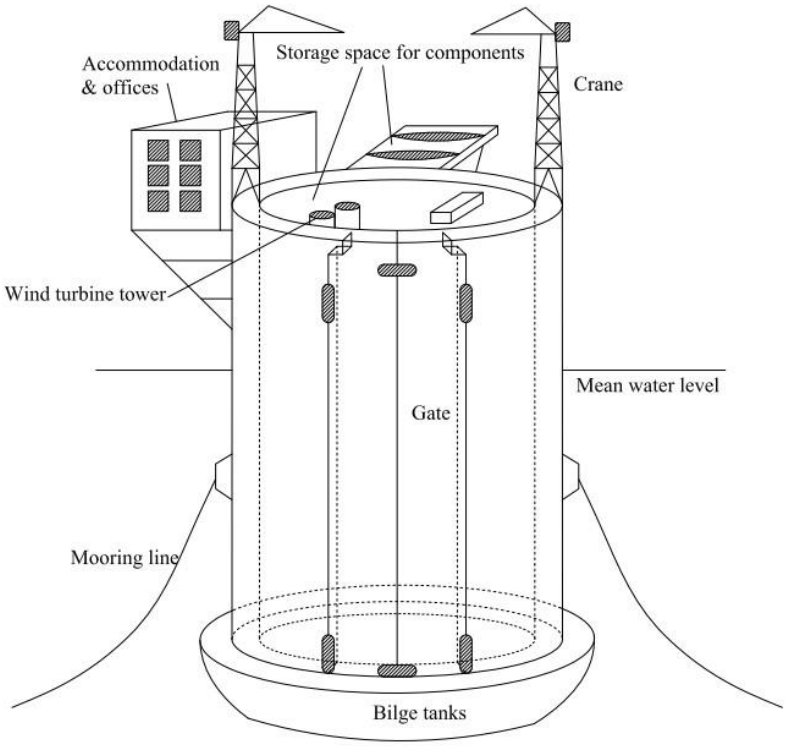


Figure 11: Floating dock concept (Jiang et al., 2020).

Two different spar designs of different geometrical properties were tested during the analyses. The RAO (response amplitude operator) plots show that the shielding provided by the floating dock helps to reduce the motion of the spar platforms inside (Figure. 12). However, sloshing mode and piston mode resonances were observed, which was a result of the small inner diameter of the dock. Even though the floating dock is theoretically feasible, the towing and ballasting operations are not yet studied. The structural design of the floating dock is also required for analysing the internal compartment and fatigue of the gate and storage modules. Detailed cost analyses are also required to check whether the construction, hiring and operation of the floating dock are economically feasible.

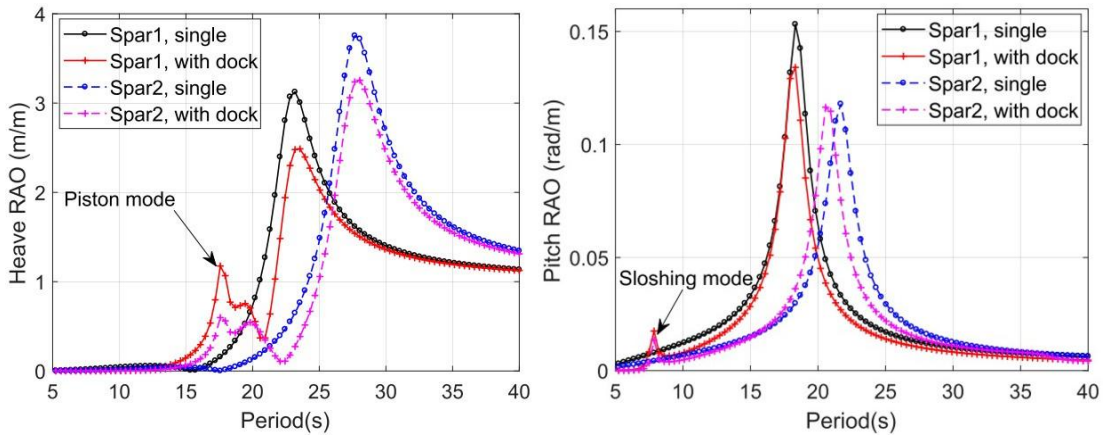


Figure 12: Comparison of the spar RAOs with and without the floating dock (Jiang et al., 2020).

Jiang et al. (2018) investigated another concept, a catamaran wind turbine installation vessel equipped with grippers that aid the installation of spar-type platforms. The vessel can carry a maximum of four wind turbines and minimise or eliminate the use of heavy-lift vessels and thereby reduce installation time. Figure 13 explains the various stages in the installation of a spar-type platform using the catamaran vessel. Jiang et al. (2018) studied the hydrodynamic performance of the system involving the catamaran, a spar foundation, mechanical couplings, mooring lines and a dynamic position system using the multi-body approach. The success of the mating is largely dependent on the relative motion between the spar and the wind turbine tower. The relative-motion radius (distance between the spar and wind turbine tower), gripper forces and the mooring line tension were the critical parameters in this process. The system was simulated under various significant wave height, peak period, wind speed and blade pitch conditions. The significant wave height was found to be the most important environmental parameter that affects the performance of the system. A maximum significant wave height of 3 m was used for the analyses, and the mating process was found to be successful. The disadvantage here is the complex mechanical structural arrangement and various dynamic loads acting on the system.

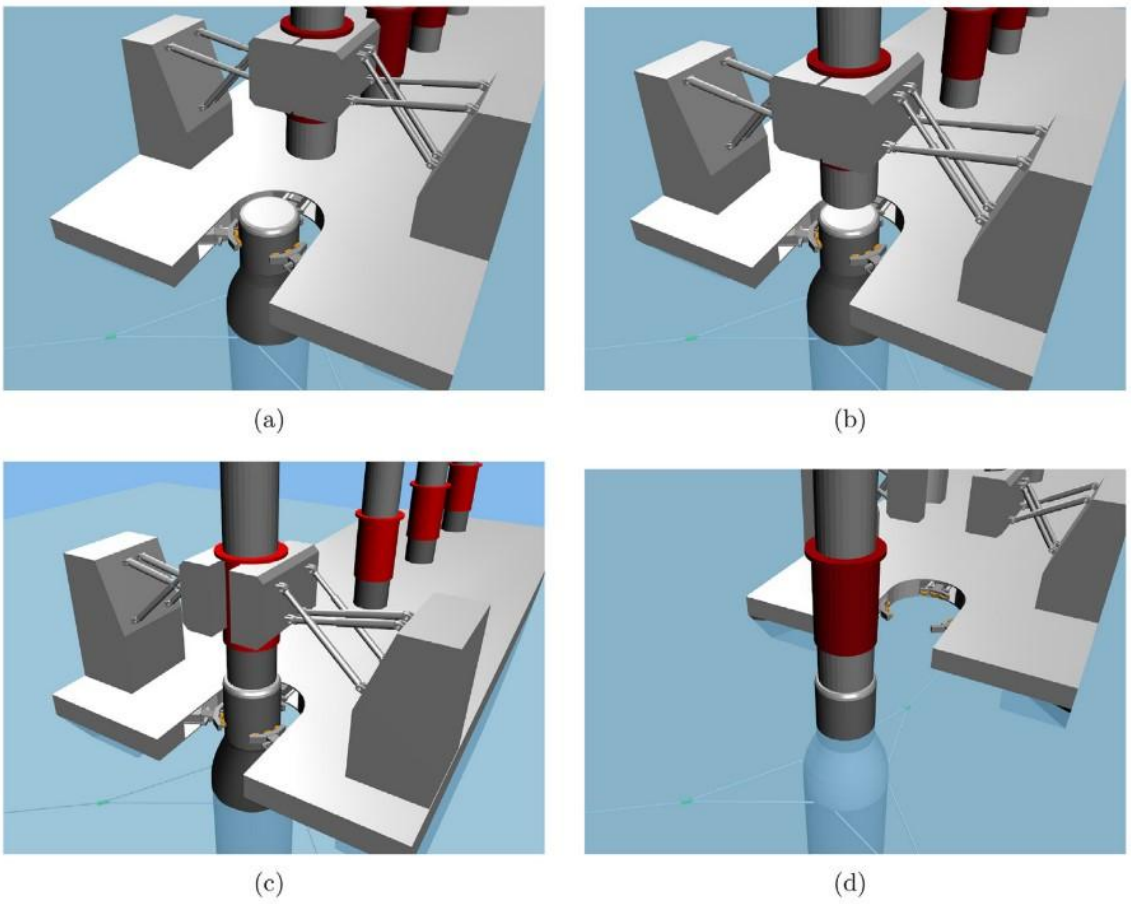


Figure 13: Stages in the installation of a wind turbine using the catamaran vessel: (a) transfer of the assembly, (b) monitoring of relative motion, (c) mating of the tower with the floater, (d) release of the foundation (Jiang et al., 2018; Hatledal et al., 2017).

Vågnes et al. (2020) proposed an improved system using winches and wires instead of grippers. This system can reduce the structural requirements of the lifting system and improve the handling of the wind turbines. The system will be installed aboard a catamaran vessel which can be used for the installation of spar-type platforms. The low-height lifting system is controlled by an active heave compensation system and tension tugger wires to ensure the balance of the tower during the mating process. Preliminary hydrodynamic analyses of the system under various weather conditions and operational layouts showed that the system is feasible and can be efficiently used for the installation of spar-type platforms. The system was tested for various significant wave height and peak period conditions. The tensions on the lifting, stabilising and attachment wires were the critical parameters. The natural periods of the FOWT were unlikely to be present at

common installation locations, but those of the catamaran and spar are likely to be present. The analyses were focused only on the positioning of the wind turbines; detailed analyses of the lowering and mating processes are necessary to evaluate the feasibility of the system. The performance of the system under various wind, wave and current conditions and experimental validation of these results are also pending.

A.5. Conclusions

The importance of focussing research on the marine operations concerning installation, O & M and decommissioning of FOWTs is discussed in this paper. As the industry matures, much research is needed to frame innovative methods and technologies to reduce the costs and LCOE. Compared to the O & G industry, offshore wind turbines provide opportunities for batch production and deployment. These opportunities should be utilised for the full commercialisation of floating wind farms. Semi-submersibles are observed to be the most cost-efficient design from an installation, O & M and decommissioning point of view, but broader research is needed to consider all the factors applicable to the whole life cycle of the wind farms. Several challenges are yet to be addressed to reduce the costs concerning spar-type platforms and TLPs. It is very important to consider the ease of installation, O & M and decommissioning in the design phase of the floater concepts for the practical realisation of these concepts. There is also plenty of room for innovation to cut costs, reduce environmental impact and improve the safety of the personnel associated with the industry.

Many challenges need to be addressed and much research is pending in the FOW domain. Some of the challenges are specific to the type of floater, but others apply generally. There is much research to be done for the easy and cost-effective installation, O & M and decommissioning of TLPs. It is important to introduce and implement innovative and cost-effective methods and technologies in this domain. Marine operations, due to the involvement of human life, environment and marine life, are of paramount importance. They are most dependent on metocean conditions, so accurate prediction is important. In situ measurements should be encouraged for getting accurate weather data throughout the life cycle of the wind farm. Sharing of these data across multiple platforms should also be encouraged for the metocean analyses of upcoming wind farms and further research. Marine operations can be improved in two different ways, i.e. either by developing better metocean prediction models, for example,

analytical models augmented by in situ measurements, or improving the operability of vessels in harsh seas by implementing innovative technologies and methods. A combination of both these methods offers synergistic advantages. With highly accurate metocean predictions, vessels can better plan routes and operations, minimizing exposure to severe conditions. Simultaneously, the improved operability of vessels allows them to function more effectively even if faced with unexpected or unavoidable harsh weather. This helps reduce downtime, increases safety, and enhances operational efficiency, leading to optimized marine operations across various environments. Specialised vessels are expensive, but by reducing costs in other areas they can lead to reductions in the overall LCOE. Generally, O & M operations have stricter weather restrictions compared to installation operations (e.g. towing). Emphasis should be given in this area, and the O & M weather conditions should be used as limiting cases for the metocean assessments. As the industry matures, it is very likely that there will be a huge demand for offshore support vessels (OSVs), AHTSs, SOVs etc. in the near future. The industry should be able to supply the vessels according to the demand or else the costs will rise. Marine operations and vessel utilisation must be optimised to reduce the LCOE of floating offshore wind energy and increase competitiveness with other energy sectors.

Data availability

No data sets were used in this article.

Author contributions

RCR did the reading and literature review and wrote the paper. CD reviewed and edited the initial drafts of the paper and contributed actively. FJ also helped review the drafts. JJS and JM supervised the work.

Competing interests

The contact author has declared that neither they nor their co-authors have any competing interests.

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Financial support

This research has been supported by Horizon 2020 (STEP4WIND, grant no. 860737).

Review statement

This paper was edited by Amir R. Nejad and reviewed by Wilson Guachamin and one anonymous referee.

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Chapter 3

Towing characteristics of a semi-submersible FOWT: Paper B

3.1 Motivation and Aim

The preceding work emphasised the criticality of towing operations for floating wind turbines. Notably, two operational floating wind farms, Windfloat Atlantic and Kincardine, have employed semi-submersibles. It was also found that a semi-submersible floater has advantages over spar-type or TLP, as they offer full construction and assembly at port/quayside. The main challenge here is that they are more responsive to waves during towing. Since they are large structures, the bollard pull requirement needs to be analysed too.

This paper provides a scientific approach compared to an experience-based approach for towing. For the analysis of towing operations, a framework is presented and applied. Various hydrodynamic factors relevant to towing operations are also outlined and discussed. Classification societies like DNV [6] [7] have provided rules and limiting conditions for general towing operations and the rules applicable to FOWTs are adopted. This paper scrutinises these factors concerning a semi-submersible, highlighting numerous critical considerations for understanding their towing operations. The main contributions of this paper are:

1. **Assessment of a framework for analysing towing operations.**

   To comprehend how Floating Offshore Wind Turbine (FOWT) systems react to metocean conditions, a scientific framework becomes essential. This paper presents a framework tailored for assessing the towing process of FOWTs. It

integrates identified relevant physical phenomena into this framework, outlining a methodology aimed at optimising towing operations.

2. **Present a hydrodynamic model for analysing motions and towing loads of the platform.**

   Metocean factors such as wind, waves, and currents significantly impact towing operations. However, this paper's scope does not encompass an exhaustive analysis of all these factors. Instead, the paper concentrates on studying the response of floating wind turbines to wave conditions. For this, a novel forward-speed hydrodynamic modelling approach was selected for the towing operation analysis — a method commonly employed in ship motion analyses but applied here for the first time in floating wind turbines. The analysis was conducted using an in-house tool developed at MARIN known as SEACAL, which involved modelling the platform and calculating Response Amplitude Operators (RAOs). To validate the findings, a towing test was conducted at MaREI, Cork, using the Innwind semi-submersible floater capable of accommodating a 10 MW wind turbine. The tests were performed at the installation draught as it was not possible to modify the draught of the existing model. Subsequently, RAOs calculated using the numerical model were corroborated against the experimental outcomes.

3. **Identifying the limiting wave conditions while towing**

   A numerical model approach has been presented for analysing the hydrodynamic response of the Innwind semi-submersible platform [8] carrying the NREL 5 MW wind turbine [9]. Using the model, the response in irregular waves and RAOs were calculated. The sea conditions in which the limiting factors set by DNV were exceeded were determined and the most limiting factor was identified.

The procedure outlined in the paper is adaptable to any environmental factor that should be analysed while towing floating platforms. The shortcomings of the hydrodynamic model were identified and methods for improving the model were investigated.

A study of the towing characteristics of a semi-submersible floating offshore wind platform

Published in

Journal of Physics: Conference Series, ISSN: 1742-6596 (Deepwind 2023)

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Abstract: A robust pipeline of floating wind energy has emerged with a general trend of projects becoming larger, further from shore and placed in increasingly energetic seas. The installation process for these farms involves the pre-assembly of components onshore or in sheltered waters before towing the platform to the operational location using tugs. It can be expected that such marine operations will be repeated in reverse at the time of decommissioning. The cost and safety of these operations will be influenced by the tugs used, towing speed, the local metocean conditions, the platform/turbine characteristics and other factors. This paper investigates the hydrodynamic characteristics of a large semi-submersible floating offshore wind turbine (FOWT) under tow. The motions of the FOWT are analysed using a numerical tool and validated using a towing test. A framework is proposed for the assessment of FOWT towing operations. Various limiting factors have been identified and the hydrodynamic performance of the system has been evaluated using the framework.

B.1. Introduction

Towing operations represent a critical phase of the FOWF's construction process. They were required during the installation of the existing FOWFs such as the Hywind Scotland, Kincardine and Windfloat Atlantic projects [1]. Despite the importance of these activities, the planning of towing operations currently primarily relies on the experience of the captain of the towing vessel whilst any of the modelling and planning tools for these critical operations usually rely on the general recommendations and standards developed for offshore structures [2]. When numerical models are used to assist with this process, they are typically not optimised for the very large, top-heavy FOWTs. Since many floater designs that vary in size and geometry have been developed, it is important to analyse the towing behaviour of these FOWTs individually, until FOWT-specific rules of thumb or standard industry practices are developed. This need for bespoke towing planning and optimisation tools for FOWFs is increasing in importance as they will roll out with large-scale deployments which are further from shore, and in areas where weather windows are likely to be reduced, compared to traditional bottom-fixed offshore wind farms.

This paper presents a framework that can be used to analyse the towing operations of fully-assembled FOWTs. A sequential approach, influencing and restricting factors and guidelines for FOWT towing are explained with the help of the

presented framework. An experimental study and results that were used for the analysis of a basic towing operation are also presented.

B.2. Framework for analysing the towing characteristics of a floating offshore wind turbine

FOWTs vary in shape and size and the geometry of the platform will affect the towability of the fully-assembled FOWT system. Therefore, it is important to analyse each floater separately before commencing towing operations. In this section, a framework is presented to analyse the towing operation of a FOWT (see Figure 1). This framework can be used to check the feasibility of towing a FOWT at a particular draught and speed.

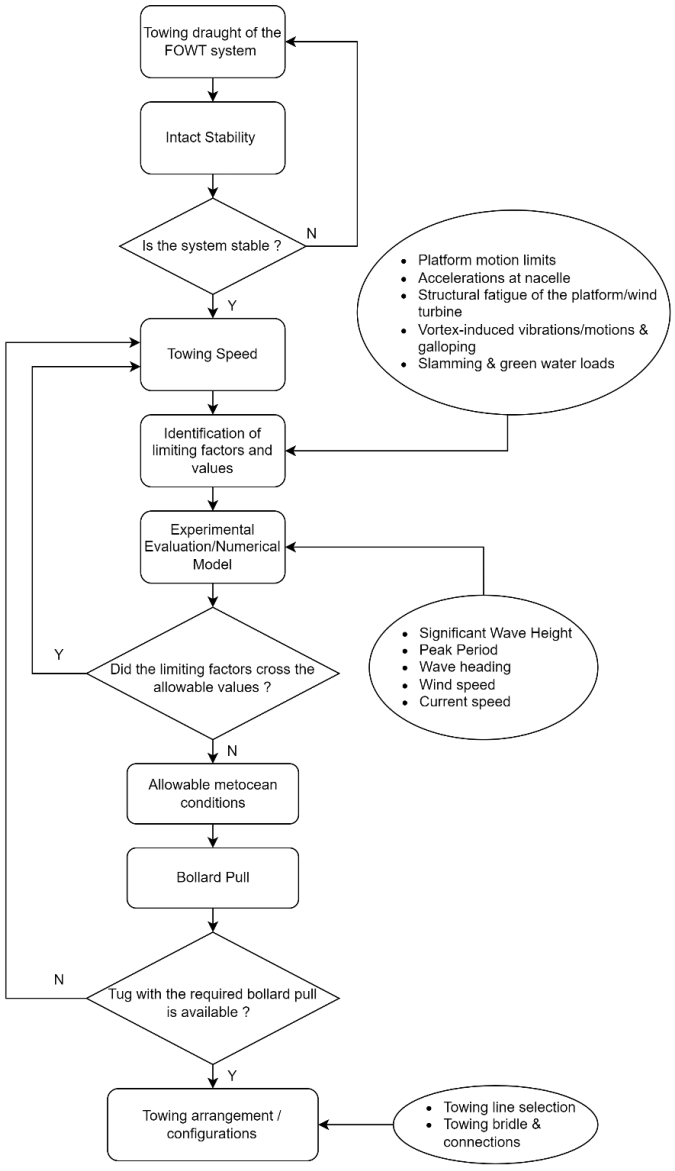


Figure 1. Framework for analysing towing of FOWTs

The first step is to check the intact stability of the FOWT at the given draught of interest. Collu et al. [3] have defined the stability requirements of FOWTs during towing operations. A minimum GM (metacentric height) of 2 m is recommended during tow-out. The static range of stability should not be less than 15 degrees and the area under the righting moment curve is to be 1.4 times more than the area under the wind overturning moment for safe towing [4]. The towing point should be positioned in such a way that the heeling moments are minimised. The maximum inclination angle, under total heeling moment, should remain below 5 degrees and under half-towline pull, should remain below 2 degrees. Furthermore, the distance between the maximum static draught and minimum water depth should be higher than 2 m or 10% of the static draught (whichever is lesser).

Det Norske Veritas (DNV) has set the limiting conditions for motions and accelerations in DNV-ST-N001, standards for marine operations [2]. Wind turbine OEMs (Original Equipment Manufacturers) have defined acceleration limits at the nacelle for operation and survival conditions. There should be sufficient freeboard at the bow to minimise damage from slamming and green water loads [5]. For long tow durations, fatigue checks should be performed for the platform as well as the wind turbines. Local areas prone to fatigue damage should be identified prior to towing and fatigue life should be assessed. The fatigue life should be higher than the entire tow duration including waiting times. For offshore structures like FPSOs (Floating Production Storage and Offloading), the hull girder strength, structural connections, local plating strength etc. are recommended to be checked [5] and this can be adopted for FOWTs also. The fatigue damage check of the structural connection between the topside and hull is also recommended by DNV [2], similarly, the connection between the tower and transition piece/platform should be checked in the case of FOWTs.

Vortex-induced motions and vibrations (VIM&VIV) are also phenomena that can affect towing operations, especially spar-type platforms and semi-submersibles with cylindrical columns [6]. These phenomena have been observed on slender oil & gas structures and were studied extensively in the past decades and this knowledge is transferable to FOWT towing operations also. VIM&VIV are strongly non-linear phenomena and no well-established analysis methods exist, but fair predictions and analyses can be made using CFD (Computational Fluid Dynamics) and model testing

[6]. One of the factors that trigger VIV is the Reynold's number [6], which is a function of speed, so towing speeds that can induce VIV should be avoided. Fishtailing is another phenomenon which should be considered while choosing the towing configuration.

A numerical/analytical model built using a suitable available hydrodynamic tool can be used to test the response of the FOWT system under various metocean conditions like significant wave height, peak period, wind speed, current speed etc. The limiting values associated with the various limiting factors and phenomena should be identified and the towing operation should be analysed numerically to find if those values are exceeded during towing in those metocean conditions. Two approaches can be followed to determine the performance of the system during the voyage:

- **Scatter diagram approach**: In this approach, for each environmental condition in a scatter diagram, the towability is determined. Based on the seasonal probability of occurrence of each entry in the scatter diagram, the feasibility of the tow can be determined. This approach is justifiable for short-distance tows. This method applies when the metocean conditions don't vary much along the towing route. For example, towing in coastal and near-offshore regions can be analysed using this method.

- **Voyage approach**: In this approach, the environmental conditions along the route are derived from a hindcast time series. The above-mentioned evaluation is applied for each condition during the voyage. This reveals whether the voyage is feasible or not depending on the starting date/time of the year in the hindcast time series. This method can be used for long-distance towing operations. For example, ocean towing from a distant port location across the ocean in a different country, where production is cheaper. In such situations the weather varies along the towing route and this approach serves better.

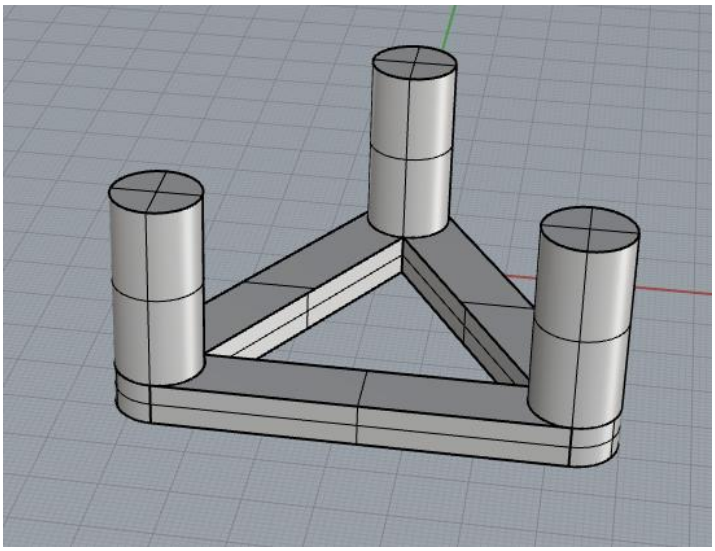
A systematic iteration of different draughts and speeds using the framework can be used to find the optimum towing draught, speed and bollard pull for a towing operation. This process requires numerous iterations to find the optimum towing characteristics, which is a lengthy and complex procedure. This method consists of:

- Determination of the least draught at which the FOWT system is statically stable. The lightweight draught (zero ballast) is the least possible draught and this is to be taken as a starting point.
- Once the draught is calculated, the towing speed is to be determined. Initially, a low towing speed (eg: 0.5 kn (knot)) is applied and then slowly raised to higher speeds.
- The various limiting factors and the permissible values are identified.
- A numerical/analytical model is built using a suitable hydrodynamic tool and the system is tested in various metocean conditions.
- If the limiting values are not exceeded during the voyage, the bollard pull can be calculated and suitable tug(s), towing line and towing arrangement can be selected. Special care should be given to check towing stability and chances of fishtailing.

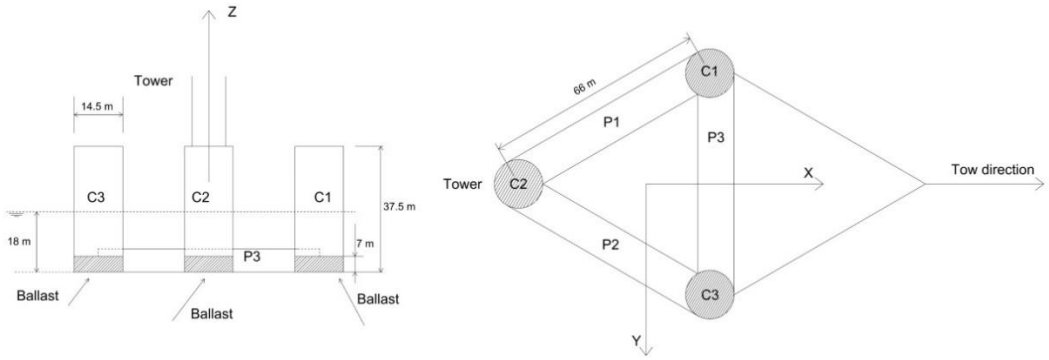
To demonstrate the usage of the framework an experimental study with a high draught and speed was performed and analysed. Focus is given to testing a particular towing speed and draught and assessing the bollard pull requirements rather than using the complete framework, which is a complex process as mentioned before. A simplified numerical model using a hydrodynamic analysis tool is used to calculate the motions and accelerations of the platform and is validated using the experimental results. Using the model, the performance of the system in various wave headings and irregular wave conditions is derived.

B.3. Model, experimental setup and testing procedure

The platform used for the study was a semi-submersible floater designed by CENER, Spain, as part of the INNWIND Project [7]. The platform is coupled with an NREL 5MW wind turbine [8]. The aluminium model was constructed at a scale of 1/50. The geometry details (see Figure 2) and main particulars (see Table 1) of the FOWT system are described below:



(a)



(b)

Figure 2. (a) CAD Model (b) Main dimensions of the floater and towing arrangement

Table 1. Main particulars of the model in the towing configuration

Main particulars	**Model Scale**	**Full Scale**
Total mass	167.3 kg	20912.5 ton
KG	0.17 m	8.5 m
GM	0.295 m	14.75 m
Draught	0.36 m	18 m
Roll moment of inertia	72481 kg m^2	2.26E07 ton m^2
Pitch moment of inertia	73413 kg m^2	2.29E07 ton m^2
Yaw moment of inertia	88849 kg m^2	2.78E07 ton m^2
T_n Heave	2.8 s (2.24 rad/s)	19.8 s (0.32 rad/s)
T_n Roll	2.9 s (2.17 rad/s)	20.5 s (0.31 rad/s)
T_n Pitch	2.9 s (2.17 rad/s)	20.5 s (0.31 rad/s)

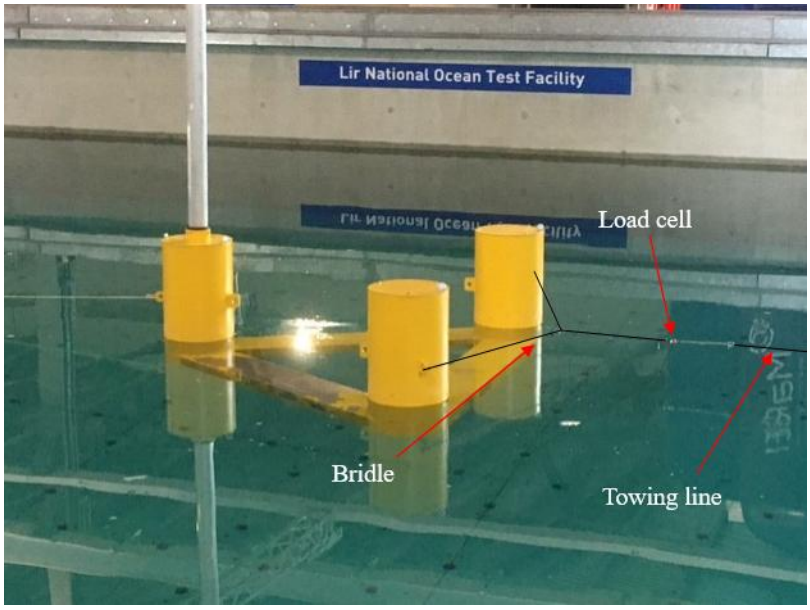
e experiments were performed in the ocean basin at the Lir NOTF (National Ocean Test Facility), University College Cork, Ireland [9]. The operational draught of 18 m is applied in the tests since the primary focus of the original test campaign was on operational conditions at zero speed. This draught is not the minimum towing draught but was adopted in the simulations because of available model test results for validation. The model was first towed at various speeds in calm water to ascertain the drag and thereby the required bollard pull. Then the system was towed in an irregular sea state. The towing line was attached to columns C1 and C3 (see Figure 3 (a)) of the model and was towed using a PI-controlled winch-motor system (see Figure 3 (b)) [10]. This system consists of a Schneider Electric BCH2 servo motor and a custom-made winch drum. The maximum rpm of the motor is 5000. The tension on the winch cable was dynamically controlled to give constant speed to the model. A spring (to absorb snap loads) and a Futek tension loadcell were mounted on the winch wire and a wave probe mounted off the instruments bridge was used to record wave elevations. The details of the instruments are shown in Table 2. A rope was tied to the stern of the model to pull it back to its start position after each test. Any potential extra drag caused by the retrieving wire was mitigated using the PI controller and adjusted on the drag measurements of the load cell. The response of the FOWT system was recorded using a Qualisys motion tracking system.

Table 2: Instrumentation used during the tests

Measured quantity	**Instrument**	**Range**	**Resolution**	**Frequency**
Position of the model	Qualisys Tracking	Several meters in X, Y, Z	1 mm	32 Hz
Towing line tension	Futek tension load cell	100N	0.1N	32 Hz
Wave elevation	EDL Wave gauge	1 m	1 mm	128 Hz
Motor system	Schneider Electric BCH2 servo motor	3.81 Nm Torque	-	32 Hz

During the tests, the motion capture camera was focussed on a small area and data was recorded only when the model passed through this area. This was a very short time period and the quality of the data obtained was very low. Two towing speeds were tested, but the towing line kept snapping during the tests in waves, which made the data useless. Based on the learnings from this campaign, better tests and numerical analyses were performed at MARIN later. These tests and the results are explained in detail in Chapter

III. The tow-out operation is usually carried out at low speeds (1.5 – 3 kn) [4], but since the ambitions are to tow at higher speeds a towing speed of 5 knots is used in the experiment as well as in the numerical calculations. Table 3 shows the details of the tests performed. The model scale and prototype values (in brackets) are shown.



(a)



(b)

Figure 3. Towing arrangement (a) and winch-motor system (b)

Table 3. Test matrix

Description	Towing speed (m/s)	Wave height (m)	Remarks
Calm water	0.07(0.5), 0.22(1.56), 0.36(2.54)	-	Head-sea
Irregular waves	0.36(2.54)	Hs = 0.06(3) m Tp = 1.13(8) s	Head-sea

B.4. Hydrodynamics of the FOWT system

B.4.1. Limiting motion criteria and conditions

According to the default motion criteria set by DNV, the maximum permissible roll and pitch amplitude must be 5 degrees and heave acceleration must be 0.1g [5]. The limits vary according to the duration of towing, but as a starting point, the towing is assumed to be a weather-restricted operation in benign conditions. A total acceleration (vector sum) limit of 1 m/s^2 for the NREL 5 MW wind turbine is chosen based on previous studies [11]. The identified limits are mentioned in Table 4. This list is not exhaustive, and it is possible that other limiting factors which are not yet identified may exist and require dedicated research for identifying them. The limiting values can also be varied depending on the floater design and the wind turbine machinery.

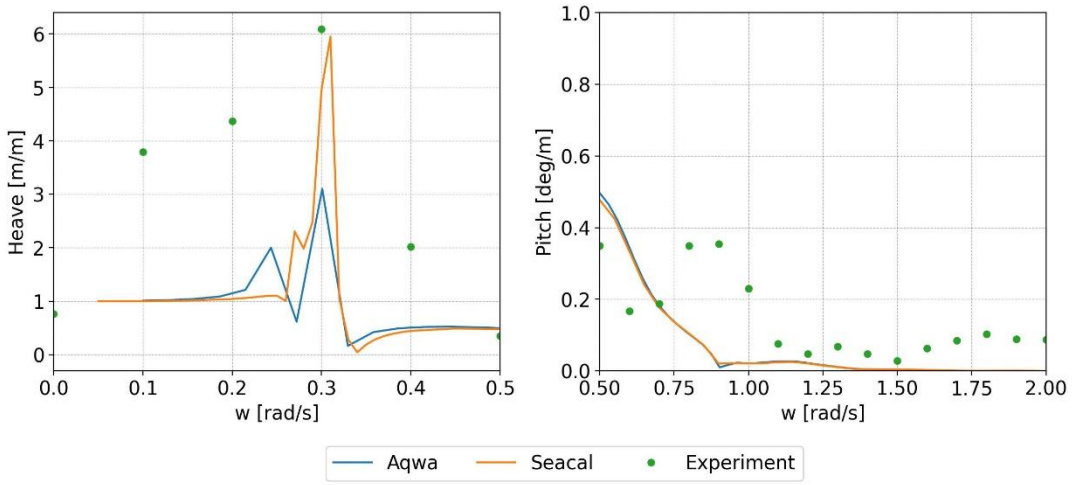
Table 4. Limiting factors and values

Limiting Factor	Limiting value (maximum)
Roll motion	5 degrees
Pitch motion	5 degrees
Heave acceleration	0.1 g
Total acceleration at the nacelle	1 m/s^2

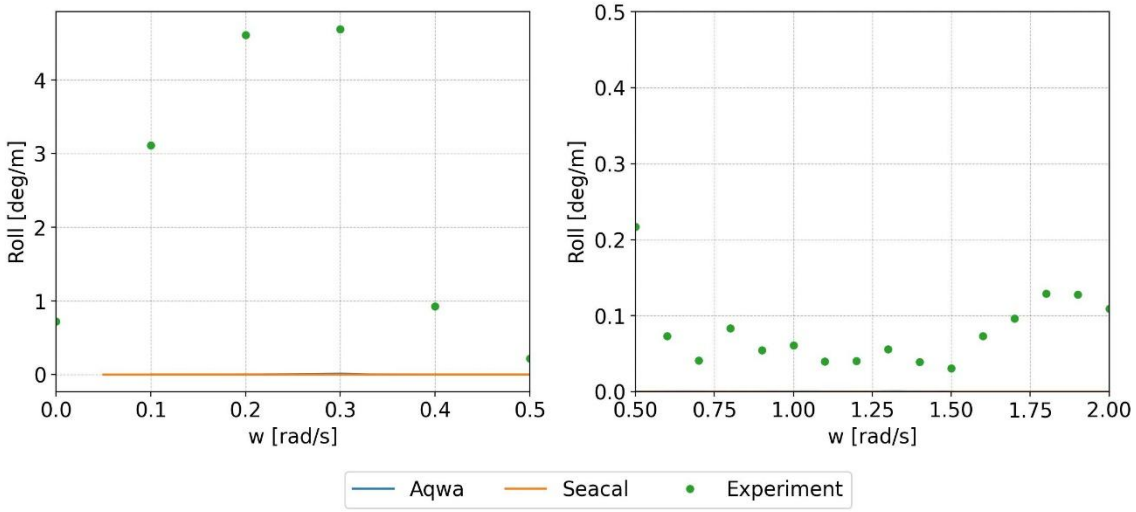
B.4.2. Motions and accelerations

The motion response of the FOWT system recorded during the tank testing is presented in this section. The RAOs (Response Amplitude Operators) of the heave, roll and pitch motions were derived by analysing the data obtained from the Qualisys motion tracking system. The phase information was not available. All the results were converted into full-scale values. In parallel, a numerical model was set up using MARIN's (Maritime Research Institute, Netherlands) in-house hydrodynamic seakeeping code SEACAL. SEACAL can perform hydrodynamic analyses of bodies with forward speed. Viscous effects were neglected for the calculations. It is assumed that the wind turbine is in

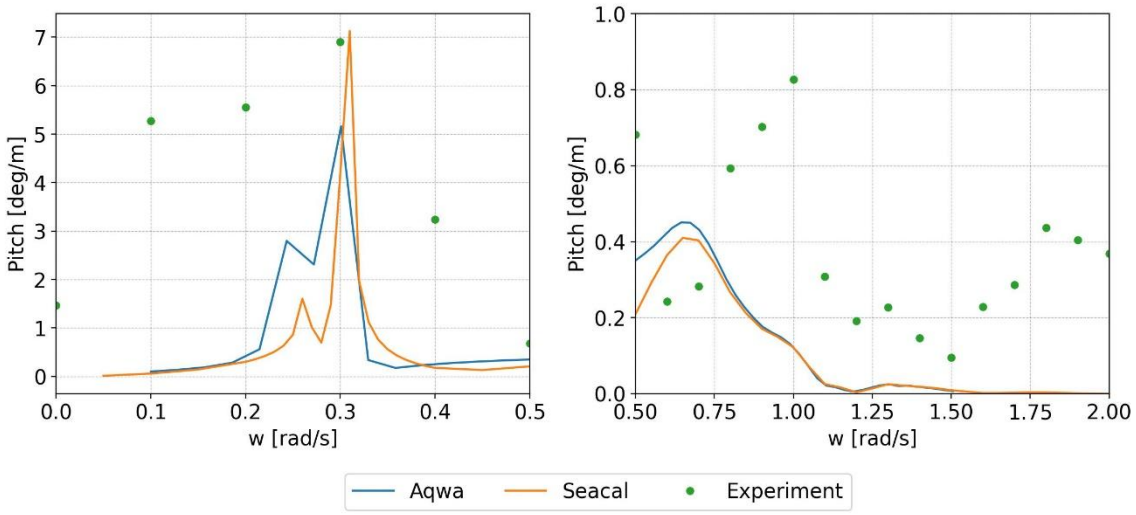
parked-feathered condition during towing. This would reduce the wind forces on the turbine during towing. The effect of wind and current would need a dedicated analysis but is neglected for this study. The commercial hydrodynamic software suite Ansys-Aqwa [12] was also used for the analysis as an additional tool and the option for analysing bodies with forward speed was utilised for analyses. The natural frequencies of the system in heave, roll and pitch have been determined experimentally in decay tests at the experimental facility (Table 1). Figure 4 shows the validation of the numerical model using the test results. The towing speed was 5 knots, in head waves.



(a)



(b)



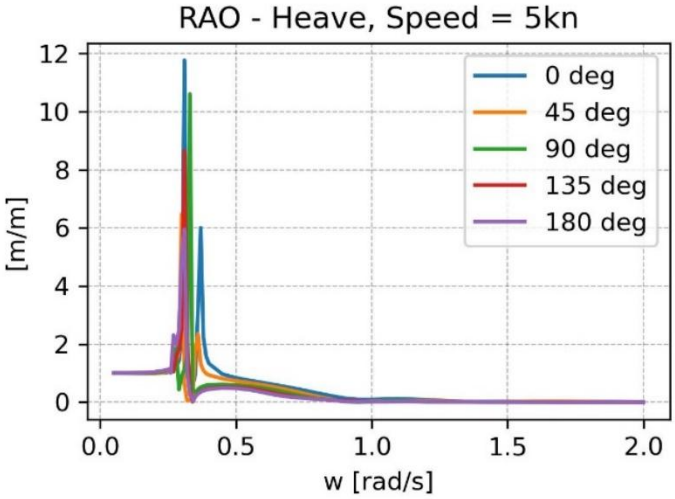
(c)

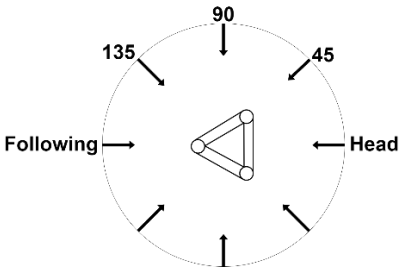
Figure 4. Comparison of motion RAOs (a) Heave (b) Roll (c) Pitch, towing speed = 2.572 m/s (5 knots)

The resonance frequency has been correctly captured by the model (see Table 1) and the motions at higher frequencies are in moderate agreement with the experimental results for pitch and heave. For frequencies lower than the resonance frequency the tests still show significant RAOs. Even though the roll motion is observed to be very low in head-sea conditions, some roll motion was observed during the experiments. This requires further investigation to check if this happened due to model asymmetry, wave reflections from the tank or unforeseen physical phenomena.

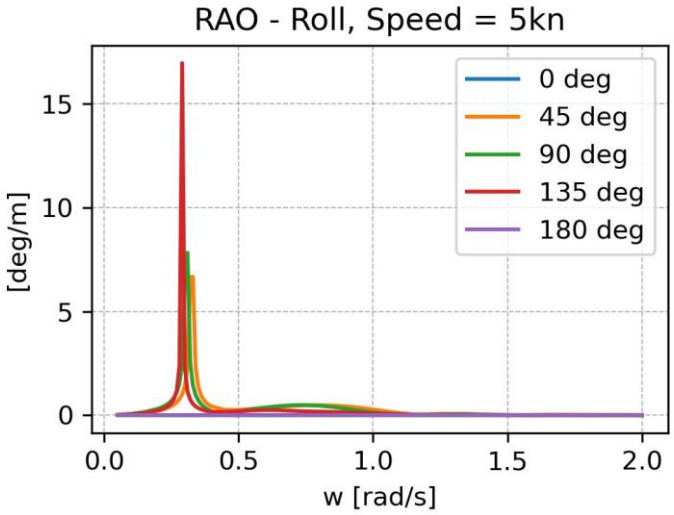
B.4.3. Motions of the system in various headings

In realistic sea conditions, the FOWT will encounter waves from different directions during towing. It is important to investigate the hydrodynamic performance of the system in various headings and to understand the effect of the direction of the incident waves on the motions of the system. In this section, the effect of the incident wave headings on the motions and accelerations of the FOWT system is presented using the validated SEACAL numerical model (The details of the SEACAL software is presented in Chapter 4, Appendix A2). Figure 5 shows the motion RAOs and acceleration transfer functions of the FOWT system under various wave encounter directions.

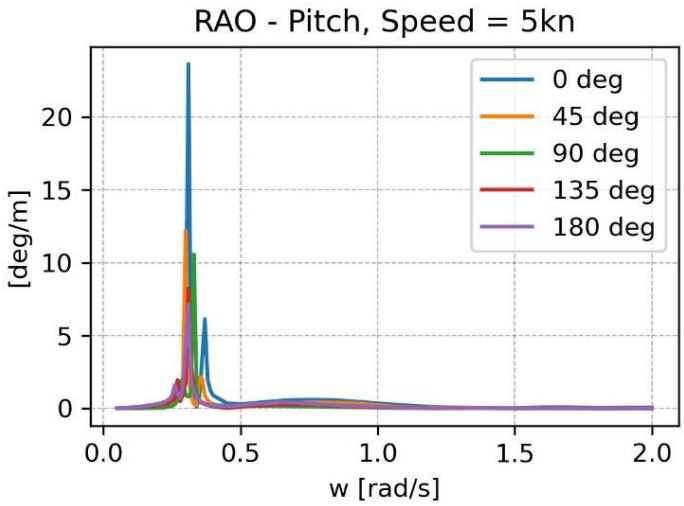

RAO - Heave, Speed = 5kn
[m/m]
w [rad/s]
0 deg
45 deg
90 deg
135 deg
180 deg


90
135
45
Following
Head

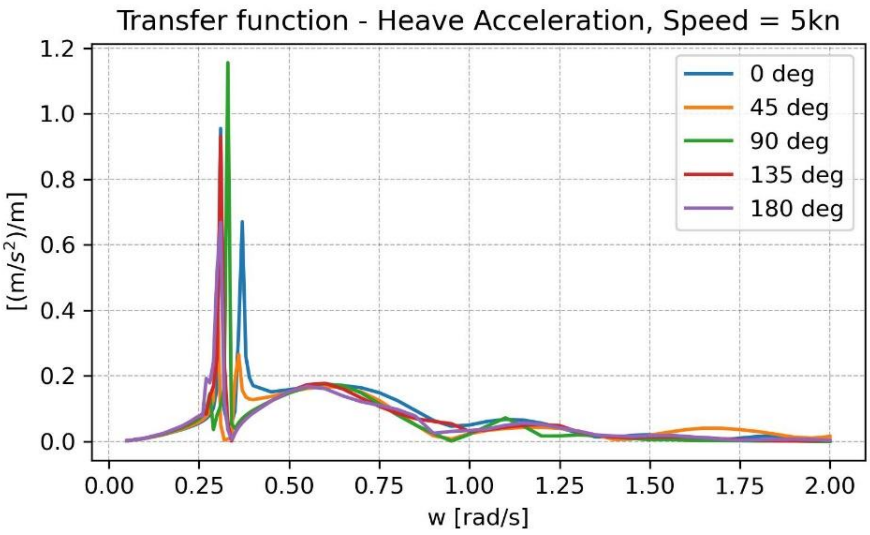
(a)


RAO - Roll, Speed = 5kn
[deg/m]
w [rad/s]
0 deg
45 deg
90 deg
135 deg
180 deg

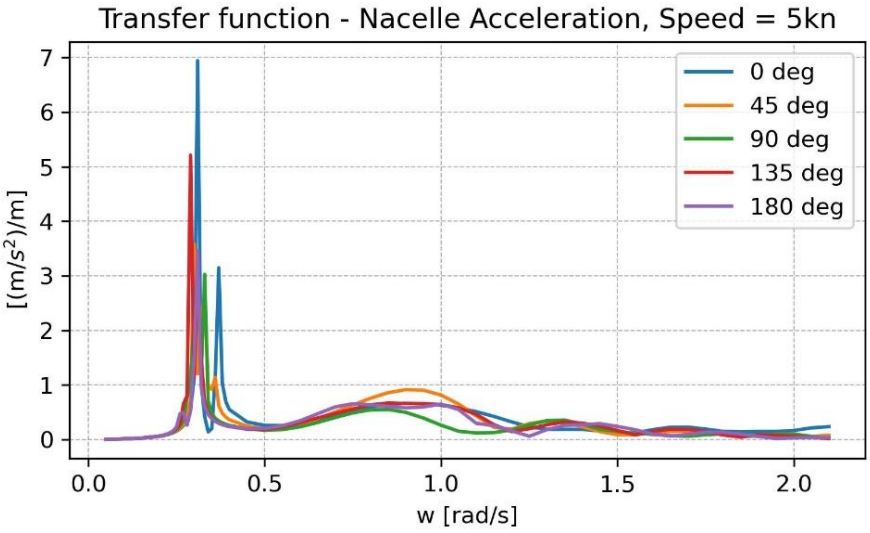
(b)


RAO - Pitch, Speed = 5kn
[deg/m]
w [rad/s]
0 deg
45 deg
90 deg
135 deg
180 deg

(c)



(d)



(e)

Figure 5. Motion RAOs (a) Heave (b) Roll (c) Pitch and acceleration transfer functions (d) Heave acceleration (e) Acceleration at nacelle, showing the influence of wave direction.

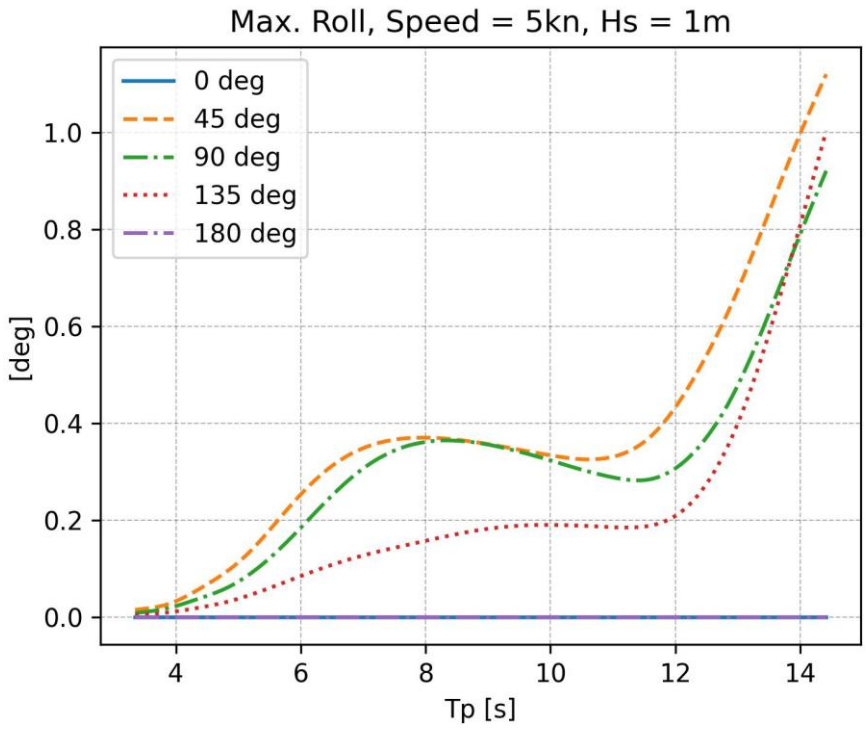
The direction of the incident waves has a considerable impact on the motions and accelerations of the FOWT system. In beam and quartering seas, the pitch and roll motions are severe. The chances of exceeding the permissible motion limits are high in such sea-states.

B.4.4. Motions of the floater system in irregular waves

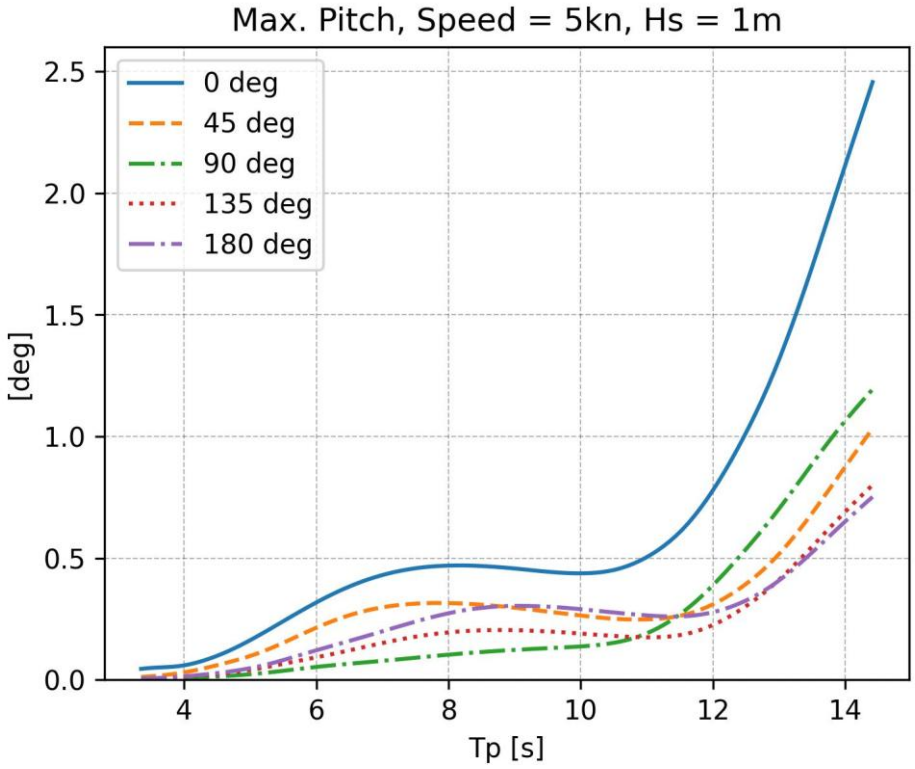
It is important to analyse the motion of the FOWT system during towing in irregular seaways as significant wave height (Hs) and peak period (Tp) impact the motions of the towed system. Moving out into deeper waters will be required in the near future to meet the energy supply demands [1]. Eventually, towing operations have to be performed in rougher seas and analysing the hydrodynamic behaviour of the floaters in rough seas is of paramount importance. Using SEACAL, the FOWT system is analysed and the results are plotted. JONSWAP (Joint North Sea Wave Project) spectrum is used for the analyses and the expected maximum values are calculated for roll motion, pitch motion, heave acceleration and nacelle acceleration. These values are plotted for various Tp conditions. From the previous numerical analyses, it was evident that the wave headings have a significant impact on the motions of the floater. So, the maximum values are plotted for various headings assuming a towing speed of 5 kn. The range of peak periods to be analysed for towing operations is given by [4]:

$$\sqrt{13Hs} \leq Tp \leq \sqrt{30Hs}$$

The range of Tp values (3.6s – 15.5s) is calculated assuming a maximum Hs of 8 m given by the above equation. Figure 6 shows the maximum values calculated for roll and pitch motions and Figure 7 shows the maximum values calculated for heave acceleration and acceleration at the nacelle for the system at a Hs of 1 m. In Figure 6, it can be observed that the FOWT system experiences maximum roll motions in stern-quartering waves. As the Tp value increases, the roll motion amplitude comes closer to 1 degree at a Tp value of 14 s. For Tp values between 7 s and 11 s, the roll amplitude remains slightly below 0.4 degrees. Pitch motion is severe in following sea conditions. At a Tp value of 15.5 s the maximum pitch amplitude is 2.5 degrees. For Tp values between 7 s and 11 s, the pitch amplitude remains slightly below 0.5 degrees.

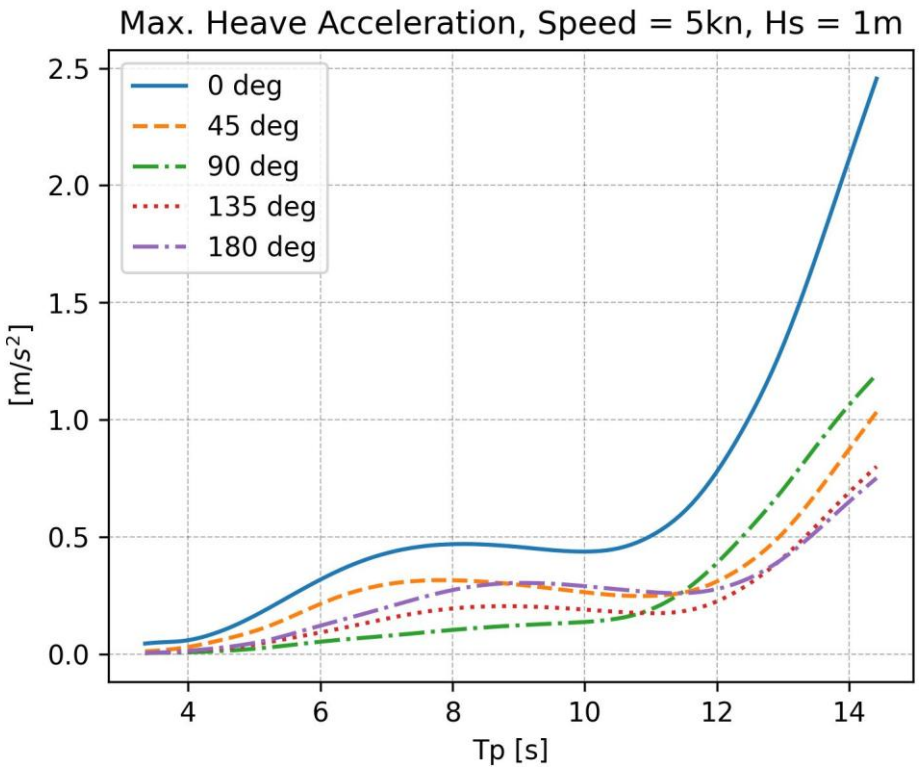


(a)

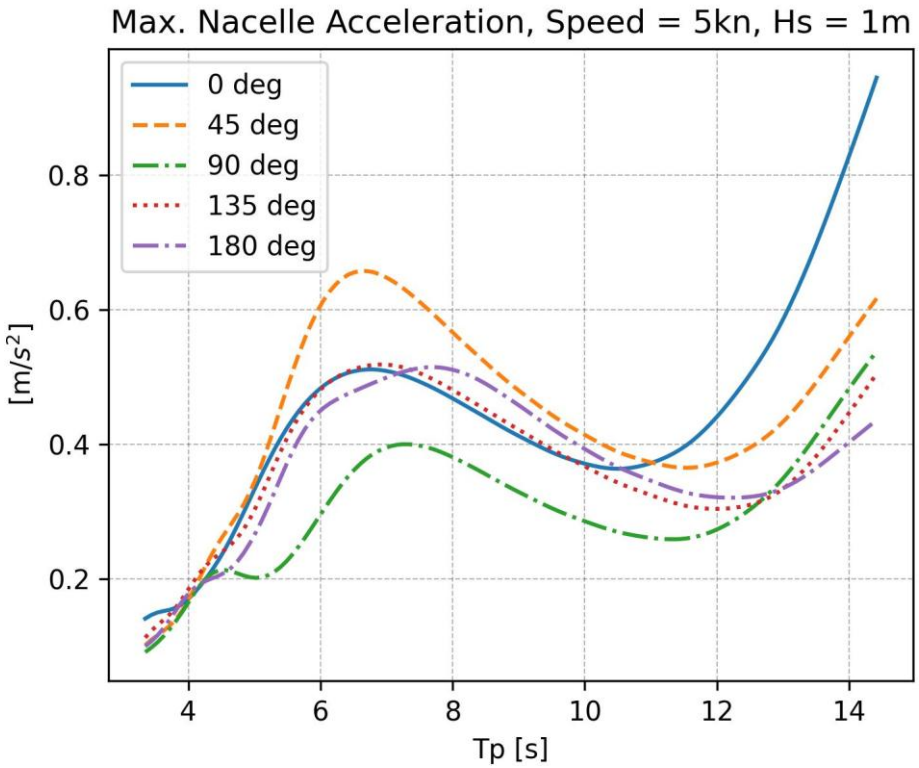


(b)

Figure 6. Maximum values of roll (a) and pitch (b) motions in various wave headings



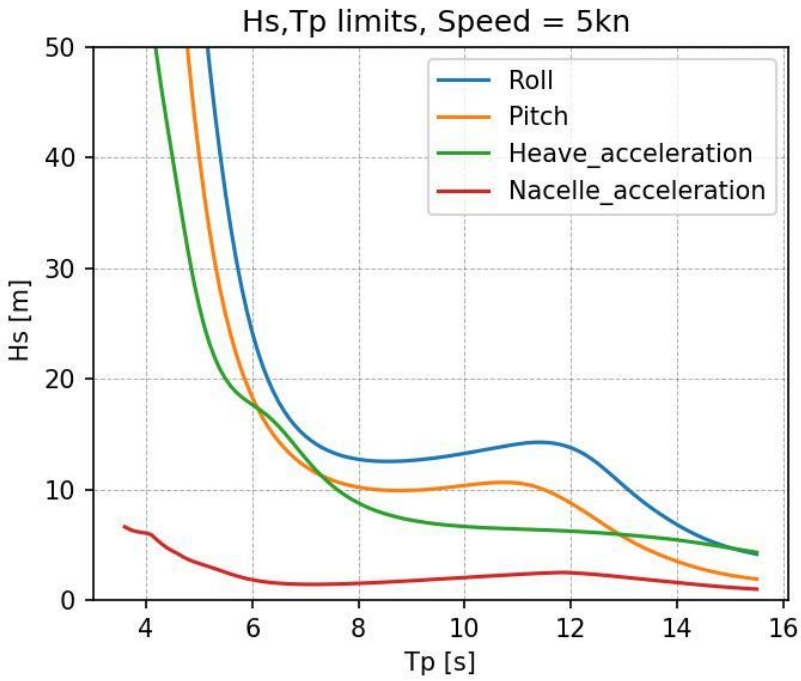
(a)



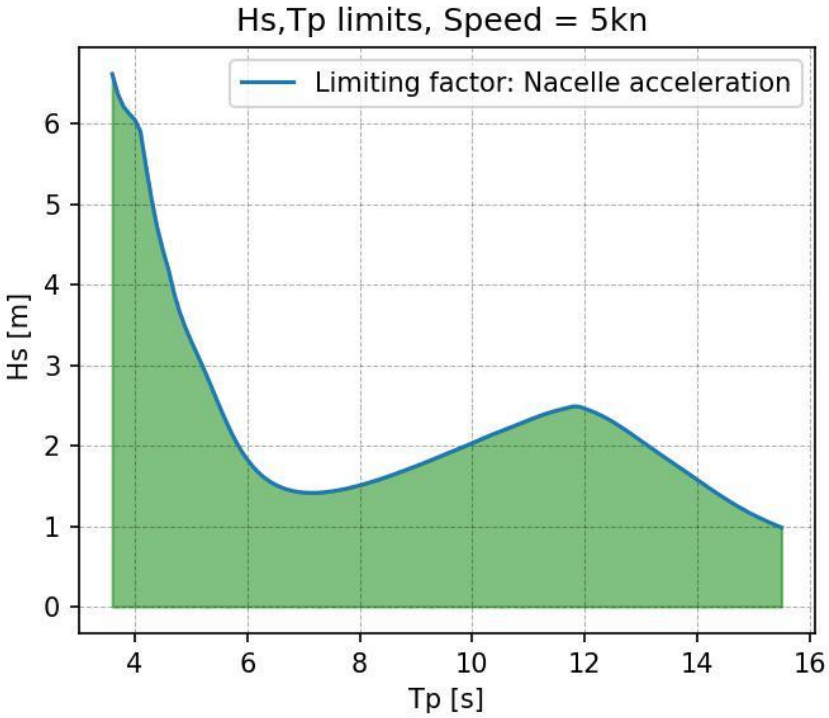
(b)

Figure 7. Maximum values of heave (a) acceleration and acceleration at nacelle (b) in various wave headings

In Figure 7, the heave acceleration exceeds the limiting value of 0.1g close to a Tp value of 12.5 s in the following-sea condition. For Tp values ranging from 7 s to 11 s, the heave acceleration remains below 0.5 m/s^2. Acceleration at the nacelle gets closer to the limiting value of 1 m/s^2 around a Tp value of 15.5 s. Assuming the motions and accelerations vary linearly with respect to Hs, the limiting Hs values can be calculated. The Hs and Tp at which the motions and accelerations remain under the permissible limits for the chosen limiting factors are shown in Figure 7. It can be observed that the acceleration at the nacelle is the strictest limiting factor and determines the towing characteristics. The wave conditions (Hs, Tp) at which the towing operation is feasible fall into the green area in Figure 8.



(a)

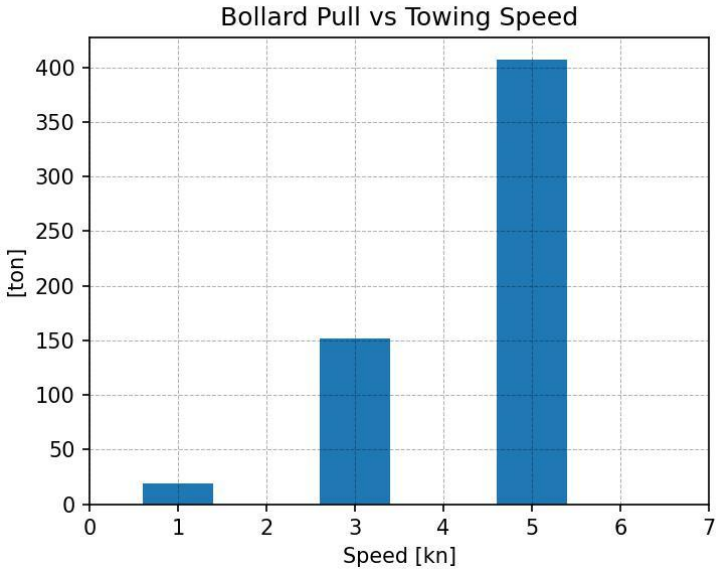


(b)

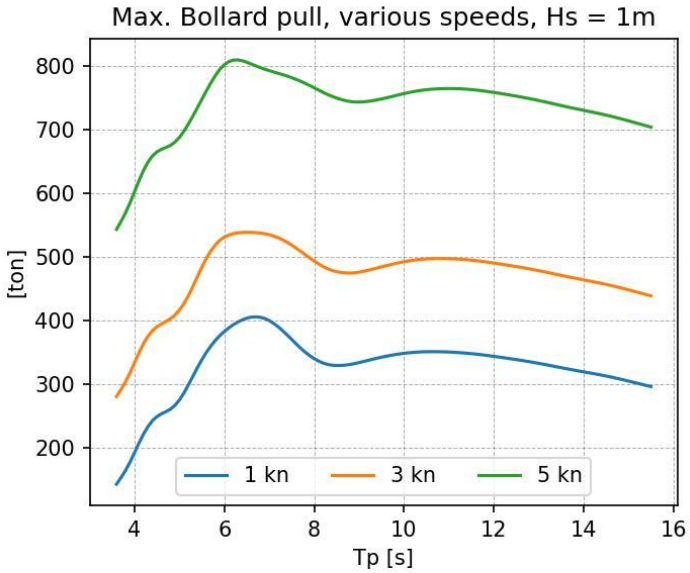
Figure 8. (a) Hs,Tp limits for various limiting factors (b) Hs,Tp limits for the strictest limiting factor

B.4.5. Bollard pull

The tension on the cable while towing was recorded and these values indicate the bollard pull for towing the FOWT system. The bollard pull for various speeds was derived from the experiment results for calm water and calculated using the numerical model for irregular waves. Figure 9 shows the variation of the required bollard pulls with respect to towing speed in calm waters and irregular waves under head-sea tow.



(a)



(b)

Figure 9: Required bollard pull in calm water vs towing speed (a) Bollard pull requirement in various sea-states (b)

Figure 9 only shows the calm water bollard pull at even keel of the FOWT. The bollard pull will increase due to wave added resistance, wind loads, trim etc. The bollard pull requirement increases quadratically as the towing speed increases. Figure 9 shows that a maximum bollard pull of around 800 tons is required for towing the FOWT with the mentioned draught and speed in irregular waves. A tug efficiency factor of 1 is assumed

for the calculation, but in reality, the value is 0.75 for ocean towing [2], which raises the bollard pull requirement even higher.

B.5. Conclusions and further research

This paper has provided a general framework for the assessment of the hydrodynamic performance of a fully assembled FOWT system in different draught, wave and towing speed conditions. For the semi-submersible platform considered, the motions of the system remain under acceptable limits for many wave conditions, but the acceleration at the nacelle is the strictest limiting factor here and hence determines the limiting environmental conditions and hence the towing characteristics. A Hs of around 1.5 m is a realistic significant wave height at the mentioned draught and speed for safe towing in all the sea-states analysed in the study. Identifying the strictest limiting factors and raising the limiting value by improving the design of the component in the FOWT system will help raise this Hs limit.

The towing speed and draught analysed in this study are not optimised and a systematic iterative study using various towing draughts and speeds can improve the towing characteristics. A basic analysis revealed that the bollard pull increases quadratically when the towing speed increases. If the required bollard pull is more than that can be handled by a single tug, multiple tugs can be used, but this increases costs.

To date, FOWTs have generally been towed by AHTSs (Anchor Handling Tug Supply) during installation. Some AHTSs have up to 300 ton bollard pull but higher bollard pulls are rare [4]. Detailed dedicated analyses are required for checking the effect of wind and current also before commencing towing operations for large floating offshore wind turbines. Further research is required for the development of the method using a voyage-analysis approach. In this approach the environmental conditions along the route are derived from a hindcast time series. Checking the towability at every time step reveals the towability of the complete voyage. Additionally, involuntary or voluntary speed or course changes can be applied for long towing operations. The effect of wind, trim of the floater and VIM should also be included in the studies. For long tows, the directional stability of the FOWT system should also be checked for course-keeping. As the FOWTs get larger, large ocean-worthy tugs with high bollard pulls might be required in the near future for the installation, major repairs and decommissioning of such FOWTs.

Acknowledgement

This research work has received funding from STEP4WIND, a European Industrial Doctorate programme, granted under the H2020 Marie-Curie Innovative Training Network initiative (H2020-MSCA-ITN-2019, grant agreement 860737).

Appendix A: Numerical tools used in the study

Ansys Aqwa (Included in Ansys student R1 2022)

Ansys Aqwa is a hydrodynamic software tool designed to analyse the behaviour of marine and offshore structures under various environmental loads, such as waves, wind and currents. Part of the Ansys software suite, Aqwa can be used for analysing the dynamics of floating structures, including offshore platforms, ships and renewable energy devices like FOWTs. Aqwa can be used to perform a variety of analyses, from static and dynamic response to advanced simulations for design optimization. One of the key features in Aqwa is its ability to analyse the effects of forward speed on the hydrodynamic behaviour of vessels, which can be used for analysing operations like towing.

The software employs a pulsating Wave Green's function (WGF) source across the mean wetted surface, along with a forward speed correction in the body boundary condition, to numerically solve diffraction and radiation potential components in the frequency domain using a three-dimensional panel method. It also incorporates the forward speed effect in the Bernoulli equation when calculating wave exciting forces, added mass, and damping coefficients. When the forward speed is small in amplitude, an approximate free surface boundary condition can be used:

$$-{\omega_e}^2\varphi + g\frac{\partial\varphi}{\partial z} = 0 \qquad \text{where } z = 0$$

Where:

ω_e is the encounter frequency

φ is the wave potential

Under this situation, the frequency domain pulsating Green's function can be employed together with a modified body boundary condition to numerically solve the diffraction and radiation potential components:

$$\frac{\partial \varphi}{\partial n} = \begin{cases} -i\omega_e n_j + U m_j & \text{for radiation} \\ -\dfrac{\partial \varphi_i}{\partial n} & \text{for diffraction} \end{cases}$$

Where:

$$(m_1, m_1, m_1) = (0, 0, 0)$$

$$(m_4, m_5, m_6) = -\frac{1}{U}\bar{U} \times \bar{n}$$

φ_i is the incident wave potential

U is the forward speed

$\bar{n}$ is the normal vector at a particular point on the body surface

A1. Workflow in Aqwa for Forward Speed Analysis

The workflow in Aqwa for conducting a forward speed analysis generally follows these steps:

1. **Geometry Definition**: The geometry of the structure is imported into Ansys Aqwa. This geometry includes the hull shape and mass properties.
2. **Hydrodynamic Mesh Generation**: Aqwa generates a hydrodynamic mesh for the structure. This mesh allows for the accurate computation of potential flow around the structure.
3. **Definition of Forward Speed and Environmental Conditions**: The forward speed of the structure is defined, along with wave characteristics, such as wave height, frequency and direction.
4. **Calculation of Added Mass and Damping Matrices**: For each wave frequency, Aqwa calculates the forward-speed-dependent added mass $A_{ij}(V)$ and $B_{ij}(V)$ matrices.
5. **Solving the Equations of Motion**: Aqwa solves the frequency-domain equations of motion, considering the added mass, damping, and forward speed effects. This solution provides the response amplitude operators (RAOs), which describe the structure's motion response to waves at each frequency.
6. **Post-Processing and Analysis**: The results are analysed to determine the structure's response characteristics, including RAOs, forces, and moments. This information is used to assess stability, predict motion behaviour, and guide design optimizations for the structure under towing or transit conditions.

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Chapter 4

Experimental towing analysis and numerical validation: Paper C

4.1 Motivation and Aim

The preceding paper assessed the necessity of analysing towing operations and emphasised the significance of employing the most effective hydrodynamic tools. This paper aims at analysing numerical models for simulating towing operations. Two distinct numerical modelling approaches have been devised for this purpose. Recognising the scarcity of experimental data in the realm of floating wind towing operations, the initial phase involved generating experimental data essential for validating the hydrodynamic model employed in towing operations. In the previous tests, the platform was towed at installation draught as it was not possible to modify the draught of the platform. This is not the typical scenario, as the towing draught usually tends to be lesser than the installation draught. Consequently, an experimental campaign was designed to acquire the experimental data using a floater at towing draught. The details are as follows:

1. **Creation of an experimental database for studying semi-submersible towing operations**

   The DeepCwind platform [10] carrying the NREL 5 MW wind turbine was used for the experiments. The towing draught was determined and the platform was towed with different towing configurations and wave conditions. The motions of the platform and towing loads were recorded. The details of the experimental campaign and major observations are detailed in the paper.

2. **Development of numerical models for analysing towing operations**

   Calculating Response Amplitude Operators (RAOs) during towing is pivotal in assessing the towed platform's response in diverse sea conditions and determining the optimum towing routes [11]. Two numerical approaches were adopted for this purpose:

   1. **A hybrid approach using potential-flow method combined with the Morison equation.**

      This method was implemented in the commercial software Orcaflex. The hydrodynamic model was built taking viscous effects into consideration. The hydrodynamic response of the platform model was calculated in time domain. The RAOs were then calculated for a range of towing speeds and wave heights.

   2. **An improved version of the forward speed approach used in the previous paper.**

      This method was implemented using SEACAL which was also used in the simulations mentioned in the previous paper. This method was further enhanced using quadratic damping coefficients extracted from decay tests to account for viscous effects.

The simulations are compared with the experimental results and presented. An uncertainty analysis of the experimental data has also been performed and added to the paper. The advantages and disadvantages of the presented numerical approaches have been identified and documented.

Towing analysis and validation of a fully assembled floating offshore wind turbine based on experimental study

Published in

Journal of Marine Science and Engineering

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Abstract: The offshore wind sector is moving into deep waters and using floating platforms to harness the higher wind speeds in exposed locations. There are various floating platform types currently in development, but semi-submersibles are considered the most prominent early movers. Such floaters need to be towed to and from wind farm locations for installation, special cases of repair and decommissioning. As with any other offshore activity, metocean limits exist for towing operations which can impact the development of a wind farm. It is important to calculate the motion and loads of the platform before commencing the towing operations and to check whether they exceed the defined limits to enable safe execution. In this paper, two approaches using two different numerical tools to predict the motion of a fully assembled floating wind platform under tow are presented and compared. A potential flow-based method derived from a low forward speed approach and a hybrid approach combining potential flow and Morison equation methods are investigated, and the numerical predictions are compared and validated against experimental results. Both methods demonstrate accurate predictions, depending on the wave condition and towing speed, albeit differing in execution time and the simplicity of the simulation setup. The first method was found to provide good predictions of the motion in low-speed (0.514–1.543 m/s) towing conditions. The second method provides better results for all the towing speeds and wave heights. As the wave height and towing speed increase, deviations from experiments were observed, signifying non-linear phenomena that are difficult to analyse using the mentioned potential-flow-based methods.

Keywords: floating offshore wind turbine; marine operations; towing

C.1. Introduction

The harnessing of wind energy from deepwater sites is the next stage of the commercialisation of offshore wind. Several pilot-scale floating wind farms are already operational worldwide, with larger-scale deployments in planning. Floating Offshore Wind Turbines (FOWTs) are specifically engineered to harness higher wind speeds in deep waters, presenting unique challenges compared to fixed-bottom wind turbines. Numerous investigations focusing on the development of floating wind turbine designs, operation conditions and numerical analysis methodologies have been developing in recent years [1]. A significant challenge involves the installation of these structures, typically accomplished by towing the FOWTs to their designated farm locations using

large ocean-going vessels. The FOWT system is susceptible to various metocean factors, including wind, waves and currents, which significantly influence towing operations. As wind farms venture into deeper waters, environmental conditions generally become more extreme, amplifying the complexity of the marine operations necessary for installation, operation, maintenance and decommissioning. It is imperative to thoroughly investigate the impact of these environmental factors on an FOWT when planning the construction of large wind farms. This comprehensive understanding will facilitate the identification of optimal weather windows and enable more reliable year-round planning for floating wind farm construction.

The installation methodology employed varies, based on the type of floater utilised to support the wind turbine. FOWTs offer a distinctive opportunity for complete construction and assembly in sheltered waters or at quaysides. Irrespective of the floater type, the installation process necessitates a crucial marine operation—towing. Following construction, the primary challenge entails transporting the fully assembled FOWT system to the designated installation site, where it is connected to preinstalled mooring lines. This task is typically accomplished using towing tugs capable of towing the system from the quayside to the wind farm site. This marine operation poses notable challenges due to often adverse sea conditions, which may subject the turbine to significant loading due to platform motion.

Semi-submersible FOWTs, which can be fully constructed at quaysides and subsequently towed to the farm location, are a popular choice for platform technology developers. As these platforms are susceptible to significant wave-induced motion [2], it is imperative to analyse the motion characteristics of fully assembled semi-submersible FOWTs under tow. This will allow an assessment of vessel requirements, turbine loading, weather windows, safety and ultimately the viability of towing these significant structures in deep waters, far from shore, where weather conditions can change rapidly. Given the sensitive nature of wind turbine structures to motion, maintaining acceptable values of motion and acceleration is essential to prevent damage to components and to maintain the high standards of Safety of Life at Sea (SOLAS).

It is worth noting that all the existing floating wind farms across the globe have utilised towing operations during their installation phases. The Windfloat Atlantic, Hywind Scotland, Kincardine and Hywind Tampen projects utilised towing vessels and

operations during their construction [3,4]. Tow-to-port and tow-to-shallow operations are planned for major maintenance activities for Kincardine and Hywind Scotland wind farms, respectively [5]. During a heavy maintenance campaign at the Kincardine wind farm, one of the platforms was detached from the mooring system and towed to a maintenance port and subsequently towed back to the wind farm location after necessary repairs [6]. Thus, towing operations remain crucial for significant repairs and decommissioning processes also, reinforcing their status as one of the most vital marine operations throughout the entire life cycle of a floating wind farm.

Numerous factors influence the towing operation of an FOWT system. Some of these concerns the motion that affects the survivability and course-keeping of the platform, whilst others deal with the forces and acceleration limits on the structure. These factors collectively ensure the secure, safe and efficient transit of the fully assembled FOWT system to its wind farm destination. Throughout the towing process, the platform contends with various metocean elements such as wind, waves and currents. It is important to avoid severe motion and acceleration and phenomena like fishtailing while towing. While FOWTs are engineered for stability at high draughts with mooring lines in place, the towing phase often necessitates the transportation of deballasted platforms at lower draughts and without the support of mooring lines. Consequently, dedicated research into platform motion during towing is imperative to facilitate safe towing operations.

Towing operations have been the subject of research in the context of Oil and Gas platforms over the past few decades, primarily during the exploration phase. Existing ocean towing practices are guided by established general rules and guidelines for marine operations [2,7,8]. In recent years, there have been emerging efforts to analyse towing operations specific to FOWTs. A critical aspect contributing to the safety of towing operations is the stability of the platform during transit. While dedicated rules and guidelines for assessing the intact stability of FOWT systems are currently lacking, certain principles can be adapted from the extensively developed standards within the oil and gas industry, which have been in use for an extended period. Collu et al. [9] conducted research in this area, proposing stability guidelines for fully assembled FOWTs during the transportation and installation phases. Furthermore, there has been a growing interest in investigating the motion dynamics of platforms during towing

operations. Ding et al. [10] conducted a numerical analysis of the towing operation involving a submerged Tension Leg Platform (TLP) wind turbine, employing a multi-body approach to examine the impact of environmental factors (e.g., wind and waves), bollard pull and towing point height on the towing process. Their study involved modelling and analysing a multi-body system comprising a tug, a towing line and an FOWT, encompassing various environmental conditions and identifying limiting factors. It showed that the platform exhibited stability up to significant wave heights of 5 m and wind speeds of 17 m/s while being towed at speeds of up to 2.8 m/s.

Buttner et al. [11] conducted an experimental investigation to examine the towing process of the Orthospar platform while subjecting it to waves propagating from different directions. Concurrently, they assessed the loading experienced due to the towing line during these experiments. In a separate study, Mas-Soler et al. [12] carried out experiments involving a Tension Leg Platform (TLP) to determine the platform's towing characteristics across various towing configurations, both in calm waters and under diverse wave conditions. Le et al. [13] analysed the towing performance of two submerged floating offshore wind turbines, evaluating platform motion under varying sea conditions. The study involved calculating maximum values for the heave, pitch and roll and using these to establish limits for towing these platforms based on significant wave height. Additionally, the study derived the bollard pull requirements for different towing scenarios. In another study, Hyland et al. [14] conducted towing tests, assessing the drag prerequisites of the GICON TLP under various operational and towing conditions, and they observed Vortex-Induced Motion (VIM) while towing in calm water.

Many of the mentioned investigations focused on towing in specific metocean conditions, depending on the type of floater and installation sites. Previous experimental investigations outlined the observations and motion characteristics recorded during the experiments, but numerical analysis methodologies have rarely been mentioned. FOWTs are usually planned for farm-scale deployments with multiple repeated towing operations compared to the towing of an oil and gas floating platform, which is usually a one-off process. Finding the optimised towing speed and ascertaining the metocean limits is crucial to enabling safe, efficient and cost-effective towing operations [3]. A comprehensive, systematic study focusing on various towing speeds and wave heights

and their effects on FOWT motion and towing loads is lacking. This paper aims to fill this gap in knowledge, and it provides an ’industry-ready’ approach to understanding and analysing FOWT towing operations. It also aims to create an experimental database for studying semi-submersible towing operations and fuelling further research.

This paper presents and analyses an experimental investigation conducted to understand the towing characteristics of a semi-submersible platform under various conditions, including different speeds, physical configurations and wave conditions. The study placed particular emphasis on the hydrodynamic drag and motion that the platform exhibited during the towing operation. The motion was simulated numerically using two distinct approaches. In the first approach, the platform was represented as a body in motion at a small forward speed, and the motion was simulated using potential-flow-based approaches. This is an analysis methodology commonly used for the hydrodynamic analysis of ships moving with a small forward speed. The forward speed can have a considerable impact on the wave forces acting on a body, especially the second-order drift forces [15]. Grue et al. [16] studied this problem and found that a forward speed of 1 m/s can increase the drift forces by up to 50% compared to a body at zero speed. Later, Grue et al. [17] extended the numerical approach to analysing bodies in waters of a restricted depth also. This paper presents a novel investigation into the applicability of this approach across a large range of speeds and wave heights, attempting to predict the dynamic response of a towed semi-submersible FOWT by incorporating quadratic damping coefficients, derived from decay tests, to accurately ascertain the impact of viscosity. The second approach involves modelling the platform under zero-speed conditions, with towing simulated by restraining the platform using towing lines and applying a current equivalent to the towing speed. Second-order drift forces play a major role here, and a similar problem was analysed by Emmerhoff et al. [18] to understand the slow-drift motion of vertical cylinders moving with a low speed (or a slow current). An explicit solution for the analysis of a single cylinder was derived and extended to analyse a rectangular arrangement of cylinders. Negative damping was observed over frequency intervals in which the wave interactions were significant. Kinoshita et al. [19] developed a semi-analytical solution to analyse cylindrical bodies oscillating in the presence of waves and a slight current. The effects of draughts and water depth were also studied. This solution worked well for cylinders moored to the sea bottom but was lacking while analysing freely oscillating cylinders. In the presented

study, the motion was simulated using a hybrid approach, i.e., a combination of potential flow and Morison-equation-based methods. The obtained results were subjected to a comprehensive analysis, allowing for a comparative assessment of the advantages and disadvantages inherent to both methods.

While designing new floaters, it is crucial to investigate and establish installation methodologies that align with the specific requirements and operational demands of the floaters [3]. If wet towing is imperative, the methodologies discussed in this paper offer designers and developers an opportunity to assess the seaworthiness and towability of forthcoming FOWTs, thereby enabling them to refine their decision-making process during the project's initial phases itself. These methods are applicable to any floater design and can be employed to calculate the motion and towing loads of the platform, and depending on the availability of resources, a suitable method can be chosen. The paper stimulates further innovation and refinement in analysis techniques, including various non-linear phenomena, flexible platforms, additional limiting factors, etc., leading to improved methodologies in the future.

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In Section 2, the details of the experimental campaign are discussed. The geometric details of the platform, the model and the towing line are outlined in this section. The measurements, dimensions, speeds and numerical simulation results provided in the paper are presented at full-scale, and the corresponding model-scale values can be derived by applying the appropriate scaling factors. Section 3 discusses the numerical approaches used for the calculations. The results obtained from the numerical

simulations are validated against the experimental results. Some of these comparisons are shown in this section, and the rest are presented in Appendices B and C. Subsequently, the following section critically analyses and interprets the obtained results from the experiments and the numerical simulations presented in the previous section. In the following section, the major insights and informed conclusions from the presented study are presented. The potential avenues for future research, highlighting areas where further exploration and investigation could enhance our understanding of the subject matter, are also discussed there.

C.2. Platform Configuration and Characteristics

C.2.1. The DeepCwind Semi-Submersible Platform

In this research, the DeepCwind semi-submersible platform [20] was used. The platform consists of a central column and three outer columns arranged in a triangular configuration (see Figure 1). The platform is designed to support a 5 MW wind turbine. The original design of the platform had an installation draught of 20 m. This draught is impractical for towing because, as the draught increases, it leads to a rise in the fluid drag acting on the platform, consequently necessitating a higher bollard pull to tow the FOWT. It is important to calculate the towing draught accurately in order to reduce the drag while towing. As the draught decreases, the drag reduces, but the motion of the body may become severe. The optimum towing draught is a balance between stability and the motion of the platform [3]. The geometry of the platform also plays a role in deciding the towing draught of the platform. For platforms like DeepCwind with large heave plates, care should be taken to ensure that the heave plates do not emerge out of the water during towing in order to avoid non-linear phenomena like slamming and green water loads. Similarly, for platforms featuring large pontoons for buoyancy, attention must also be paid to these phenomena.

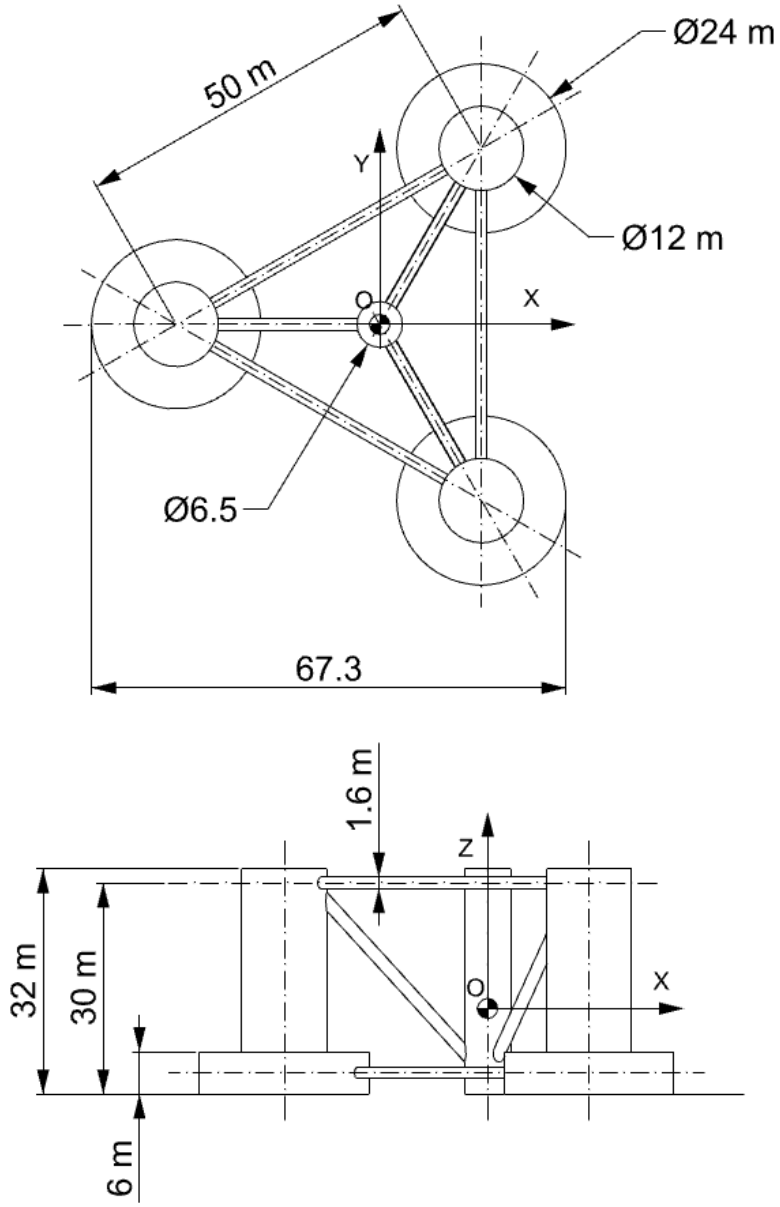


Figure 1. Platform geometry.

C.2.2. Determination of towing draught

The draught was determined using a basic intact stability study. The GM (metacentric height) values which influence the stability of the platform were calculated at different draughts. The righting arm (GZ) at various draughts (T) was calculated using an opensource tool called BEMRosetta [21,22]. BEMRosetta provides a simple calculation of the righting arm and righting moment at various heel angles using the submerged volume calculated from the mesh file of the platform. This is a simplified approach as it doesn't take the effect of the change in equilibrium position and the change in the instantaneous centre of rotation into consideration during the calculations. These results

can be improved using advanced stability analysis tools used in the industry. The calculated values are plotted in Figure 2. As mentioned before, the stability rules applicable to FOWTs are still not fully developed, and in the presented study, stability checks were performed using the general IMO stability criteria [8,23] and the MODU (Mobile Offshore Drilling Units) rules [9,24]. The wind turbine was assumed to be kept in a parked–feathered condition to minimise the wind loads on the structure [25]. Even in this turbine configuration, the wind loads could be significant, depending on the wind speed, but it takes dedicated research to understand the effect of wind, which is beyond the scope of this paper.

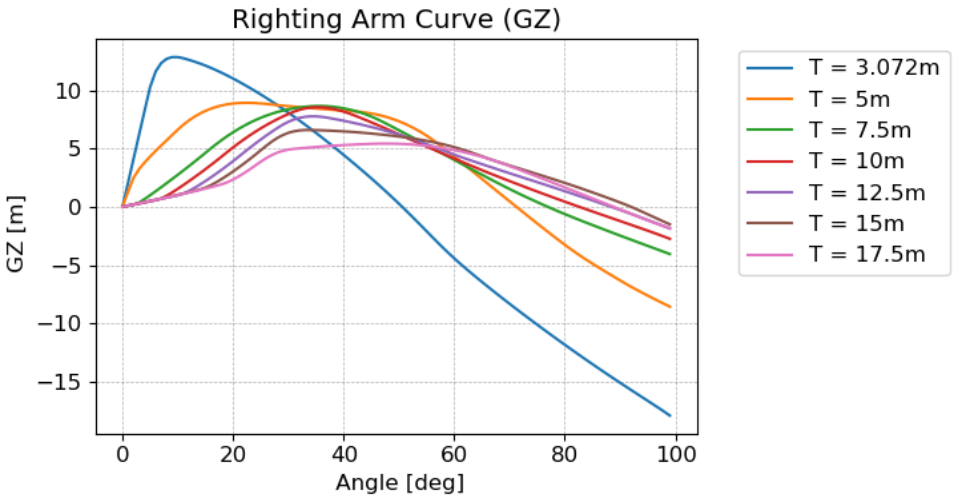


Figure 2: Righting lever (GZ) curve for various platform draughts

The stability criteria were provided by [8,9,23,24] as follows:

- Initial GM or metacentric height should not be less than 1 m [9,24].
- The righting moment curve is to be positive over the entire range of angles from upright to the second intercept [23,24].
- The maximum inclination under the total heeling moment should not exceed 15°.
- Righting lever GZ should be at least 0.2 m and angle of heel $\Theta \geq 30°$ [23].
- Maximum righting lever should occur at heel >30° preferably but not less than 25° [23].
- The Area of the GZ curve should be at least [23].:
  - 0.055 m radian up to $\Theta = 30°$
  - 0.090 m radian up to $\Theta = 40°$

- 0.03 m radian between 30 and 40 or between 30 and angle of down flooding.

- The maximum righting arm should occur at an angle of heel preferably exceeding 30° but not less than 25° [23].
- The static range of stability should not be less than 15° at the draught during towing [23].

For the selected draughts mentioned in Figure 2, 3.072 m (zero-ballast) and 5 m did not pass the stability tests and were, hence, considered unsuitable for towing. All the other draughts (see Figure 2) satisfied the criteria for stability. While planning towing operations in rough seas, the draught should be high enough so that the heave plates or pontoons remain sufficiently immersed and, hence, green water and slamming loads can be avoided. The immersion is determined via various factors like the wave steepness and the significant wave height, etc., of the waves expected along the towing route [26]. Increasing the draught reduces the air gap in the case of platforms with a deck. This may lead to increased wet-deck slamming, and care should be taken to avoid green-water loads on the top of the cylindrical columns. The thickness of the heave plate of the DeepCwind platform is 6 m, and choosing a draught of 7.5 m corresponds to a distance of 1.5 m between the water surface and the top of the heave plate, while opting for a 10 m draught provides a distance of 4 m. A higher draught reduces the probability of the heave plate surfacing during the towing process [25], but it also increases the fluid drag on the hull. Consequently, the draught was chosen at 10 m for the experiments. Further refinements in the calculation of the towing draught are possible, but they are beyond the scope of the presented study.

C.3. Experimental Configuration

C.3.1. Test facility

The tests were conducted in the freshwater Concept Basin at the Maritime Research Institute Netherlands (MARIN). The Concept Basin has a length of 220 m, a width of 4 m and a depth of 3.6 m. The basin is equipped with a stiff carriage which has a maximum speed of 10 m/s. The details of the model can be found in Figure 3. Waves were generated from a wave generator on one end of the basin, and the other end employed a beach to absorb the waves.

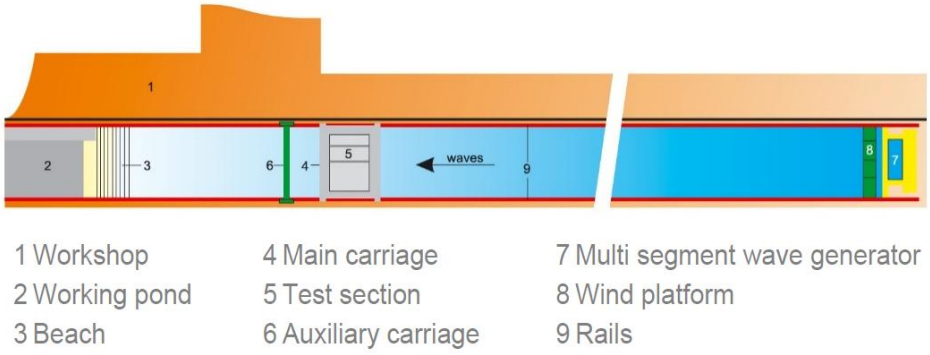


Figure 3: Concept Basin

C.3.2. Platform Model, Towing Setup and Configurations

A 1:50 scale model of the DeepCwind semi-submersible platform was used for the tests. The model represents the towed FOWT system (platform + NREL 5 MW wind turbine), and its geometry and characteristics can be found in Figure 4 and Table 1, respectively. The Froude number and Reynolds number are presented in Table 2. The diameter of the outer column was taken as the characteristic length for the calculation [27,28].



Figure 4. Platform model.

Table 1: Comparison of platform and model properties.

Property	Unit	Target	Realised	% difference
Mass	[ton]	10357.1	10410.3	-0.51
L	[m]	67.3	67.3	0.00
LCG	[m]	-0.009	-0.01	-11.11
TCG	[m]	0.017	0.02	-17.65
VCG	[m]	12.159	12.09	0.57
Kxx about COG	[m]	33.854	30.54	9.79
Kyy about COG	[m]	34.073	31.01	8.99
Kzz about COG	[m]	36.326	31.13	14.30
Ixx about COG	[tm2]	1.19E+07	9.71E+06	18.40
Iyy about COG	[tm2]	1.20E+07	1.00E+07	16.67
Izz about COG	[tm2]	1.37E+07	1.01E+07	26.28

Table 2. Towing speeds and corresponding Froude and Reynolds numbers of the model (model-scale).

Speed (m/s)	Speed (m/s) (Full-Scale)	Froude Number	Reynolds Number
0.073	0.514	0.047	1.75×10^4
0.145	1.029	0.095	3.49×10^4
0.218	1.543	0.142	5.24×10^4
0.291	2.058	0.190	6.98×10^4
0.364	2.572	0.237	8.73×10^4
0.436	3.086	0.284	1.05×10^5

The platform was placed in the basin, and the towing lines with/without a bridle were attached to the platform. The other end of the main towing cable was attached to a spring which represented the stiffness of the towing line (ref. Table 3). The towing line was then attached to a stiff rod which was connected to the carriage. A load cell was connected to the towing line to record the tension on the towing line. The motion of the platform was recorded using an optical tracking camera. Wave measurements at various towing speeds were performed prior to the tests to obtain the calibration data required for calculations. The setup was specifically designed for the tests to fit the DeepCwind platform. Figure 5 shows the test setup used for the experiments.

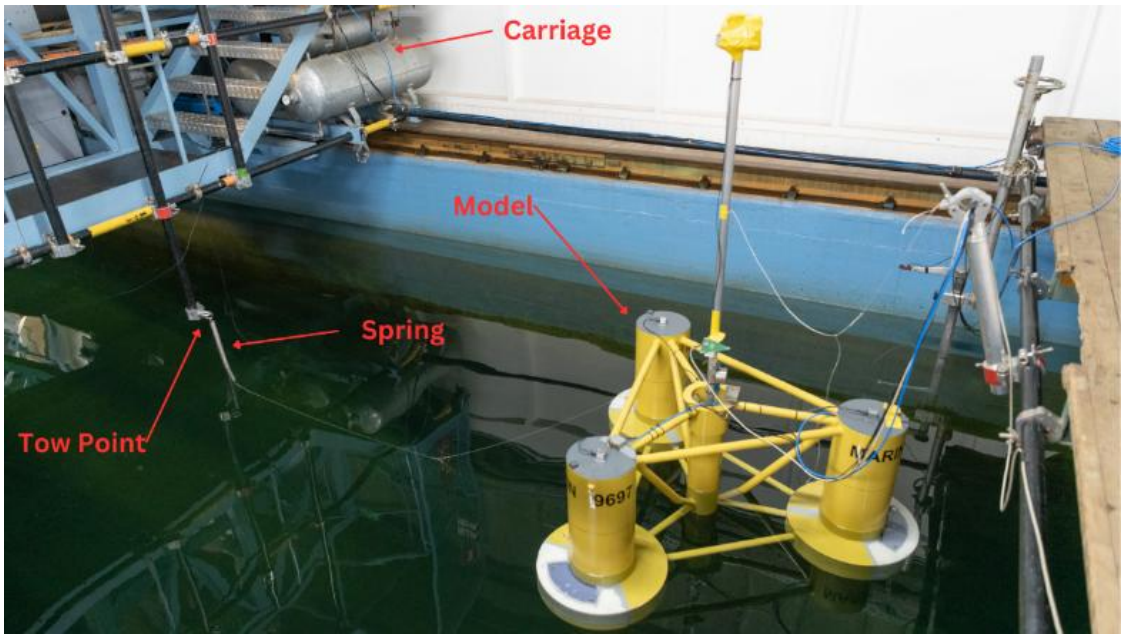


Figure 5: Towing test setup

Table 3: Towline properties

Property	**Value**
Length	900 m
Modulus of Elasticity	9.16E x 10^{10} Pa
Rope diameter	0.09 m
Stiffness	647.5 KN/m

Two configurations/towing setups were tested during the experiments. In configuration 1, a bridle was used for towing. The angle formed at the apex of the bridle, as specified in reference [25], could range between 45 and 60 degrees. For this configuration, a selection of 60 degrees was made. In configuration 2, the towing line was directly connected to the platform. The towing configurations tested during the campaign are shown in Figures 6 and 7. In both configurations, the towing point/points were at the same level as the centre of gravity of the platform, as this was essential to avoid unbalanced moments due to the towline pull. This approach is not always feasible in practical scenarios, particularly when the centre of gravity (COG) is below the water surface, as the towing line must remain above the water to prevent additional drag.

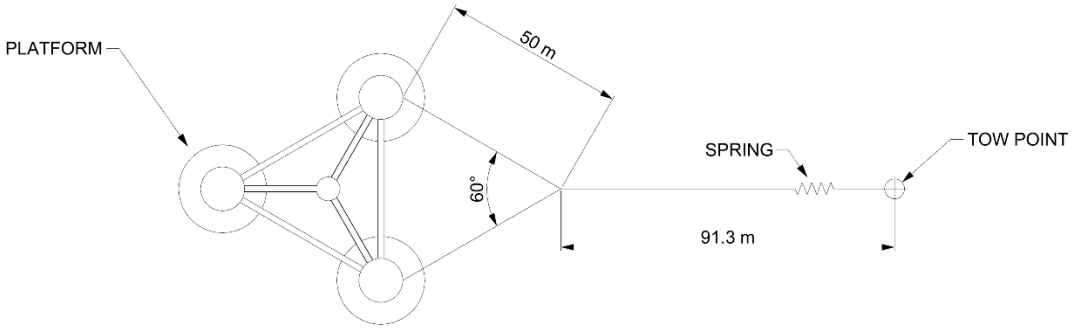


Figure 6: Towing test configuration 1

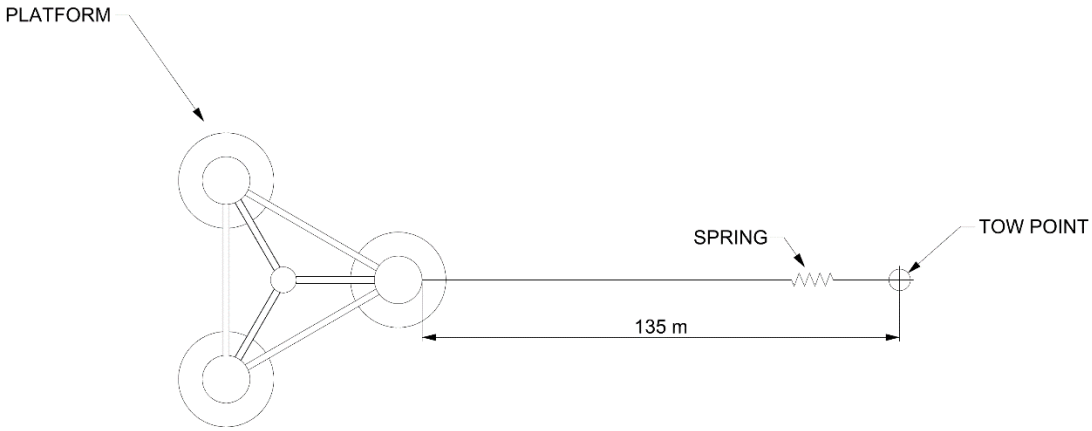


Figure 7: Towing test configuration 2

C.3.3. Towing Line

The towing line was selected according to the Maritime Safety Committee-MSC/Circular 884-Guidelines for Safe Ocean Towing [8]. The length of the towing line is determined using the following formula:

$$Towline\ Length = (BP/BL) \times 1800 \quad (1)$$

When the Bollard Pull (BP) is higher than 883 KN (90 tons), the Breaking Load (BL) is approximately twice the bollard pull [7]. The stiffness of the towing line is determined based on DNV-RP-H103 [7]:

$$Towline\ Stiffness = (EA/L_r) \times 1800 \quad (2)$$

where E is the modulus of elasticity, A is the cross-sectional area and Lr is the length of the rope. The rope diameter and elasticity are determined according to ISO 2307:2010 [29]. The calculated towline properties are shown in Table 3.

An available spring with the nearest stiffness value, K = 718.23 KN/m, was used for the towing tests. The tow line length of 900 m would scale to 17 m in the basin. For practical purposes in the basin, the tow line length was reduced to 135 m (full-scale).

C.3.4. Test Campaign

Towing tests were performed for both configurations with various towing speeds and wave conditions. The model was placed in the basin, and the measurement devices were connected to the carriage. Comprehensive checks were performed to ensure the model's unobstructed movement. The initial stage involved conducting decay tests to determine the natural frequencies of motion, specifically in heave, roll and pitch. The calm water towing tests for speeds ranging from 0.514 m/s to 3.086 m/s were performed for both configurations then to ascertain the drag and, thereby, the bollard pull required for towing in calm water. Fewer tests were carried out for configuration 2, primarily because configuration 1, which employs a bridle, is the most widely employed and recommended towing setup in the offshore industry [25].

Following the calm water tests, towing tests were conducted under various regular wave conditions. The primary objective was to determine the platform's motion responses and the associated drag, which are vital for calculating added resistance in waves of varying frequencies. Detailed test specifications are provided in Table 4, encompassing tests at speeds of 1.029, 2.058 and 2.572 m/s with seven wave periods spanning from 6.26 s to 20.94 s. Given the focus on assessing the performance with high waves, the majority of the tests were conducted under high wave conditions.

Table 4: Test Cases - Regular waves

Configuration	Speed (m/s)	Wave Height (m)	Wave period (s)	Case
Configuration 1	1.029	1	6.28	1

		2	6.98	2
		4	8.38,10.47,15.71,18,20.94	3-7
	2.058	1	6.28	8
		2	6.98	9
		4	8.38,10.47,15.71,18,20.94	10-14
	2.572	1	6.28	15
		2	6.98	16
		4	8.38,10.47,15.71,18,20.94	17-21
Configuration 2	1.029	1	6.28	22
		2	6.98	23
		4	8.38,10.47,15.71,18,20.94	24-28
	2.058	1	6.28	29
		2	6.98	30
		4	8.38,10.47,15.71,18,20.94	31-35

Subsequent to the assessments under regular wave conditions, tests were conducted involving white noise waves, with the primary aim being the determination of the platform's Response Amplitude Operators (RAOs) for motion. Refer to Table 5 for detailed information. The tests covered a range of towing speeds—0.514, 1.543, 2.572 and 3.086 m/s—and encompassed significant wave heights of 1, 2, 4 and 6 m. For higher speeds, tests were conducted for significant wave heights of 1, 2 and 4 m only.

Table 5: Test Cases - Irregular waves

Configuration	**Speed (m/s)**	**Wave Height (m)**	**Wave period (s)**
Configuration 1	0.514	1	5-25
		2	5-25
		4	5-25
		6	5-25
	1.543	1	5-25
		2	5-25
		4	5-25
		6	5-25
	2.572	1	5-25
		2	5-25
		4	5-25
	3.086	1	5-25
		2	5-25
		4	5-25

Configuration 2	0.514	1	5-25
		2	5-25
	1.543	1	5-25
		2	5-25
	2.572	1	5-25
		2	5-25

C.3.5. Observations

The platform motion was checked and observed throughout the experimental campaign for interesting and unexpected phenomena. Since the motion of the platform was of interest, it was measured during towing. The roll motion was found to be very minimal during the towing process, which was expected because only head waves were used in the experiment. Sprays and splashes were also observed during many of the tests (Figure 8). As the significant wave height increased, the motion became severe compared to the lesser wave heights.

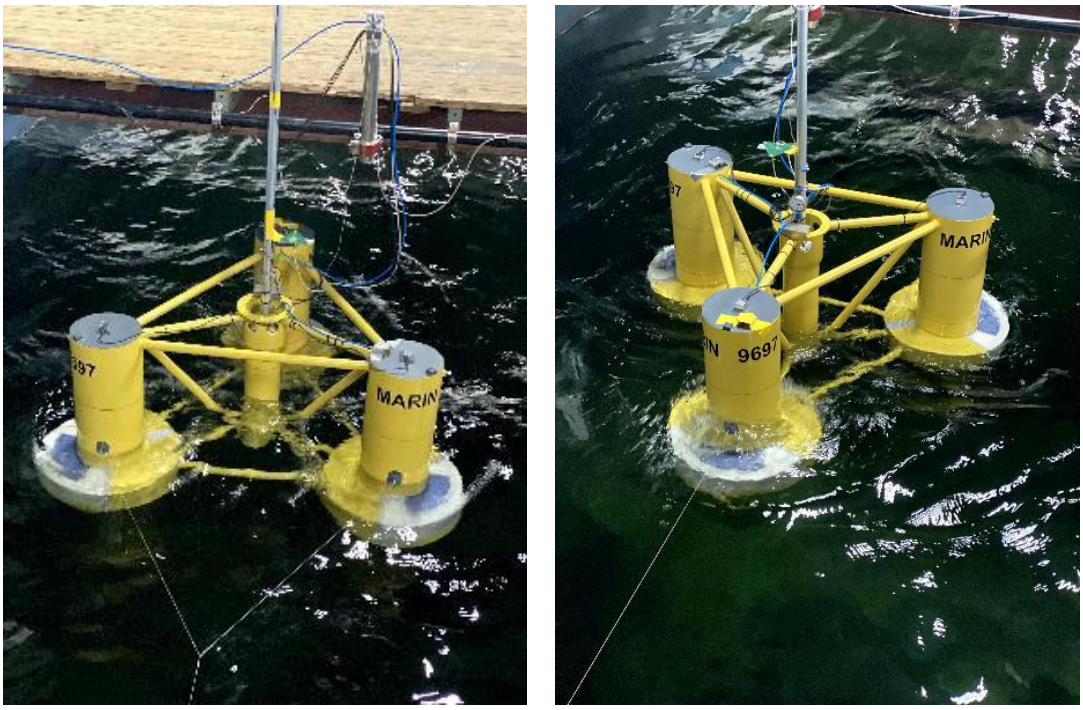


Figure 8: Platform motions during towing

An additional significant observation pertained to the Fluid-induced Motions (FIMs) of the platform during the towing process. A comparative analysis of the platform's motion in configurations 1 and 2 was conducted and the outcomes are examined in the next section. It was evident that configuration 1, involving the use of a bridle, exhibited reduced FIMs.

C.3.5.1. Fluid-induced motions (FIMs)

As mentioned before, some oscillatory motion was observed during towing in calm water. To check for VIM, which is a special kind of FIM, the nominal A/D values which represent the amplitude of the motion [30] were calculated and plotted (Figure 9) for both configurations. The nominal A/D value is determined as follows:

$$(A/D)_{nom} = \sqrt{2}\frac{\sigma_y}{D} \quad (3)$$

Where D is the column diameter and σ_y is the standard deviation of the motion in the direction perpendicular to the incoming flow (sway). It was shown that configuration 1 exhibits a lesser nominal A/D value at the tested speeds, which indicates better course-keeping.

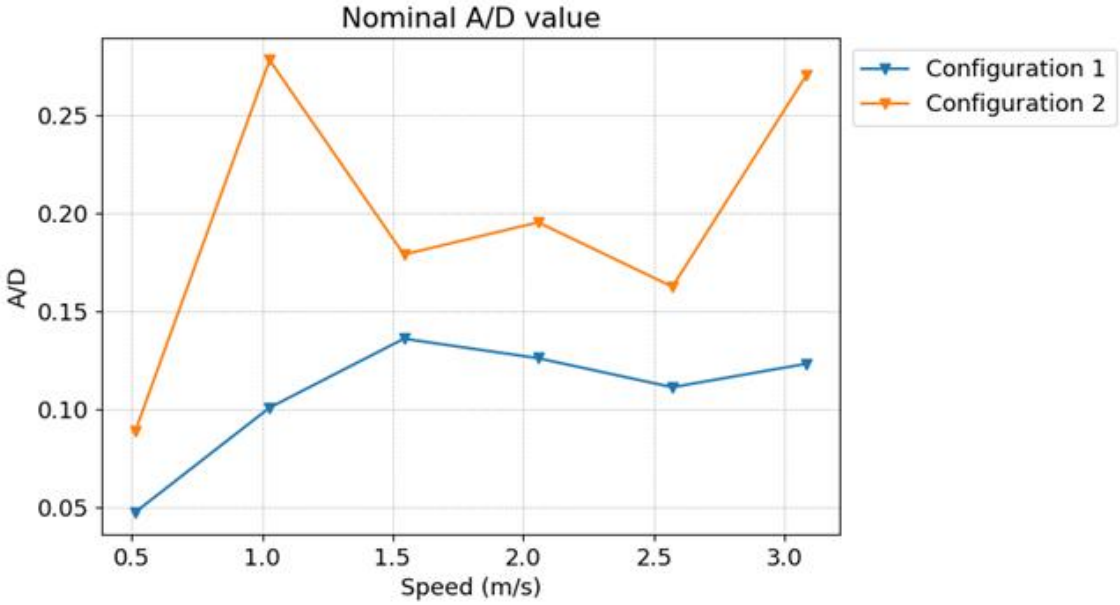


Figure 9: Nominal A/D values for both configurations

C.3.5.2 Drag and bollard pull

The recorded tension on the towing line during calm water tests is presented and analysed here. This measurement shows the required bollard pull to tow the system at different speeds, and it shows that this value fluctuates according to the speed of towing. The maximum, minimum and mean towing forces were calculated for both configurations (labelled as C1 and C2 for better presentation) and they are presented in Table 6. As the speed increased, it was observed that the variation of the towing force also increased. It was observed that the configuration 2 exhibits slightly lower drag at

higher speeds. This may be due to the FIMs observed during the towing tests or viscous phenomena like vortex shedding. It can also be hypothesized that a destructive interference occurs due to the wave patterns generated by the forward column interacting with those produced by the aft columns, similar to the effect observed with the bulbous bow of a ship. These hypotheses can be tested only using advanced numerical methods like CFD. The statistical properties of the values are plotted (Figure 10). The bars represent the maximum, 25^{th} percentile, mean, 75^{th} percentile and minimum values. An uncertainty of ~ 2.2 % also applies to these values.

Table 6: Towing force (N) and bollard pull (tons) (in brackets) for both configurations (C1 & C2)

	Speed (m/s)	**Minimum (N)**	**Maximum (N)**	**Mean (N)**
C1	0.514	7.56E+04 (8)	8.85E+04 (9)	8.17E+04 (8)
	1.029	2.67E+05 (27)	3.14E+05 (32)	2.90E+05 (30)
	1.543	5.75E+05 (59)	6.93E+05 (71)	6.37E+05 (65)
	2.058	1.02E+06 (104)	1.35E+06 (138)	1.18E+06 (120)
	2.572	1.73E+06 (176)	2.23E+06 (228)	1.93E+06 (197)
	3.086	2.63E+06 (268)	3.29E+06 (336)	2.93E+06 (299)
C2	0.514	8.02E+04 (8)	9.38E+04 (10)	8.91E+04 (9)
	1.029	2.46E+05 (25)	2.93E+05 (30)	2.56E+05 (26)
	1.543	5.23E+05 (53)	9.52E+05 (97)	6.26E+05 (64)
	2.058	9.22E+05 (94)	1.20E+06 (122)	1.06E+06 (108)
	2.572	1.55E+06 (158)	2.20E+06 (224)	1.74E+06 (177)
	3.086	2.32E+06 (237)	2.79E+06 (285)	2.55E+06 (260)

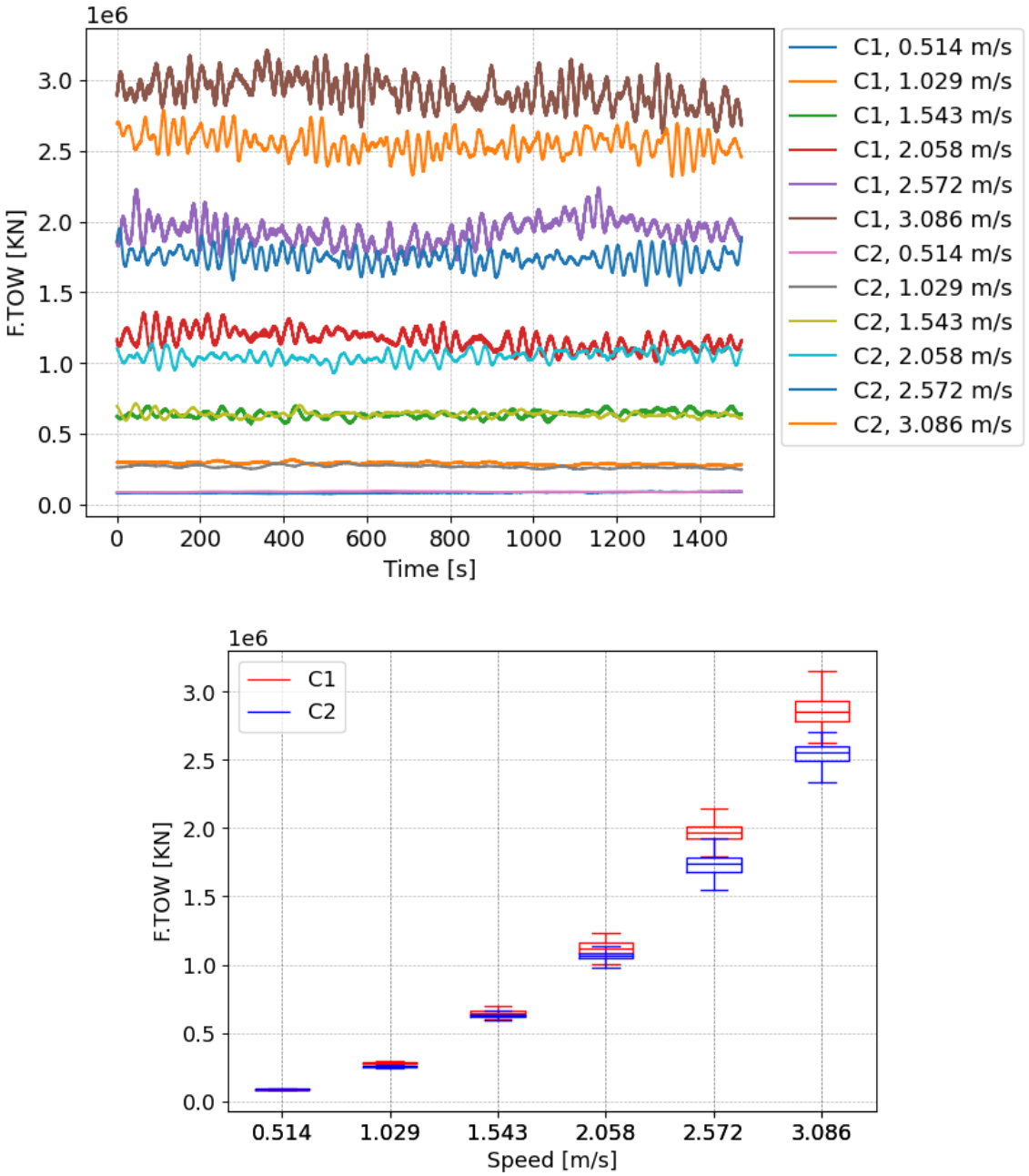


Figure 10: Towing force plot (top), variation of the towing force (bottom)

C.4. Numerical Validation

Two distinct methods were employed to conduct a comparative analysis of the results. The numerical simulations were performed using the realised model properties mentioned in Table 1. In the first method, the platform was presumed to be in forward motion at a speed equivalent to the platform's towing speed. Utilising SEACAL [31], in-house seakeeping software developed at MARIN, based on 3D potential flow methods, the platform's motion was simulated in the frequency domain. An inherent challenge in

this method lies in accurately determining the damping coefficients governing heave, roll and pitch motion, which is influenced by various types of nonlinearities. The precise calculation of these damping coefficients is crucial to accurately simulate this motion. The damping values were derived from the decay tests, which yielded damping values at the natural frequency. This value was then incorporated as additional damping, and simulations were executed to calculate the Response Amplitude Operators (RAOs).

In the second method, the platform was modelled in Orcaflex [32] as a stationary body (zero-speed), while a current matching the towing speed was imposed on the body. The platform was constrained using towing lines, and its motion in various wave conditions and current speeds was simulated. Firstly, the platform was modelled as a 3D panel mesh, and a frequency-domain hydrodynamic analysis was executed utilising Orcawave [33]. The second-order drift forces play a major role in the motion of bodies moving with a slow speed and it is important to calculate them accurately. A mesh convergence study based on the second-order heave and pitch drift loads was performed, and it is presented in Appendix A. No additional damping was used here for the frequency domain analysis. Subsequently, this model and its associated hydrodynamic properties were imported into Orcaflex for the purpose of performing time-domain simulations. The towing system modelling and following analyses were conducted within the Orcaflex environment. To account for viscous effects, Morison elements were integrated into the model along the columns, braces and pontoons of the platform. The details of the Morison elements were obtained from the example cases provided by Orcina [34], and they are listed in Table 7. Only drag was considered while using the Morison elements in the version of Orcaflex used for the analyses. This is because adding the inertia coefficients would lead to a double calculation of inertia effects, as these are already accounted for by Orcaflex. Only the viscous component needs to be considered. In this approach, motion was simulated in the time domain, and RAOs were determined through subsequent analysis. The RAOs obtained from both calculations were then compared with the results obtained from the experiment, facilitating a comprehensive evaluation of the simulated and observed behaviours of the platform. The details of the numerical tools and the setup used for the simulations are outlined in Appendix A.

SEACAL is based on zero-speed green functions with a correction for forward speed, depending on the encounter frequency. Low-speed approximations were used while modelling the hydrodynamic motion of the platform. It was assumed that the flow was uniform and equal to the platform's speed everywhere around the platform. The radiated and diffracted waves were calculated independently of the forward speed; i.e., for all speeds, they were propagating in circles around the platform at zero speed. This method generally gives good predictions for small forward speeds (Fn < 0.25). However, a forward speed of 3.086 m/s (Fn = 0.284) was also investigated, given its slight Froude number proximity to 0.25, to explore the code's performance at a higher speed. The low-speed approximations hold true only for low values (<0.25) of the Strouhal number (also known as the Brard number), τ, determined via $\tau = \omega_e U/g$ [15,35]. While modelling waves and the current together, Orcaflex employs the conventional super-positioning of waves and the current, and it does not take the wave–current interaction into consideration [36]. The effect of the current on a structure is similar to the effect of the forward speed on a vessel [16,35], but in practice, this applies to conditions under which Strouhal numbers are sufficiently low ($\tau < 0.25$). This is a limiting condition that applies to both the methods employed in this study. A Strouhal number check was performed to ascertain the frequencies and forward speeds at which the limiting value was exceeded ($\tau > 0.25$). This threshold was surpassed when the encountering frequencies were greater than or equal to 1.2 rad/s, 1 rad/s and 0.8 rad/s for forward speeds of 2.056 m/s, 2.572 m/s and 3.082 m/s, respectively. This signifies that the simulation results using these methods may not be accurate for analysing these towing conditions. However, the results are presented from a curiosity perspective and to check how much they deviate from the experimental results.

Table 7: Morison elements details

Member	**Diameter (m)**	**Drag Coefficients (Cd)**		
		x	**y**	**z**
Upper Column	12	0.61	0	0
Lower Column	24	0.68	0	4.8
Central Column	6.5	0.56	0	0
Braces and Pontoons	1.6	0.63	0	0

C.4.1. Decay tests

Decay tests play a vital role in discerning the natural frequencies and facilitating the computation of damping coefficients. In this context, specific decay tests were executed to ascertain the natural frequencies of heave, roll and pitch motion while simultaneously allowing for the calculation of damping coefficients required for the simulations. The damping values are quadratic in nature and are dependent on the motion amplitudes, and these values were calculated and are listed in Table 8. These values were provided as an input for SEACAL, and the damping values at various motion amplitudes were interpolated via the software during the simulations.

Table 8: Damping coefficients calculated from decay tests

	Total damping at 0 m/deg	**Total damping at 20 m, deg**
Heave	0.3 kNs/m	32,376,337 kNs/m
Roll	35,475 kNs/rad	8,804,178 kNs/rad
Pitch	30,330 kNs/rad	7,610,552 kNs/rad

The decay tests themselves were simulated using Orcaflex, with the resulting outcomes subjected to a thorough comparative analysis. The time-domain simulation results exhibited a strong alignment with the experimental findings for heave and pitch motion, though they marginally underestimated the results for roll motion (see Appendix A, Figures A7–A9). The natural frequencies were also derived from the RAO simulations performed using SEACAL. These values were directly calculated by SEACAL and confirmed against simulations with zero speed. A comparative analysis of the natural periods, derived from both the experimental measurements and simulations, is presented in Table 9.

Table 9: Natural periods

	Experiment	**Orcaflex**	**SEACAL**
Heave	17s	17s	19s
Roll	35s	33s	33s
Pitch	35s	34s	33s

C.4.2. Towing in regular waves

FOWTs are usually towed from ports which have calm sea conditions into more exposed open seas. Depending on the location of the wind farm, the sea conditions get harsher, and the FOWT system starts to encounter waves of varying physical properties. In order to quantify the maximum allowable limits, it is vital to understand the response of the FOWT system in regular waves. In this section, the response of the platform during towing operations under various wave conditions is studied. Its motion and the added resistance that the system encountered are the main focus.

C.4.2.1 Towing forces and added resistance in waves

It is crucial to calculate the total towing force required to tow the system in different wave systems in order to find the required bollard pull and a suitable tug for towing. One phenomenon is the added resistance in waves experienced by the floater in regular waves. Added resistance is a second-order phenomenon, and it contributes to the bollard pull requirements of tugs to tow a fully assembled platform in various sea conditions. Once the added resistance in waves is obtained for different wave conditions, the mean added resistance in an irregular seaway can be obtained using the following formula [37]:

$$R_{AW} = 2\int_0^\infty S(\omega_e)\frac{R_{aw}(\omega_e)}{\zeta^2}d\omega_e$$

Here, ω_e represents the wave encounter frequency, $S(\omega_e)$ is the energy spectrum of the irregular sea, R_{aw} (ω_e) is the added resistance corresponding to a particular encounter frequency, ζ is the wave amplitude.

The added resistance was calculated for various speeds from the experimental data by subtracting the mean towing force in calm water from the mean towing force in the wave system. Since the added resistance is proportional to the square of the wave amplitude, the obtained added resistance values were normalised by the square of the corresponding wave amplitude. The mean towing force and mean added resistance in waves were simulated using Orcaflex and compared with the experiments in Figures 11–13. The mean added resistance in waves for various speeds is plotted against the λ/L, where λ is the wavelength and L is the length of the floater (see Figures 11–13).

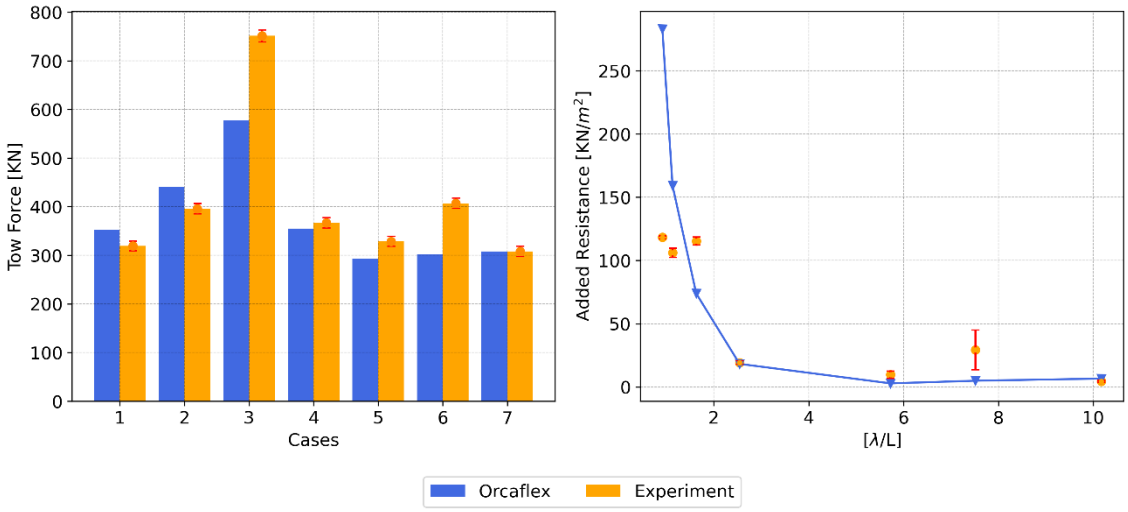


Figure 11: Towing Speed = 1.029 m/s, Experiment vs Simulation

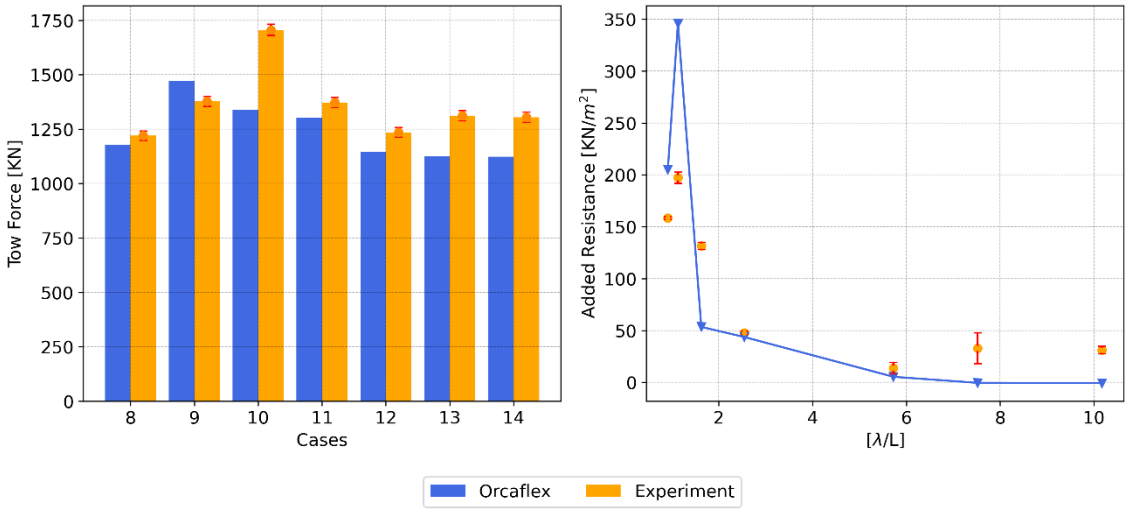


Figure 12: Towing Speed = 2.058 m/s, Experiment vs Simulation

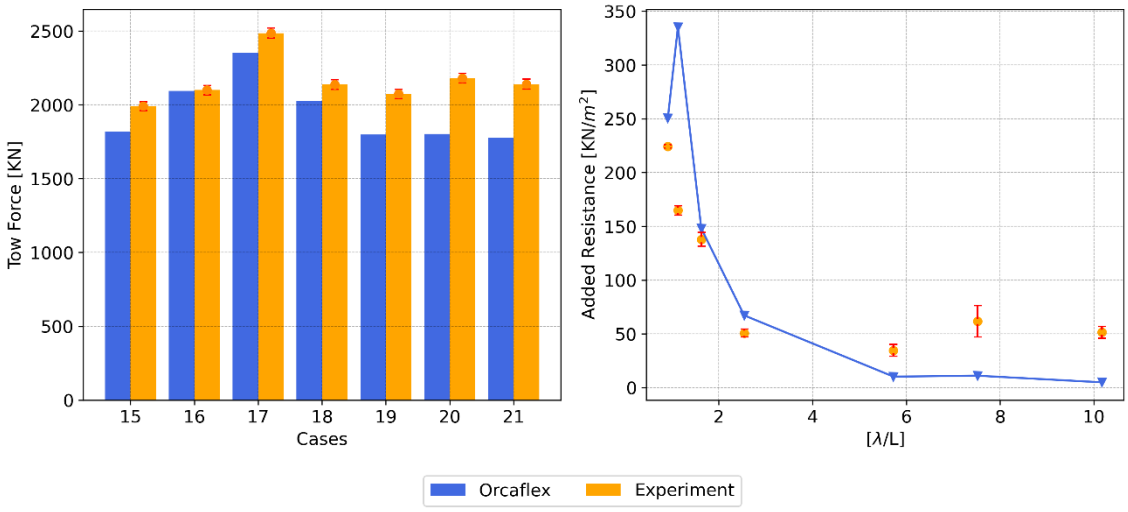


Figure 13: Towing Speed = 2.572 m/s, Experiment vs Simulation

C.4.2.2. Motions of the platform

The primary motion of interest here was heave and pitch, with the roll motion observed to be negligible when towing against head waves. The same model employed to conduct decay tests was also utilised in the towing simulation. Additionally, the modelling process incorporated the towing lines, including the bridle configuration, within the Orcaflex framework (Figure 14). The setup usually depends on the geometry of the floater which maybe modified when other floaters are used. For wave modelling, the wave encounter frequency was utilised, while the effect of forward speed was introduced by applying a current matching the towing speed. This approach allowed for the calculation of the platform's time-domain response in the presence of waves, with the simulation results subsequently subjected to validation against experimental data (see Appendix C, Figures A10–A12 for examples). The modelling of the bridle system was done while ensuring that the overall stiffness of the system equated to the stiffness of the spring. Orcaflex was employed to compute the tension in the main towing line, consequently yielding the total towing force required to tow the system in various wave conditions directly. The RAOs were also calculated using SEACAL for comparison.

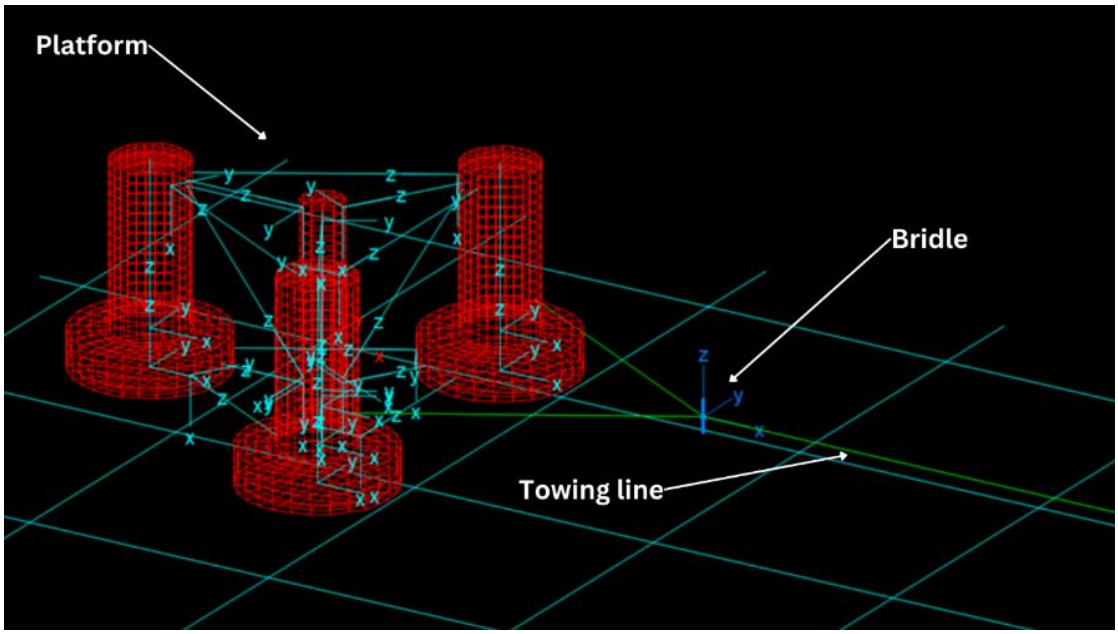


Figure 14: Towing setup in Orcaflex

The time-domain comparison was performed as shown in Appendix B. Orcaflex was able to simulate the results with reasonable accuracy, and it agreed with the experimental results in most cases. The heave and pitch amplitude were calculated for all the test cases mentioned in Table 4. The simulation results demonstrate a commendable alignment

with the experimental data. The mean amplitude of the heave and pitch motion calculated from all the test cases was compared against the simulations (see Figures 15–17).

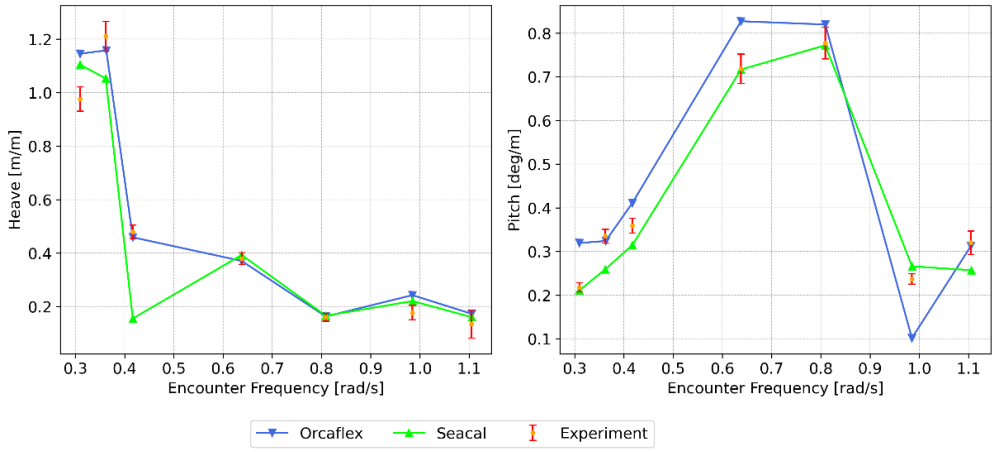


Figure 15: Towing Speed = 1.029 m/s, Experiment vs Simulation

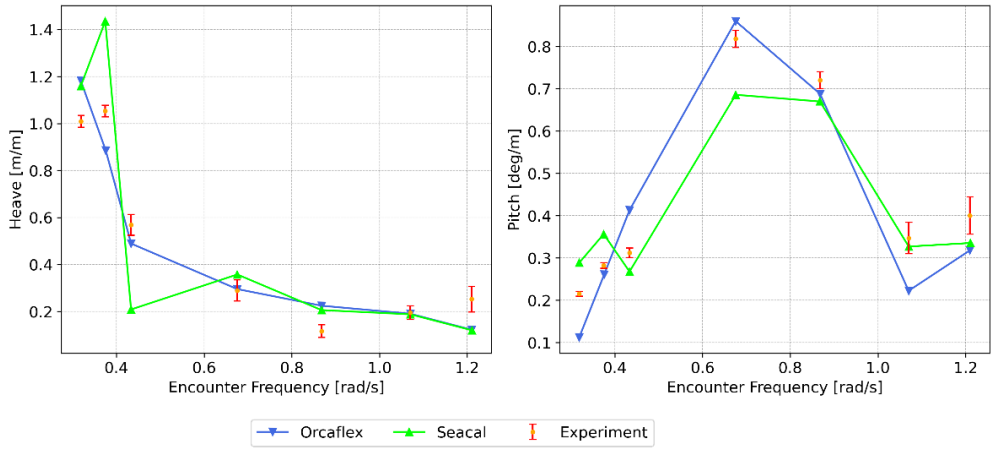


Figure 16: Towing Speed = 2.058 m/s, Experiment vs Simulation

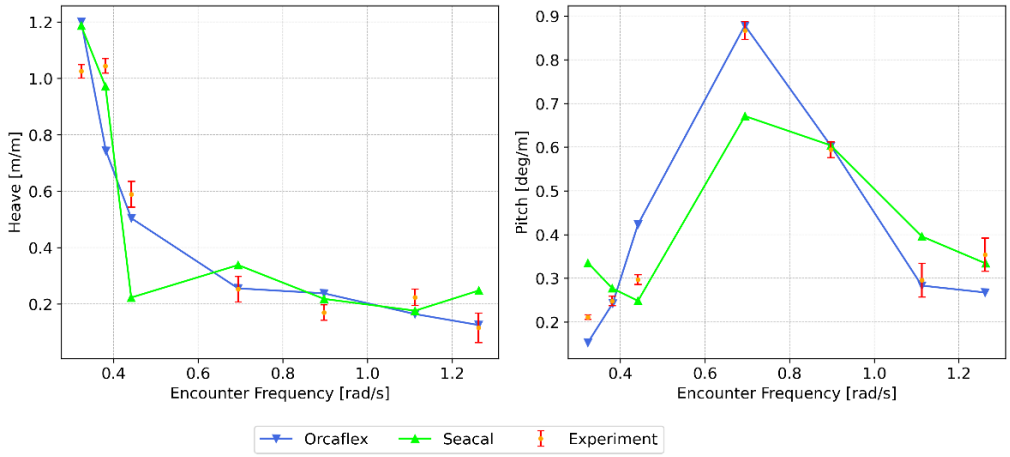


Figure 17: Towing Speed = 2.572 m/s, Experiment vs Simulation

C.4.3. Towing in irregular waves

The platform was towed in the white-noise wave conditions shown in Table 5, and RAOs were calculated using spectral approaches. The RAOs were simulated using SEACAL at the tested towing speeds. These calculations incorporated the determined damping values to enhance the accuracy of the platform's motion predictions. Using Orcaflex, time-domain simulations were performed for numerous wave frequencies for all the tested regular wave conditions. From these simulations, the RAOs were obtained by calculating the amplitudes of the pitch and heave motion. Subsequently, RAOs for heave and pitch are graphically presented in the next section (Figures 18–21 and Appendix C). The outcomes from both approaches are plotted in Appendix C, facilitating a comprehensive comparison between the two sets of results.

Motions of the platform

Figures 18–21 show the calculated RAOs for a towing speed of 0.514 m/s and its comparison with the simulations performed using both approaches (Orcaflex and SEACAL). The RAOs corresponding to the other tested towing speeds are presented in Appendix C, arranged according to the towing speed.

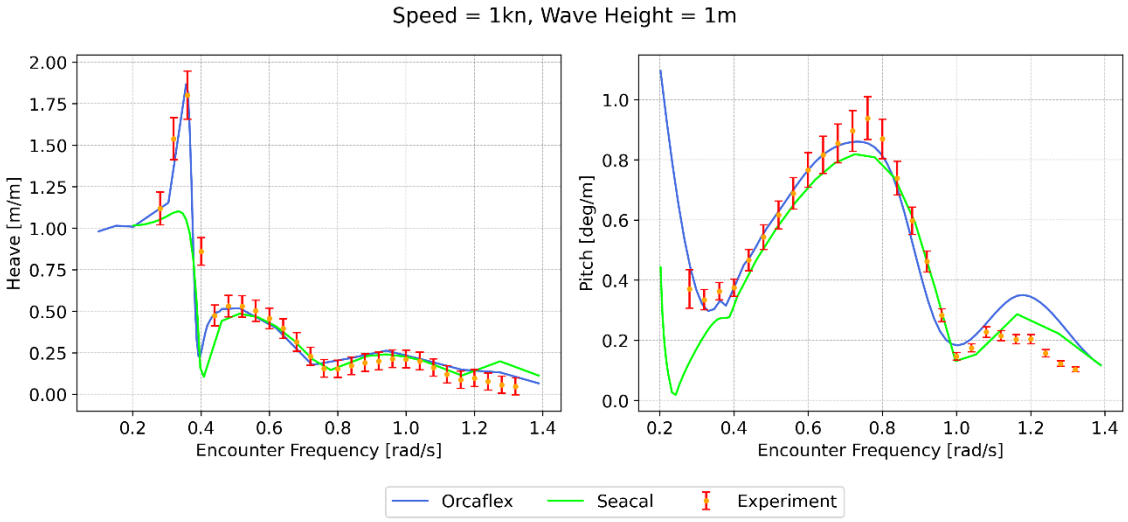


Figure 18. RAOs: towing speed = 0.514 m/s, Hs = 1 m.

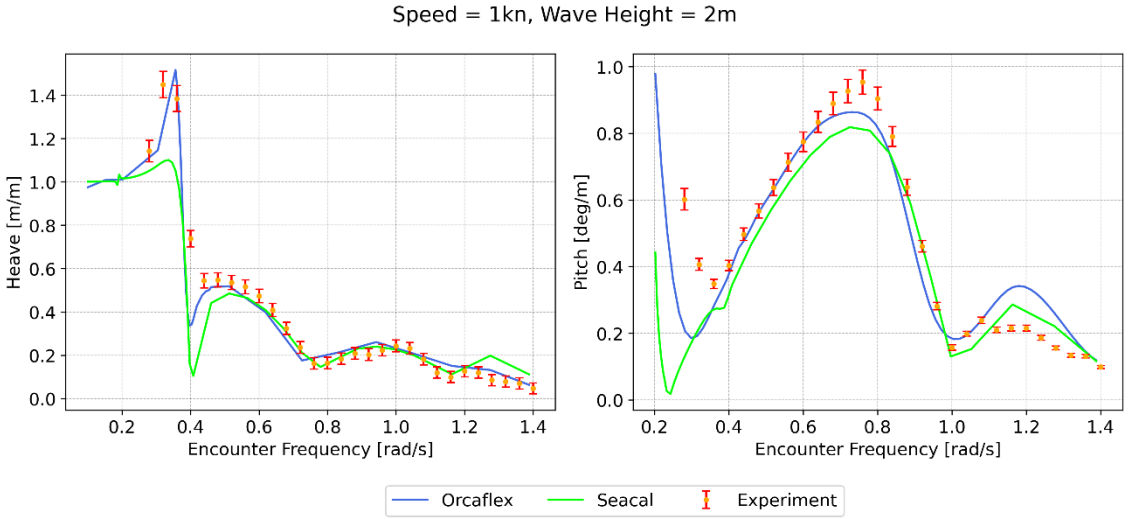


Figure 19. RAOs: towing speed = 0.514 m/s, Hs = 2 m.

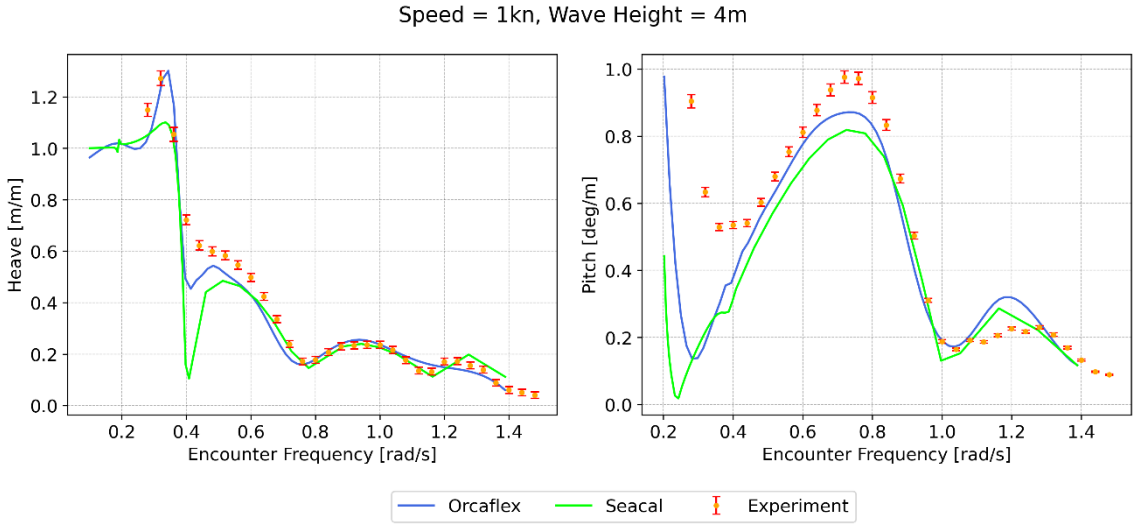


Figure 20. RAOs: towing speed = 0.514 m/s, Hs = 4 m.

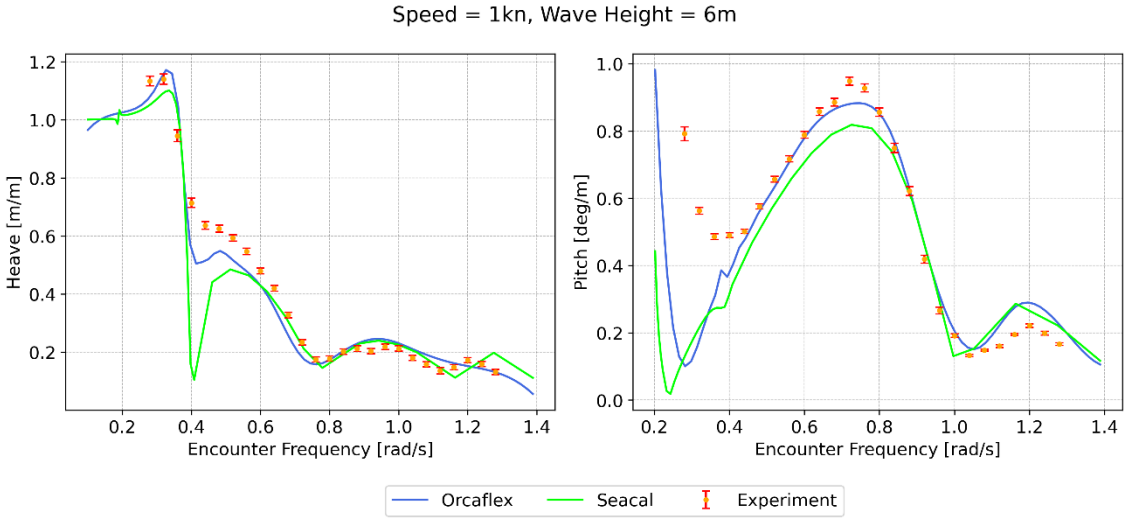


Figure 21. RAOs: towing speed = 0.514 m/s, Hs = 6 m.

C.5. Discussion

This study presents a comprehensive towing analysis of a semi-submersible FOWT system with various wave conditions, towing speeds and towing configurations. Determining the ideal towing draught plays an important role when planning towing operations. The optimum towing draught is often set as a balancing point between the intact stability and hydrodynamic motion of the floating body. However, it is equally important to exercise caution and account for various non-linear phenomena like FIMs, green water shipping and wave run-ups on the columns, as observed in towing tests, while determining the towing draught.

In Figure 10, it can be observed that the drag on the platform varies quadratically with respect to the towing speed. This agrees with the observations from previous towing experiments using the INNWIND semi-submersible platform [3]. This is important, as this value provides an idea about the towing in calm water or calm sea states. This plays an important role in calculating the bollard pull and the selection of the tugs for towing. Tug vessels with a maximum bollard pull of around 228 tons and 336 tons are required to tow the platform at 2.57 m/s (5 knots) and 3.09 m/s (6 knots), respectively. Some large tug vessels with bollard pulls of 300 tons exist but are rare [25]. During a major repair campaign of the Kincardine wind farm, tug vessels with a bollard pull higher than 200 tons were chartered at record-high rates for over a decade [6]. These elevated rates were due to the construction of the Hywind Tampen project, which was taking place at the same period in Norway. This signifies that, for towing at high speeds, vessels with high bollard pulls are required, which can have a direct impact on costs.

The precise prediction of the FOWT motion and towing loads in a seaway is a challenging task. Two numerical approaches were applied: a frequency-domain potential flow approach (SEACAL), including a slow forward speed and linearised damping, and a hybrid time-domain approach (Orcaflex), employing potential-flow calculations and Morison elements to account for viscous effects. The hybrid approach slightly under-predicted the mean towing force but was able to predict it with a mean absolute percentage error of 5.9%, 8.4% and 9.5% for test cases with towing speeds of 1.029 m/s, 2.058 m/s and 2.572 m/s, respectively. The added resistance was not properly predicted, but a rough prediction was possible, and it requires further investigation to improve the predictions. The highest added resistance occurs when λ/L is close to 1, i.e., when the

length of the encountering wave is equal to the length of the platform, and this was properly captured using the model.

The heave RAOs calculated using the hybrid approach are in good agreement with the experimental results for all significant wave heights (Figures 18–21 and Appendix C). In the case of pitch motion, the predictions are in good agreement with the experiments at a low significant wave height of 1 m but show deviation from the experimental results as the significant wave height increases. The deviation occurs at encounter frequencies (0.2–0.4 rad/s) close to the natural frequency of the pitch (0.18 rad/s) for which viscous effects dominate. This shows the presence of highly non-linear damping or other physical phenomena which cannot be predicted using potential-flow-based methods. At higher encounter frequencies (0.4–1.5 rad/s), the simulations are in good agreement with the experimental results. This method enables the modelling of different towing line configurations, encompassing both bridle and non-bridle setups, facilitating an analysis of the tension experienced by the main line, the bridle and the bridle legs. Even though reasonable predictions are possible, this method is very time-consuming and laborious, as it involves simulations of various combinations of different wave frequencies, wave heights and towing speeds in the time domain and their post-processing.

It can be observed that the simple potential-flow-based method with a correction for viscous effects is effective for low-speed (0.514–1.543 m/s) towing simulations. Heave RAOs were observed to be under-predicted at encounter frequencies close to the natural frequency of the heave (0.37 rad/s) in all test conditions. This maybe due to the inaccuracies in the predictions of the damping coefficients used for the analysis. The damping coefficient for forward speed were calculated by SEACAL automatically. As the towing speed increases the heave predictions close to the natural frequency matches the experimental data and the Orcaflex simulation results. The prediction of the pitch was reasonable only in low speeds (0.514–1.543 m/s) with an error up to 35% for encounter frequencies higher than the natural frequency (0.4–1.5 rad/s) of the pitch (0.18 rad/s) (see Appendix C, Figures A13–A16). As the towing speed increases, the pitch motion predictions deviate considerably from the experiments (see Figures A17–A22). This may occur due to the inaccuracy of the damping coefficient values used for the correction or other non-linear phenomena. With accurate calculations of damping

coefficients for various speeds and wave heights, better simulations may be feasible, but it is a challenging task. This method is faster, as it involves the direct calculation of frequency-domain RAOs in a single simulation compared to the calculation of RAOs from the time-domain results using the previous method. At higher speeds (2.572 m/s and 3.086 m/s), the Strouhal number threshold is exceeded as the encounter frequency increases, and a deviation from the experimental results is observed. This is expected, and better numerical tools (e.g., the Rankine source method [38]) are required to improve both heave and pitch predictions.

An uncertainty assessment was conducted to evaluate the reliability and accuracy of the results and is presented in Appendix D. This process aimed to quantify the potential deviations in the data caused by various factors such as experimental setup, model inaccuracies and measurement noise. The uncertainty assessment followed the guidelines outlined in the ISO GUM framework, which is widely recognized for its systematic approach to uncertainty quantification [44]. The 95% confidence interval bars have been plotted over the graphs wherever the experimental data has been used. For lower speeds and wave heights the SEACAL and Orcaflex simulations results lie within the calculated uncertainty limits at high frequencies (>0.4 rad/s) and the comparison has improved. The heave RAOs comparisons also slightly improve at low wave heights (≤ 3m) and low frequencies (< 0.4 rad/s). The uncertainty calculations provide a better understanding the data and enhance the reliability of comparisons with the simulation results.

C.6. Conclusions and further work

Accurate predictions of the motion of an FOWT system hinge upon a thorough understanding and estimation of the various non-linearities inherent to the fluid dynamics concerning the platform motion. Among these factors, damping assumes a pivotal role, particularly in forecasting the pitch, roll and heave motion of the platform. The precise determination of damping coefficients is imperative to ensure the accuracy of system motion predictions. A hybrid approach, combining potential flow principles and the Morison equation, offers a reasonably accurate means of estimating platform motion. However, it is important to note that this method may not be fast, as it demands substantial time to simulate time-domain results and derive RAOs from them. When relying solely on potential flow methodologies, accurate damping calculations become

crucial. This might be challenging, given the necessity of estimating damping across a range of frequencies and wave amplitudes—a task that can prove difficult to execute. Damping estimation at natural frequencies, as obtained from decay tests, can offer reliable predictions, particularly in scenarios where damping is primarily influenced due to viscous effects.

During the experiments, significant pitch and heave motion was observed, with the heave plates emerging from the water at specific wave frequencies near the natural frequencies of heave and pitch motion. This phenomenon is highly nonlinear, and its impact on the platform's motion cannot be adequately analysed using potential-flow-based methods. Additionally, phenomena like vortex shedding can influence motion and warrant dedicated research. It was observed that the Reynolds number exceeded a value of 1×10^5 (see Table 2 as the towing speed increased to 0.436 m/s (6 kn) and entered the sub-critical flow regime [39] characterised by the slow transition of laminar vortices into turbulent vortex shedding. Similar phenomena are expected during towing in waves, affecting the platform's motion and potentially contributing to the observed deviations between the Orcaflex and SEACAL simulations and the experimental results under high-wave, high-speed and low-frequency conditions. Addressing these phenomena requires dedicated research using high-fidelity methods such as Computational Fluid Dynamics (CFD) or Smooth Particle Hydrodynamics (SPH). Investigations by Rongé et al. [40] have demonstrated that CFD methods can provide better predictions of second-order and third-order wave loads compared to strip-theory methods and potential-flow methods. This could potentially enhance predictions of Response Amplitude Operators (RAOs) and towing loads, warranting further investigation. SEACAL can also use the Rankine source method to analyse higher towing speeds and improve the results ($\tau > 0.25$). This approach necessitates discretizing both the hull and the water surface to accurately calculate the waves generated from the floating body. However, it is computationally demanding and requires further optimisation to be applicable to the analysis of semi-submersible platforms.

In the presented study, the focus was solely on head-seas. The emphasis was placed on heave and pitch motion, as well as the corresponding assessment of damping coefficients, which are of primary importance. However, in different heading conditions, roll motion can also become significant, necessitating the estimation of roll damping for

precise motion predictions. It is safe to assume that roll predictions could also be possible using the approaches mentioned in the paper. The accuracy of these motion predictions is paramount due to the established motion limits during towing stipulated by classification societies. The estimation of viscous damping is crucial during numerical simulations because, in its absence, motion limits are surpassed even in calmer sea conditions, subsequently shrinking the available weather windows for towing operations.

Another important factor is the drag on the platform that influences the selection of tugs and towing lines for towing operations. In certain wave conditions, the added resistance in waves increases dramatically, hence the bollard pull requirement for towing. The mean added resistance in waves should be estimated before commencing towing operations. This also plays a role in the selection of towing ropes/cables. Towing using a bridle is advantageous over towing without a bridle, as it reduces the chances of fluid induced motion.

The further assessment of non-linear effects such as VIM/fishtailing, galloping and pitch-induced wave run-up are some of the non-linear phenomena expected while towing, and some of them were observed during the towing tests. These phenomena will lead to downtime and should be avoided either via a better understanding or via mitigation. It requires dedicated research to understand their effects on the towing system and develop numerical models so that precautions can be taken to avoid them. The effects of wind and current on the parked turbine during transit should also be studied to understand and predict the motion and loads on the FOWT system. It is important to analyse the towing route using statistical approaches to perform voyage simulations in order to determine the operability (uptime/downtime) during wet towing.

The DeepCwind platform is one of the earliest FOWT designs and is now considered somewhat outdated. Over time, FOWT designs have evolved significantly, so the results presented may not be fully representative of all current designs. Notably, the platform's large heave plate was observed to emerge from the water during towing, potentially leading to non-linear loads caused by phenomena such as green-water shipping and wave run-up, both of which were observed during testing. Despite these design-specific observations, the methodologies and numerical models developed in this study remain broadly applicable and can be adapted for use with any floater type.

Author Contributions: The experiments were conducted by Rahul Chitteth Ramachandran under the supervision of Jorrit-Jan Serraris and Erik-Jan de Ridder. Jaume Montfort Hernandez advised and assisted in the SEACAL calculations. The paper was written by Rahul Chitteth Ramachandran and edited and modified by Jorrit-Jan Serraris. Cian Desmond reviewed the paper. Erik-Jan de Ridder and Jimmy Murphy reviewed the final manuscript.

Funding: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860737.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A: Numerical Validation Tools and Setup

Appendix A.1. Orcaflex

Orcaflex (version 11.0) [32] is a software tool designed for the analysis and simulation of offshore systems, particularly those involving flexible structures and marine operations. Developed by Orcina Ltd. (Ulverston, UK). Orcaflex offers a comprehensive platform for the modelling and simulation of dynamic behaviour in various marine environments. Its applications extend to the analysis of floating structures, such as offshore wind turbines, floating production systems and moored vessels. Orcaflex can simulate the complex interactions between structures, environmental forces (waves and currents) and dynamic components like cables and risers.

Towing simulations were performed in Orcaflex using its capability to model the platform along with the towing cable and bridle. A 3D model of the platform was developed in the Rhinoceros [41] modelling software first. This model was then exported as a .gdf file and provided as an input for Orcawave [33], the diffraction analysis tool provided by Orcina. A diffraction analysis was performed, and the results were exported into Orcaflex to set up the towing simulations. The Morison elements were incorporated into the model first. Subsequently, the towing lines were modelled as 'links' [42], and the bridle was modelled as a '3D-buoy' [43]. As mentioned before, towing was simulated by constraining the platform using the towing lines and applying a current equal to the speed of towing. A Python script was developed to create a batch file that contains the simulation conditions combining various wave frequencies, wave

heights and current speeds. Using this file, batch simulations were executed in series using Orcaflex. The results were then postprocessed using the Python interface of Orcaflex, and the motion and towing loads were generated. Mesh convergence checks were performed, and the simulations were performed on a normal desktop. See Table A1 for mesh details and simulation conditions.

Table A1. Numerical simulation setup.

Numerical Tool	Number of Elements	Range of Frequencies (Steps)
Orcaflex	3072	0.1 (0.01) 0.35 0.355 (0.005) 0.545 0.55 (0.05) 1.5
SEACAL	10,020	0.1 (0.005) 0.22 0.23 (0.01) 0.4 0.45 (0.05) 1 1.1 (0.1) 1.5

Appendix A.2. SEACAL

SEACAL (version 7.2.0) is an in-house potential 3D panel code developed at MARIN for the calculation of ship behaviour in waves. It can be used to calculate the response to waves for various vessels at arbitrary speeds and headings. SEACAL consists of three main programs:

- HYDMES divides the hull into a number of quadrilateral panels, up to the undisturbed free-surface. Hydrostatic calculations are performed, and the flexural modes are determined.
- HYDCAL solves the linearised boundary value problem and uses a simplified, zero-speed, free-surface condition. The forward speed is included by means of the wave encounter frequency according to the following equation:

$$-{\omega_e}^2\phi + g\frac{\partial\phi}{\partial z} = 0 \quad \text{(A1)}$$

- RESCAL computes the dynamic response of the vessel. Since viscous damping may be of importance in determining the magnitude of the resonant response, empirical formulas based on experimental results are used in addition to those

determined from linearised potential flow theory. After the equations of motion are solved, internal loads and RAOs are calculated.

The 3D geometry of the platform was modelled in Rhinoceros [41] and exported into SEACAL as a .vtk file. Only the underwater surface was modelled for the calculations. Lid meshes were used to close the open surfaces at the waterplane to suppress the irregular frequencies during the simulations. The simulations were performed on an HPC (High- Performance Cluster).

As mentioned before, an accurate determination of the second-order drift loads is required for the precise calculations of motion and wave loads on large marine structures. A mesh convergence study based on the heave and pitch mean second-order drift loads is presented here. The zero-speed cases used in SEACAL and Orcawave were analysed to find the optimum mesh count. A cross-comparison of the drift load calculated in SEACAL and Orcawave was also performed. For Orcawave, since both medium and fine meshes yielded comparable results, the medium mesh (N = 3072) was chosen because the Orcaflex simulations were faster compared to simulations using the fine mesh, which often made the computer freeze and took too long. SEACAL simulations can be performed on an HPC; hence, a high mesh count (N = 10,020) was chosen. See Table A1 for the final mesh details and simulation conditions.

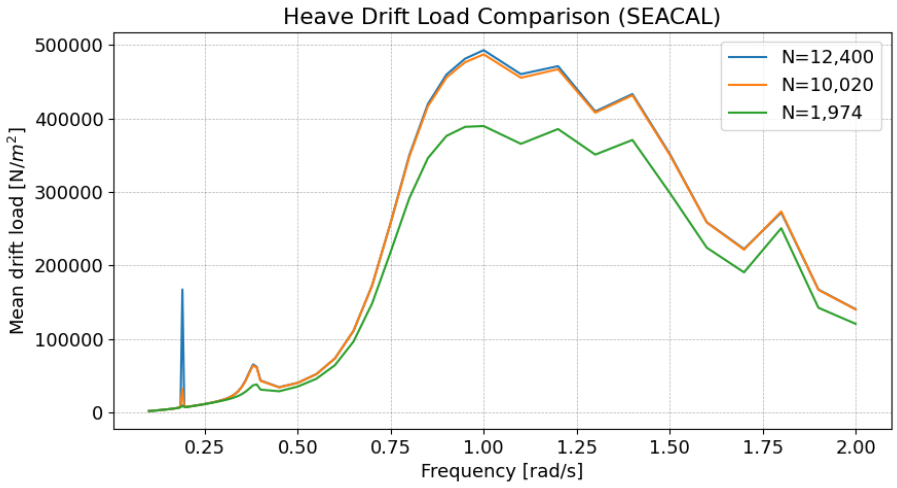


Figure A1. SEACAL mesh convergence−mean heave drift loads.

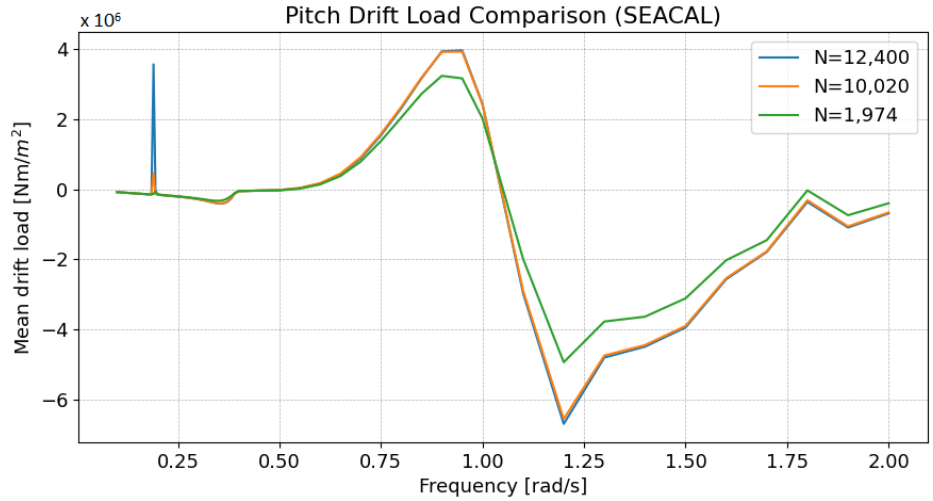


Figure A2. SEACAL mesh convergence−mean pitch drift loads.

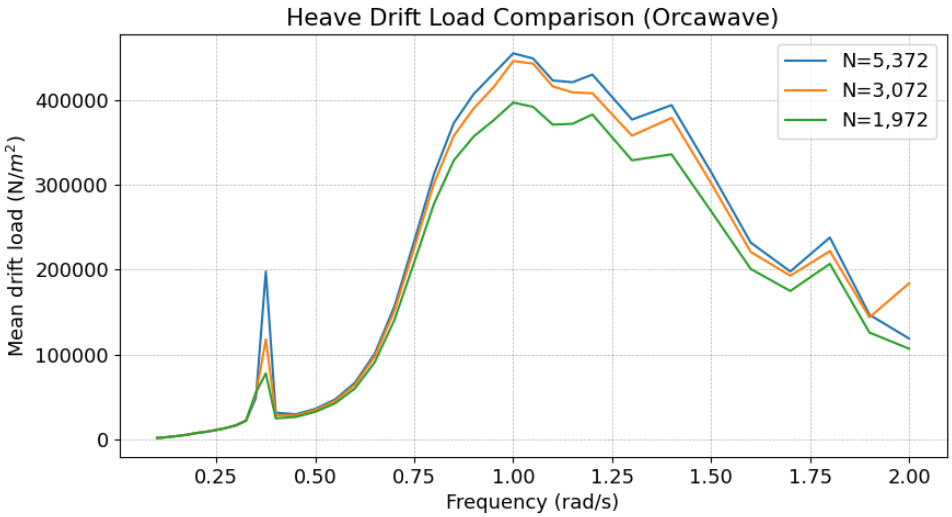


Figure A3. Orcawave mesh convergence−mean heave drift loads.

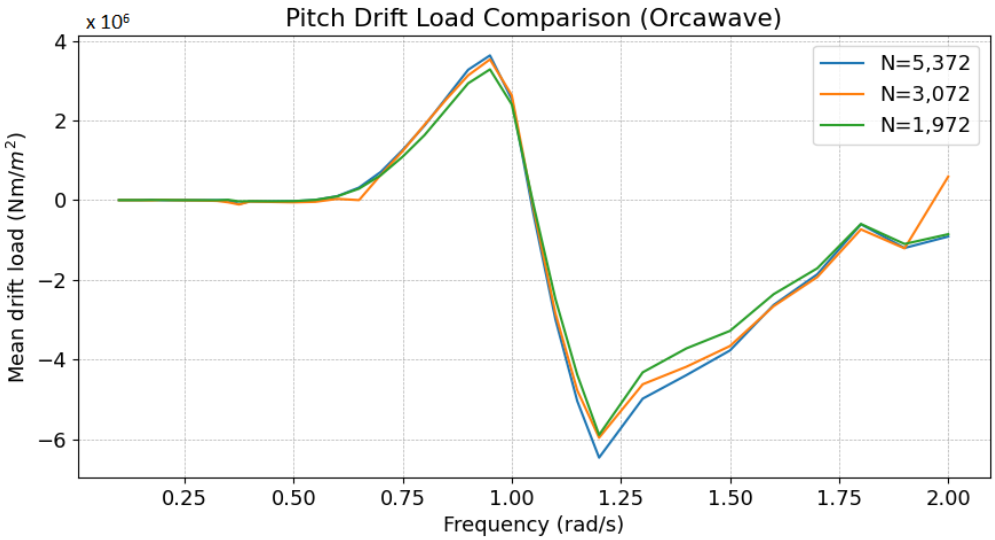


Figure A4. Orcawave mesh convergence−mean pitch drift loads.

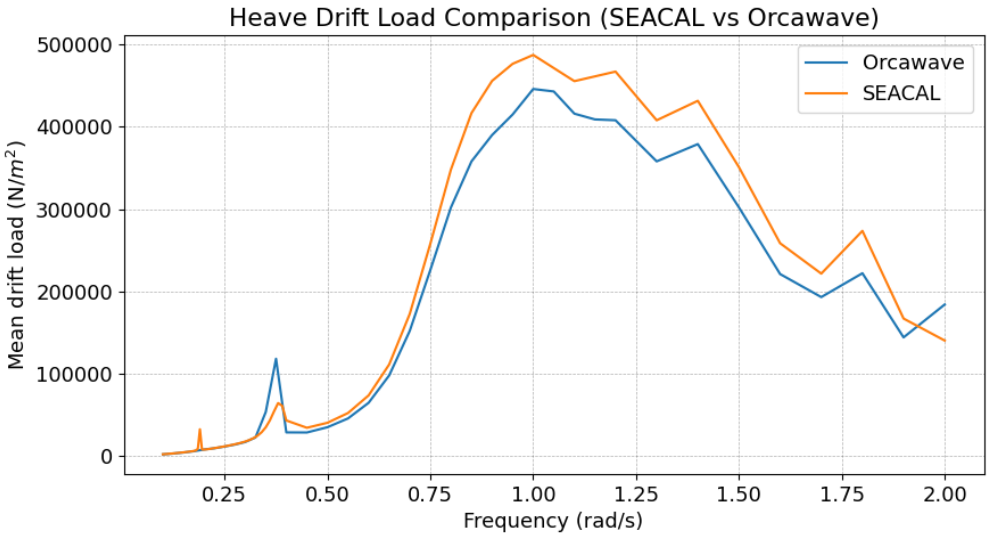


Figure A5. Mean heave drift loads−Orcawave vs. SEACAL.

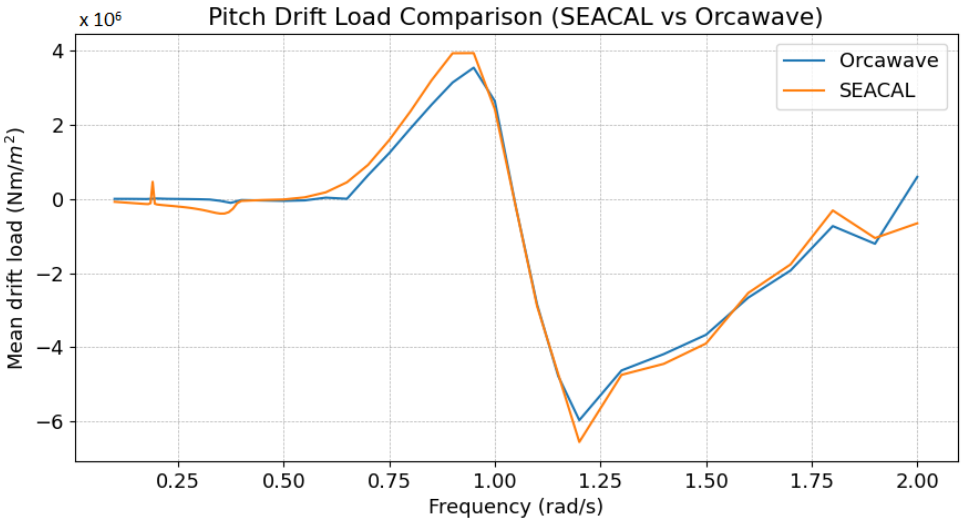
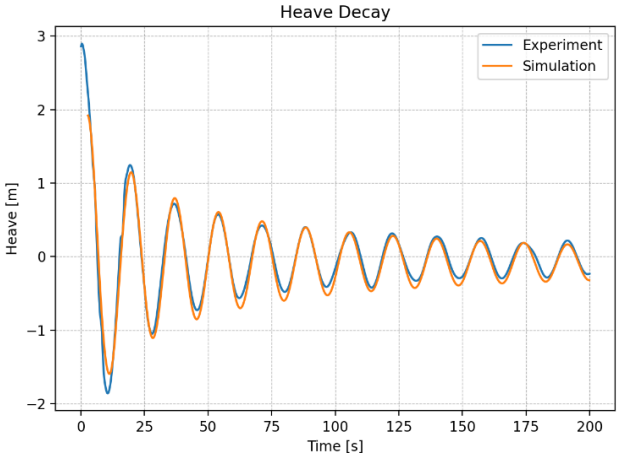
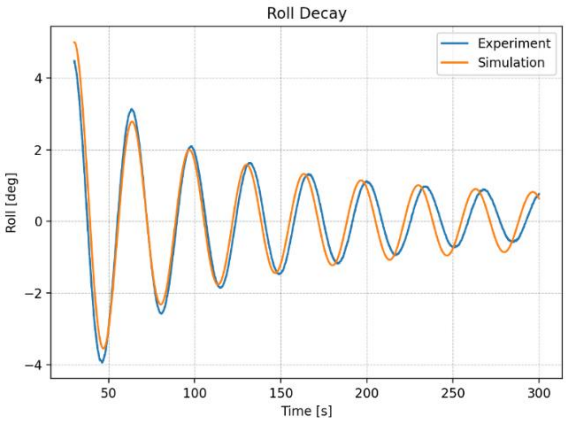


Figure A6. Mean pitch drift loads−Orcawave vs. SEACAL.

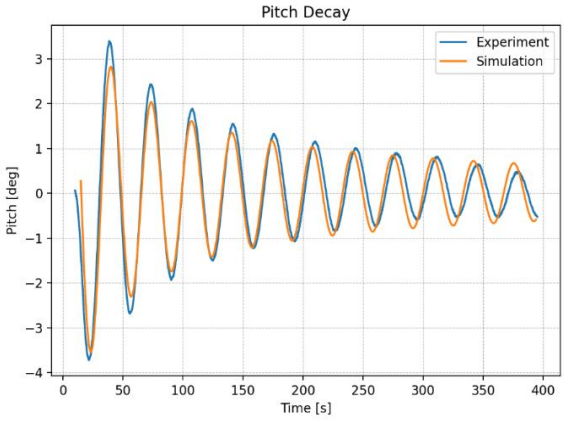
Appendix B: Validation of decay tests and examples of motions in regular waves using the hybrid approach (Orcaflex)



(a)



(b)



(c)

Figure B1: Validation of decay tests (a) Heave (b) Roll (c) Pitch, using the hybrid approach (Orcaflex)

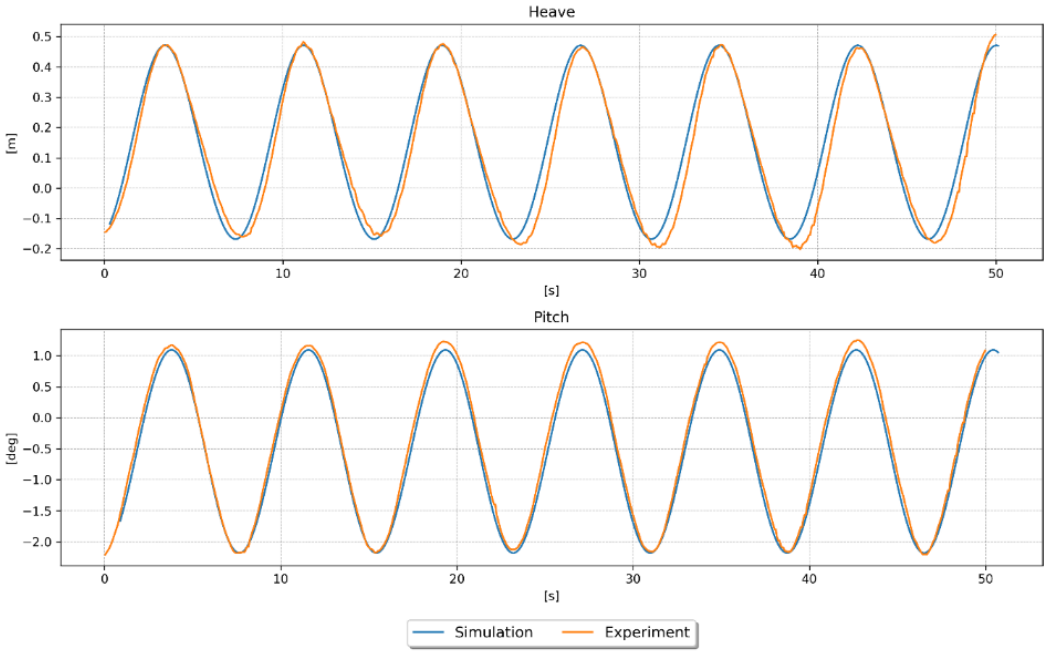


Figure B2: Configuration 1, Speed =1.029 m/s, H = 4m, Period = 8.38s

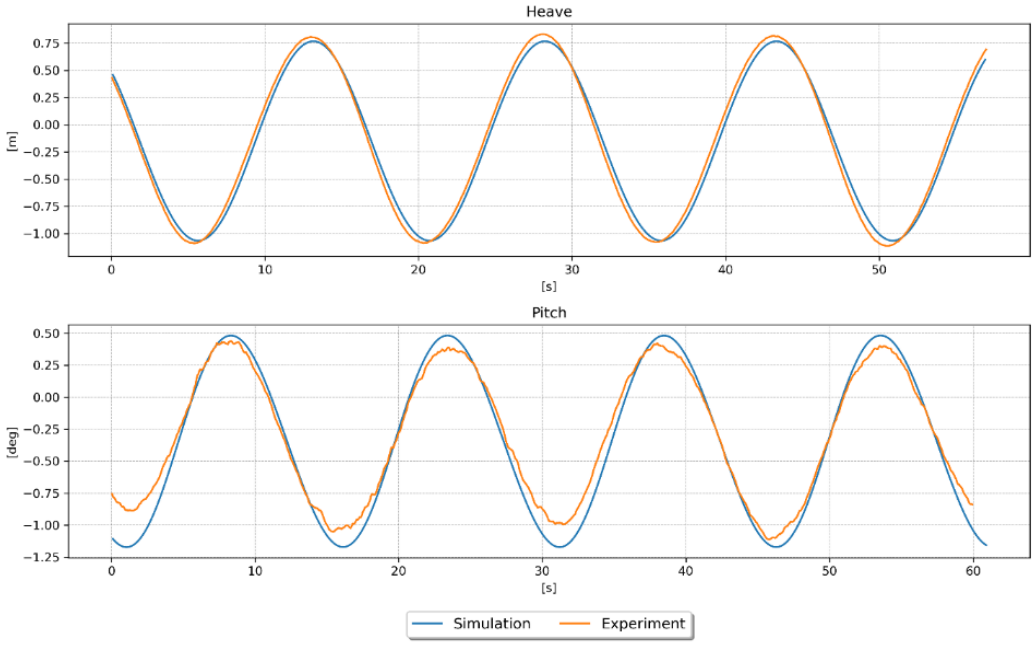


Figure B3: Configuration 1, Speed =1.029 m/s, H = 4m, Period = 15.71s

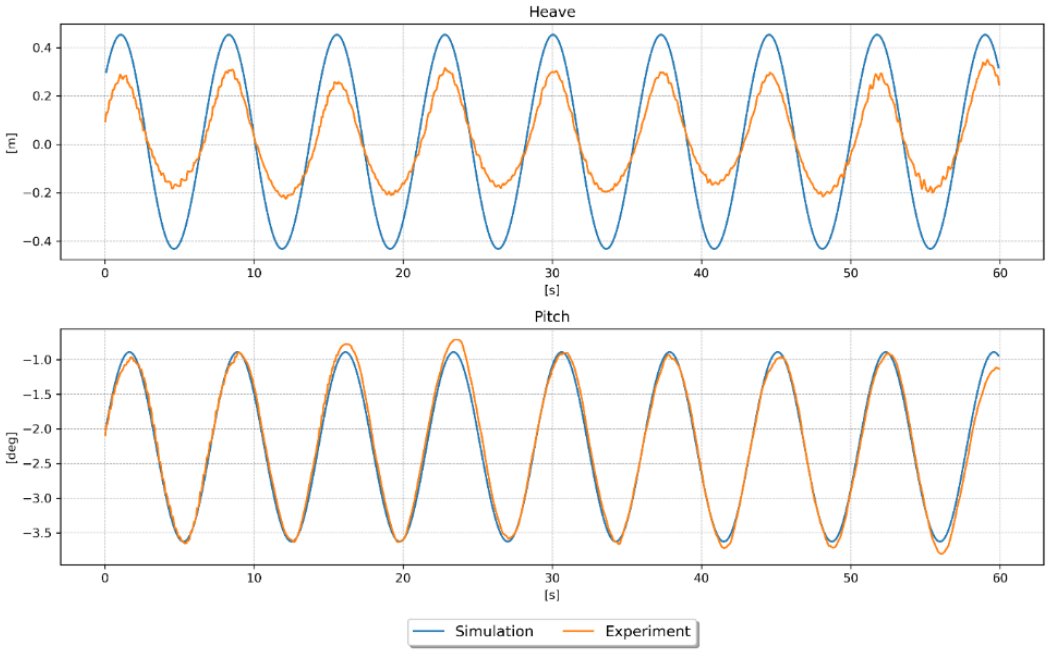
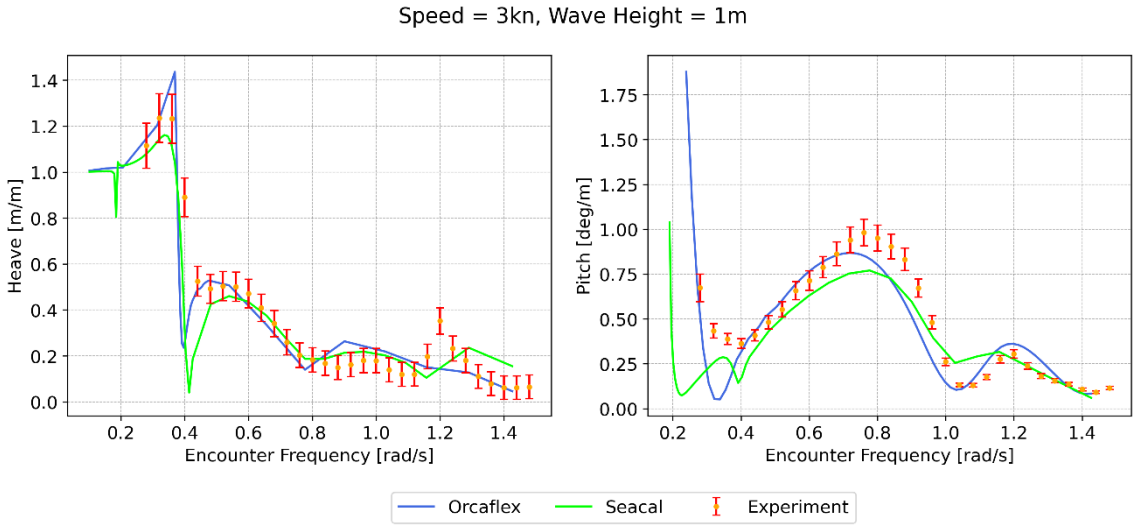
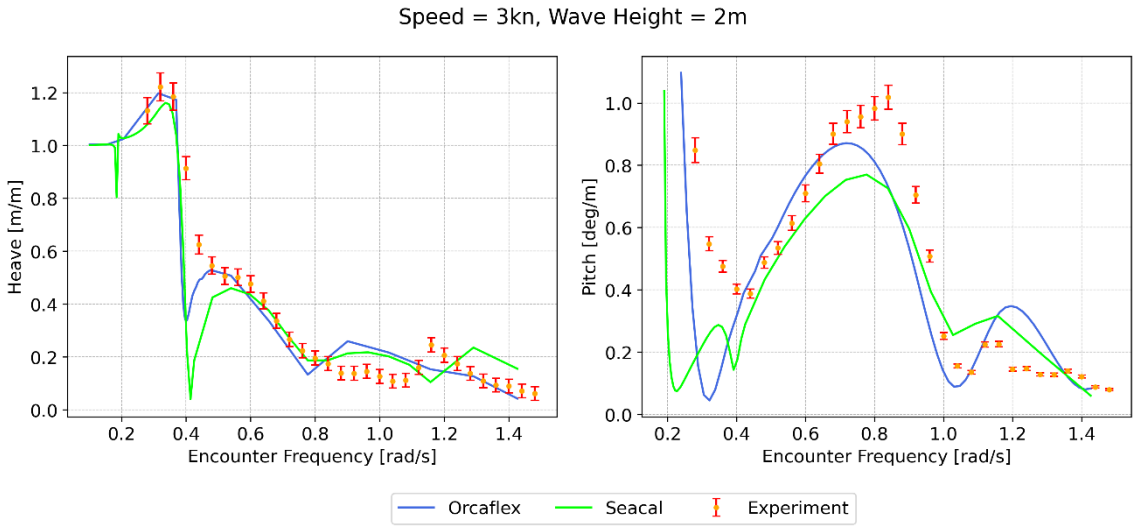


Figure B4: Configuration 1, Speed =2.058 m/s, H=4m, Period=8.38s

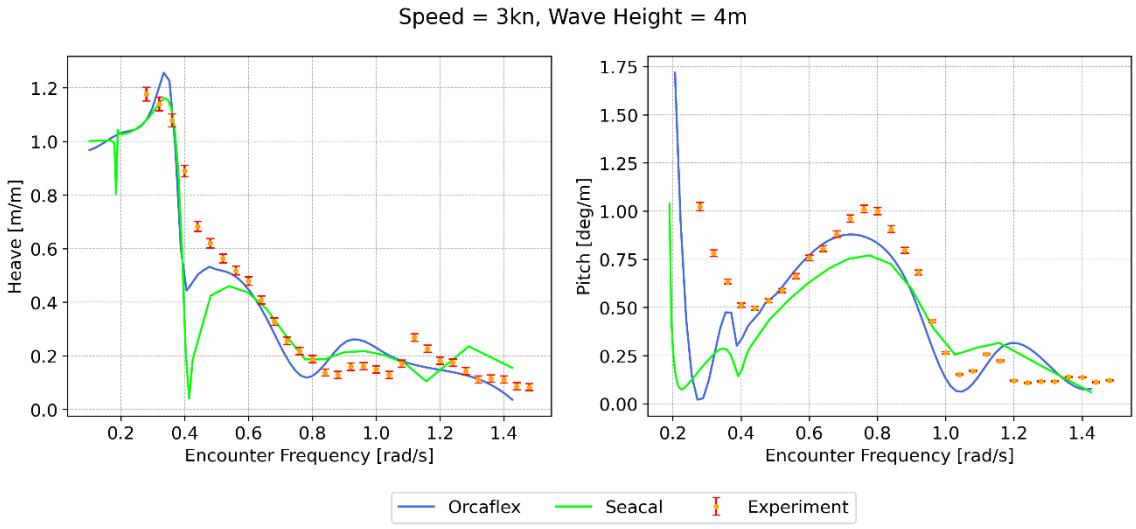
Appendix C: Validation of RAOs calculated from white-noise waves using SEACAL and Orcaflex.



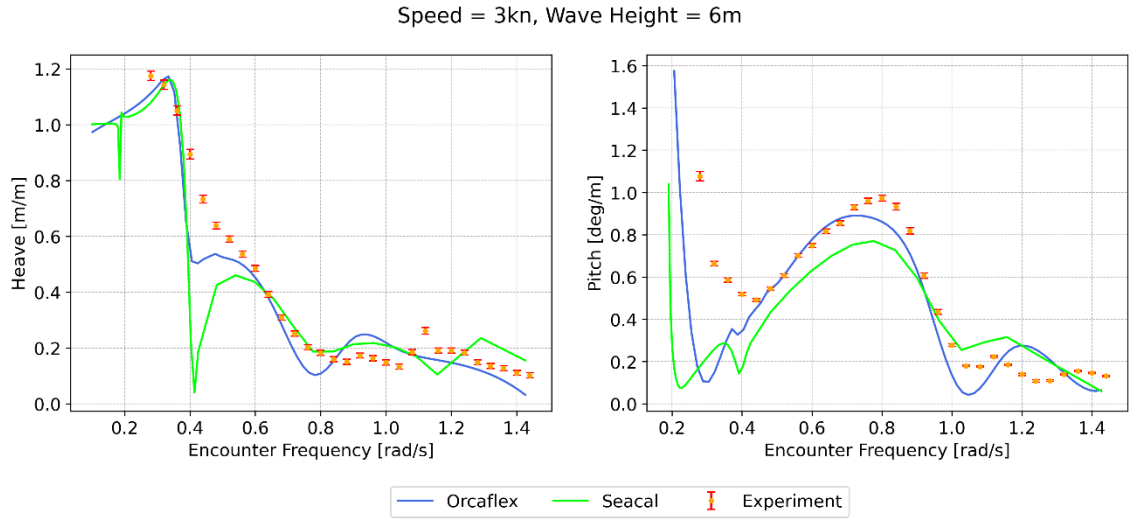
(a)



(b)

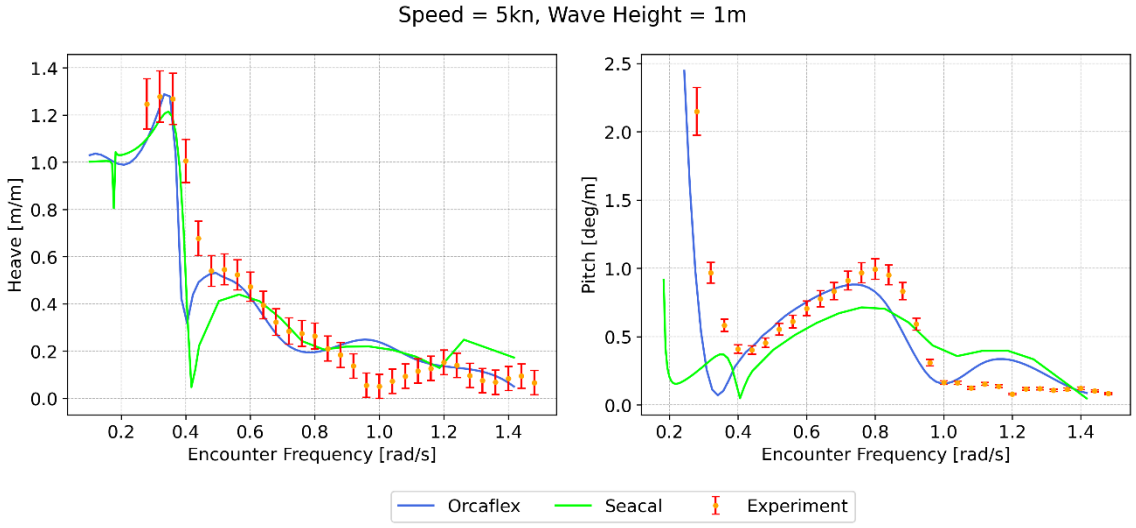


(c)

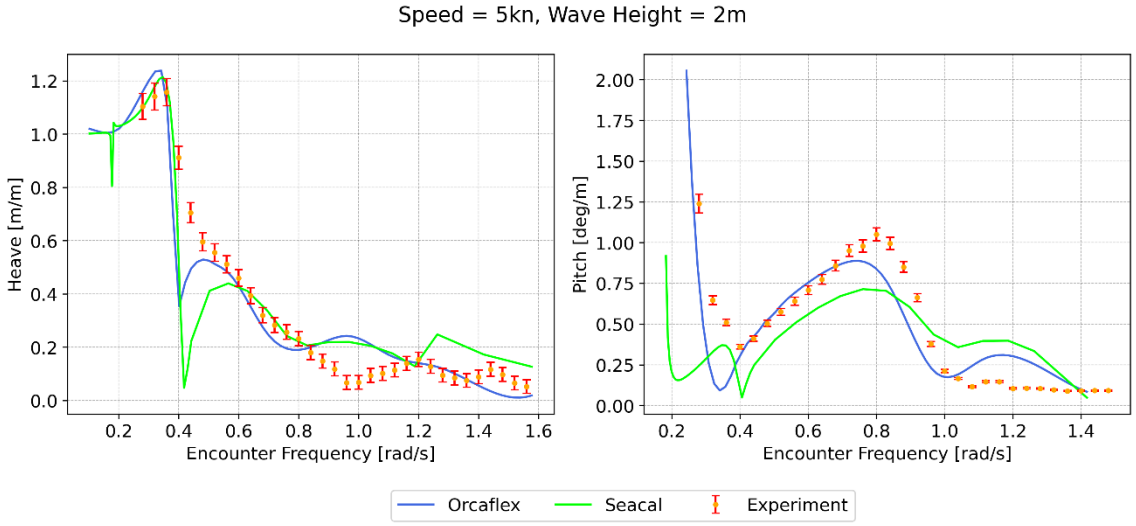


(d)

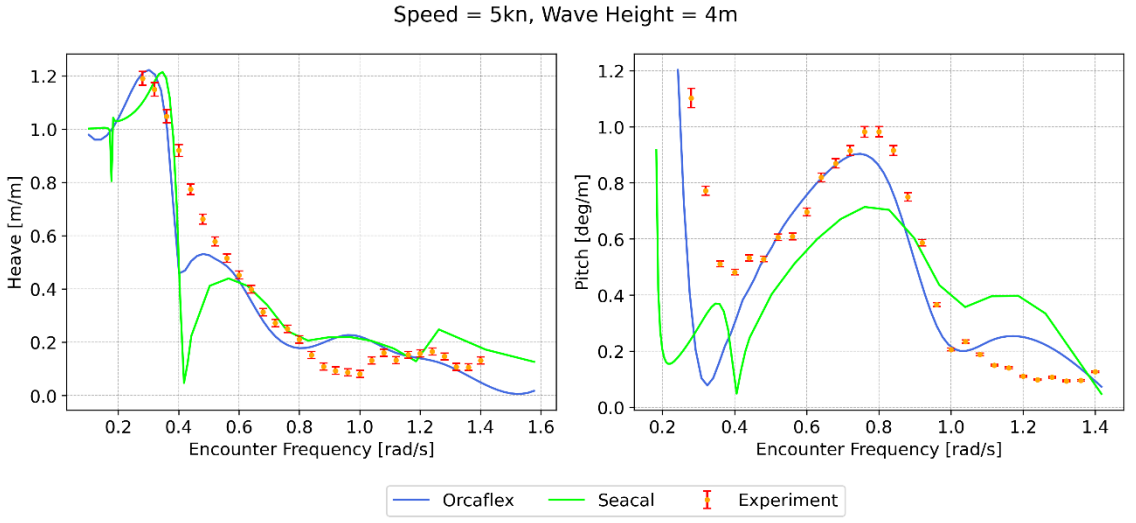
Figure C1: RAOs, towing speed = 1.543 m/s (a) Hs =1 m (b) Hs =2 m (c) Hs = 4 m (d) Hs = 6 m



(a)

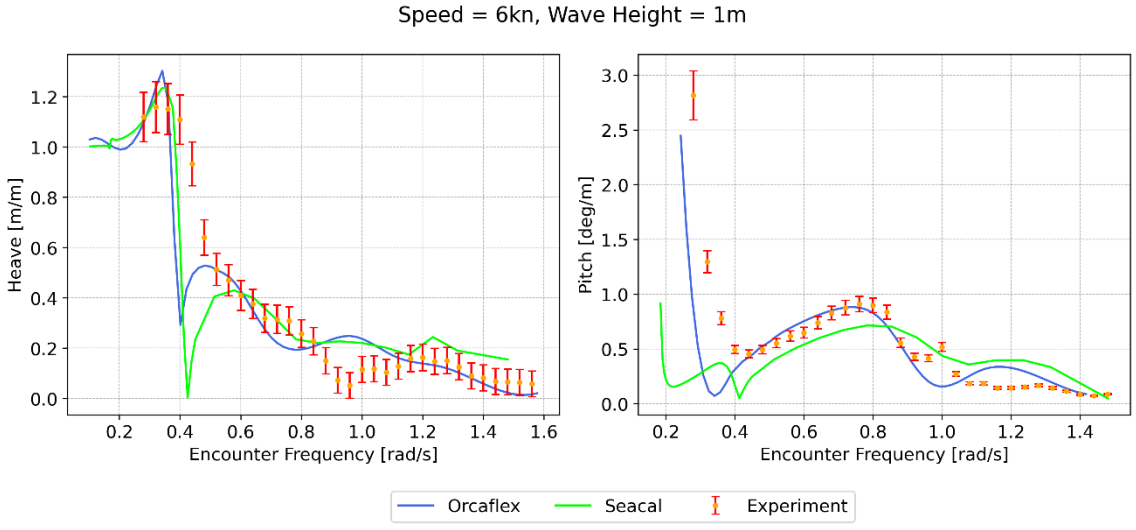


(b)

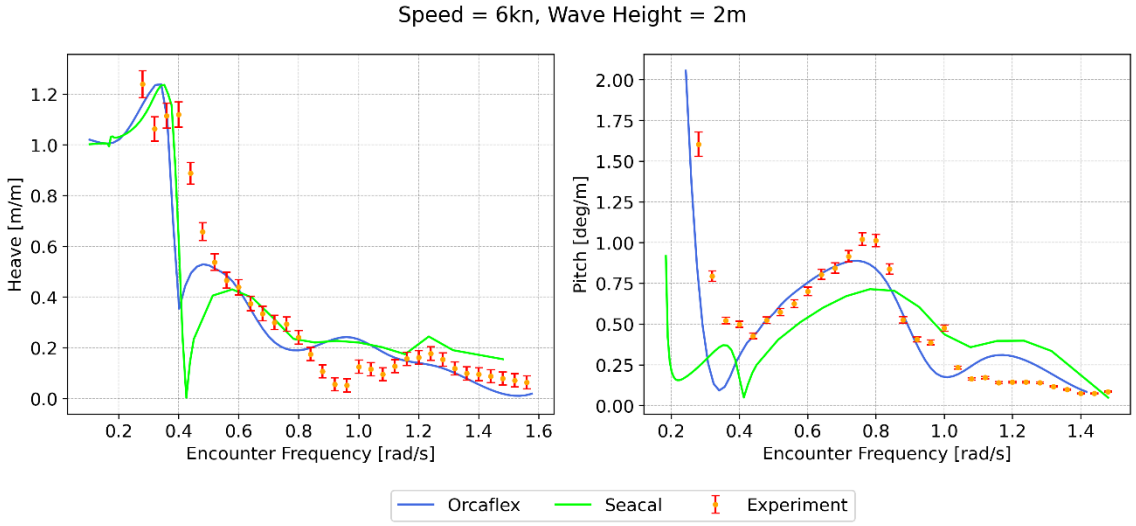


(c)

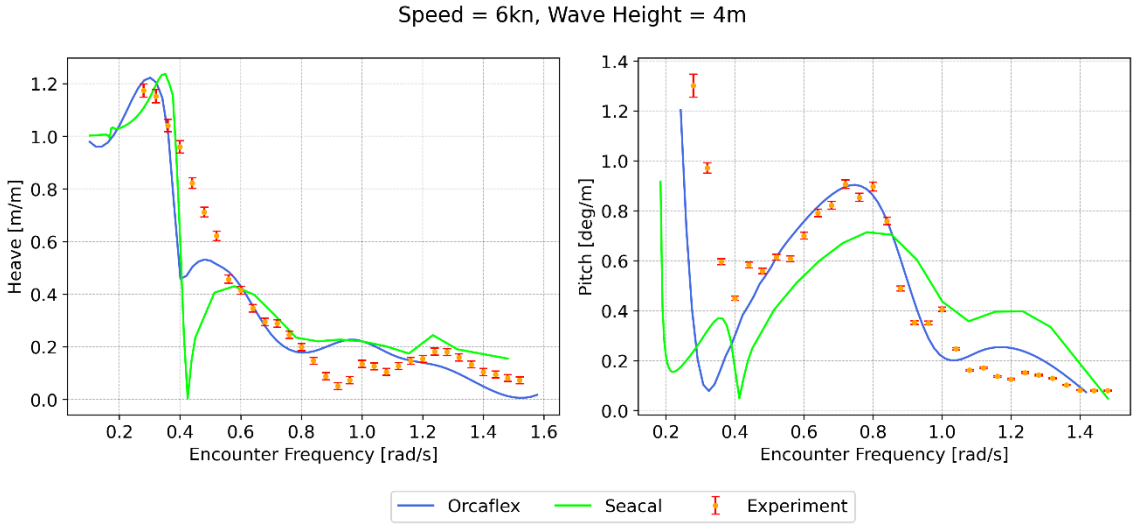
Figure C2: RAOs, towing speed = 2.572 m/s (a) Hs =1 m (b) Hs =2 m (c) Hs = 4 m



(a)



(b)



(c)

Figure C3: RAOs, towing speed = 3.086 m/s (a) Hs =1 m (b) Hs =2 m (c) Hs = 4 m

Appendix D

Uncertainty Analysis of the experimental data

The uncertainty analysis of the experimental data has been done using the International Towing Tank Conference (ITTC) guidelines. Uncertainty analysis in seakeeping studies ensures that experimental or computational results are reliable and conform to standardized quality control practices. The International Towing Tank Conference (ITTC) and the ISO Guide to the Expression of Uncertainty in Measurement (GUM) provide structured methodologies for assessing uncertainties in seakeeping tests [44].

D1. Steps in seakeeping uncertainty analysis:

1. **Define measurement quantities**
    - These are the quantities of which the uncertainty analysis is performed. In this analysis, the drag, heave and pitch are the quantities.
2. **Identifying the sources of uncertainty**
    - Instrumental errors: Calibration inaccuracies in wave gauges, motion sensors and load cells.
    - Environmental factors: Variability in wave amplitude and towing speed
    - Data Processing: Errors introduced during retrieval of data from the measurement system
3. **Quantifying individual uncertainty contributions**
    - The uncertainty in each contributing quantity is ascertained. These values can be the accuracy of the measurement devices or observations from the laboratory
    - The sensitivity coefficient is calculated using formulas or by numerical differentiation. The influence of some quantities is derived and some examples are given below. This aids the calculation of uncertainties contributed by factors like residual flow and accuracy of the speed of the carriage.

Influence of speed/residual flow on drag

$$Drag, F = 0.5 C_d \rho S V^2$$

$$\frac{\partial F}{\partial V} = 2 \times 0.5 C_d \rho S V = \frac{2F}{V}$$

Influence of sinkage

heave = $\text{heave}_{\text{measured}}$ + S

h = h_m + S

$$\frac{h}{H_a} = \frac{h_m}{H_a} + \frac{S}{H_a}$$

$$\frac{2 \times h}{H_{2a}} = \frac{2 \times h_m}{H_{2a}} + \frac{2 \times S}{H_{2a}}$$

$$RAO = RAO_m + \frac{2 \times S}{H_{2a}}$$

$$\frac{\partial RAO}{\partial S} = \frac{2}{H_{2a}}$$

Influence of wave probe error

$$H_{2a} = H_{2a_m} + \Delta E$$

$$RAO = \frac{2 \times h}{H_{2a}}$$

$$\frac{\partial RAO}{\partial H_{2a}} = -\frac{2 \times h}{{H_{2a}}^2}$$

$$\frac{\partial RAO}{\partial H_{2a}} = -\frac{RAO}{H_{2a}}$$

Where S is the sinkage

h is the heave amplitude

H_{2a} is the wave height

H_a is the wave amplitude

ΔE is the wave probe error

S is the surface area

V is the flow velocity

ρ is the density of fluid

C_d is the drag coefficient

Similar to heave, the uncertainty in the estimation of pitch can also be analysed.

- In some cases, a direct differentiation is not possible as there are not direct formulas connecting to different quantities. In such cases numerical differentiation is used to derive the influence parameter. For example, the effect of towing speed of the platform is estimated by performing the numerical differentiation of the available experimental data. The slope of the fitted line in Figure D1 gives the influence parameter, ie. 0.0198 in this particular case, for a towing speed on 0.514 m/s.

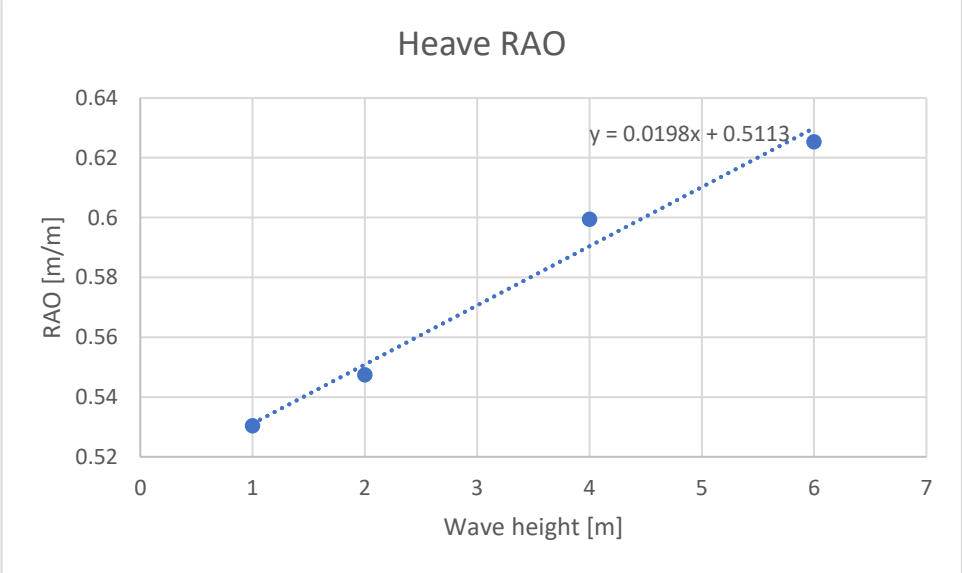


Figure D1: Sensitivity of heave RAO to wave height (V = 0.5144 m/s)

4. Combining uncertainties using GUM principles

- The characteristic value of a particular source is multiplied with a factor *kappa*, *k*, depending on the probability density distributions (PDD) according to Table D1.

Table D1: Kappa values

PDD	Equivalent Standard Deviation	*kappa*	Use
Normal	$s = \sigma$	1	When the quantity is known to follow normal distribution

Triangular	$s = \frac{1}{\sqrt{6}}\sigma$	0.4	For quantities with hard limit errors Eg: Noise. vibration
Rectangular	$s = \frac{1}{\sqrt{3}}\sigma$	0.6	When variation limits are known Eg: Calibration certificates, Manufacturer specifications
U-shaped	$s = \frac{1}{\sqrt{2}}\sigma$	0.7	For cyclic influences Eg: Temperature variation
Step	$s = \frac{1}{2\sqrt{3}}\sigma$	0.3	When resolution is limited Eg: digital readouts, verniers, scale read by operator

- Uncertainties are combined as the root sum of squares (RSS) of independent contributions

$$u_c = \sqrt{\sum_{i=1}^{n} u_i^2}$$

5. Report Expanded Uncertainty

Multiply the combined uncertainty (u_c) by a coverage factor k, typically $k = 2$ for 95 % confidence:

$$U_c = k.u_c$$

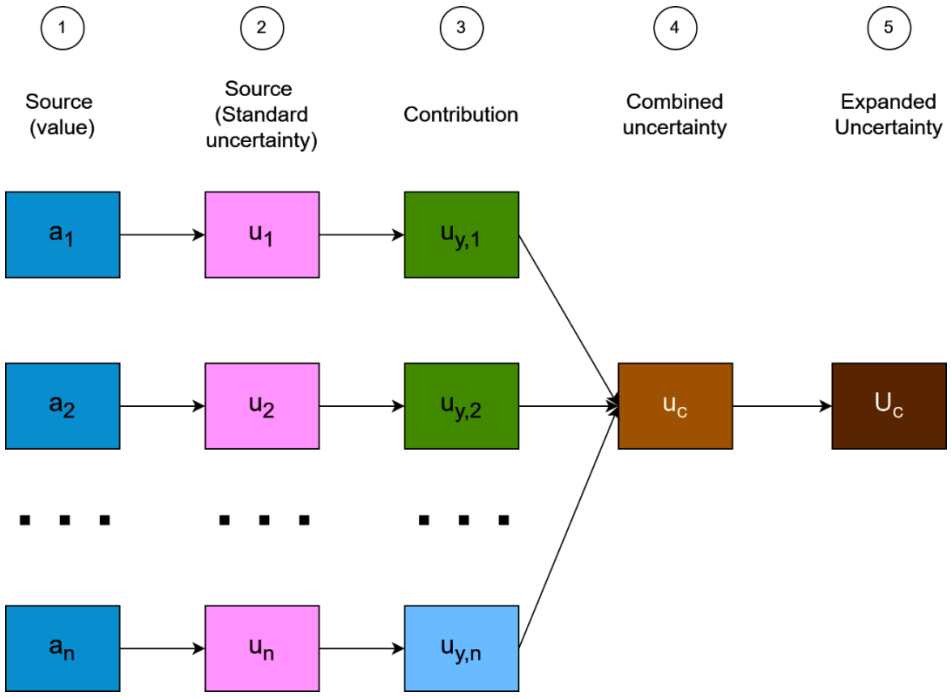


Figure D2: Uncertainty estimation by ISO GUM

D2. Towing in calm water

This section explains the calculation of uncertainties in the estimation of drag while towing in calm water. The quantities affecting the drag and their contributions on model scale are listed in Table D1. Table D3 shows a sample calculation of the uncertainty based on these factors. Similarly, the uncertainty assessment is carried out for all the measurements during the campaign and the results are presented in Table D5.

Table D1: Quantities affecting drag measurements (model scale)

Quantity	Standard uncertainty
Sinkage of the platform	0.5 mm
Accuracy of the force transducer	1 %
Residual flow in basin/waiting between measurements	1 %
Residual waves in basin	2 mm
Accuracy of the speed of carriage	0.0061%
Water temperature/density	0.15 kg/m^3
Completion of measurement results – rounding error	0.0005 N

D3. Towing in waves

The uncertainty of the analysis of the total drag, heave RAO and pitch RAO while towing in various wave conditions are analysed here. The quantities used for calculating the uncertainty are presented in Table D2. Similarly, the uncertainty assessment is carried out for all the heave and pitch RAOs and the results are presented in Table D6, Table D7.

Table D2: Quantities contributing to uncertainty in drag and RAO values (model scale)

Quantity	Standard uncertainty
Sinkage of the platform	0.5 mm
Accuracy of the motion capture system	Heave: 0.105 mm Pitch: 0.00485 deg
Residual flow in basin/waiting between measurements	1 cm/s
Residual waves in basin	2 mm high long wave
Accuracy of the speed of carriage	0.0061%
Completion of measurement results – rounding error	0.0005 mm/deg

D4. Observations

It was observed that the sinkage of the model had a significant effect on the drag and heave RAOs for towing tests in waves. The residual flow in the tank also has a significant influence on the drag. As the RAO values decrease, the percentage error is observed to be increasing. This is because, some factors like sinkage, residual waves and wave calibration errors contribute an absolute error rather than a relative error. This is a notable observation for low speeds and low wave heights. The uncertainties are plotted as error bars and added to the respective chapters where these experimental data are used.

Table D3: Sample calculation of the uncertainty assessment of a drag measurement in calm water towing

Speed of towing	0.5144 m/s
Drag measurement	81692 N

variable	**dimension**	**value**	a_{kar}	a_{kar} / ***Value***	**distribution**	***kappa***	c_p	$u_{y,i}$	$u_{y,1}^2/u_c^2$
Sinkage of the platform	m	10	0.025	0%	rectangular	0.58	8.17E+03	1.18E+02	2%
Residual flow in basin/waiting between measurements	m/s	0.5144	0.005144	1%	triangular	0.41	3.18E+05	6.67E+02	56%
Residual waves in basin	N	0	0.1	~	triangular	0.41	8.09E+03	3.30E+02	14%
Speed of carriage	m/s	0.5144	0.001255	0%	rectangular	0.58	3.18E+05	2.30E+02	7%
Accuracy of the force transducer	N	81692	816.92	1%	U95	0.50	1.00E+00	4.08E+02	21%
Water temperature/density	kg/m^3	999.13	0.15	0%	rectangular	0.58	8.18E+01	7.08E+00	0%
Completion of measurement results	N	81692	40.846	0%	Step	0.29	1.00E+00	1.18E+01	0%
							u_c =	887.62	
							U =	1,775.24	
							U/Y =	2.2%	
					Y =	81,692	+-	1,775	

Table D4: Sample calculation of the uncertainty assessment of a heave RAO while towing in waves

Speed	0.5144 m/s
Wave height	4 m
Frequency	0.28 rad/s
Heave RAO value	1.149 m

variable	**dimension**	**value**	a_{kar}	$a_{kar}/value$	**distribution**	***kappa***	c_p	$u_{y,i}$	$u_{y,1}^2/u_c^2$
Sinkage of the platform	m	10	2.50E-02	0%	triangular	0.41	5.00E-01	5.10E-03	17%
Residual flow in basin/waiting between measurements	m/s	0.5144	7.07E-02	14%	triangular	0.41	1.15E-02	3.31E-04	0%
Residual waves in basin	m	4	1.00E-01	3%	triangular	0.41	2.35E-03	9.60E-05	0%
Speed of carriage	m/s	0.5144	3.14E-04	0%	rectangular	0.58	1.15E-02	2.08E-06	0%
Accuracy - wave gauges	m	4	7.50E-02	2%	U95	0.50	-2.87E-01	1.08E-02	74%
Accuracy - motion capture system	m	1.1490	5.10E-03	0%	U95	0.50	5.00E-01	1.28E-03	1%
Measurement rounding error	m	1.1490	2.50E-02	2%	Step	0.29	5.00E-01	3.61E-03	8%
							u_c =	0.0125	
							U =	0.0250	
							U/Y =	2.2%	
					Y =	1.1490	+-	0.0250	

Table D5: Uncertainty in drag measurements in calm water

Speed (m/s)	Drag (N)	Uncertainty (N)	% Uncertainty
0.514	81692	888	2.20
1.029	289602	3066	2.10
1.543	637001	6711	2.10
2.058	1180161	12412	2.10
2.572	1934565	12402	2.10
3.086	2932150	30800	2.10

Table D6: Uncertainty in drag and RAO measurements in waves

Speed (m/s)	Wave Height (m)	Frequency (rad/s)	Total drag (KN)	Total Drag Uncertainty (KN)	%Total Drag Uncertainty	Added Resistance (KN)	Added Resistance Uncertainty (KN)	% Added Resistance Uncertainty
1.0288	4	0.3	307.78	10.61	3.45	18.18	0.74	4.09
1.0288	4	0.349	406.76	10.60	2.61	461.66	15.75	3.41
1.0288	4	0.4	328.55	10.20	3.11	76.90	2.93	3.81
1.0288	4	0.6	366.50	10.55	2.88	38.95	1.41	3.62
1.0288	4	0.75	751.26	12.24	1.63	117.16	3.21	2.74
1.0288	2	0.9	395.75	10.34	2.61	106.15	3.63	3.42
1.0288	1	1	319.17	9.85	3.09	29.57	1.12	3.79
2.0576	4	0.3	1304.90	23.69	1.82	124.74	3.56	2.85
2.0576	4	0.349	1311.57	23.11	1.76	525.91	14.82	2.82
2.0576	4	0.4	1235.22	22.46	1.82	191.46	5.46	2.85
2.0576	4	0.6	1371.62	23.62	1.72	55.06	1.54	2.79
2.0576	4	0.75	1706.07	25.37	1.49	131.41	3.49	2.66
2.0576	2	0.9	1377.37	23.11	1.68	197.21	5.46	2.77
2.0576	1	1	1219.76	21.80	1.79	39.60	1.12	2.83
2.572	4	0.3	2140.39	32.87	1.54	205.83	5.52	2.68
2.572	4	0.349	2181.43	32.45	1.49	551.26	14.64	2.66
2.572	4	0.4	2073.27	31.48	1.52	202.95	5.42	2.67
2.572	4	0.6	2137.51	32.33	1.51	138.71	3.70	2.67
2.572	4	0.75	2485.82	34.35	1.38	246.87	6.41	2.60
2.572	2	0.9	2099.32	31.46	1.50	164.76	4.39	2.66
2.572	1	1	1990.64	30.29	1.52	56.08	1.50	2.68

Speed (m/s)	Wave Height (m)	Frequency (rad/s)	Heave RAO (m)	Heave Uncertainty (m)	%Heave uncertainty	Pitch RAO (deg)	Pitch Uncertainty (deg)	%Pitch Uncertainty
1.0288	4	0.3	0.98	0.05	4.68	0.22	0.01	4.74
1.0288	4	0.349	1.21	0.06	4.64	0.34	0.02	4.75

1.0288	4	0.4	0.48	0.03	5.29	0.36	0.02	4.69
1.0288	4	0.6	0.38	0.02	5.74	0.72	0.03	4.68
1.0288	4	0.75	0.16	0.01	9.15	0.78	0.04	4.68
1.0288	2	0.9	0.18	0.03	15.44	0.24	0.01	5.12
1.0288	1	1	0.13	0.05	39.03	0.32	0.03	8.45
2.0576	4	0.3	1.01	0.03	2.49	0.22	0.01	2.76
2.0576	4	0.349	1.05	0.02	2.32	0.28	0.01	2.37
2.0576	4	0.4	0.57	0.04	7.85	0.31	0.01	3.63
2.0576	4	0.6	0.29	0.05	15.73	0.82	0.02	2.49
2.0576	4	0.75	0.12	0.03	22.89	0.72	0.02	2.78
2.0576	2	0.9	0.20	0.03	14.90	0.35	0.04	10.70
2.0576	1	1	0.25	0.05	21.68	0.40	0.04	10.98
2.572	4	0.3	1.03	0.02	2.30	0.21	0.01	2.49
2.572	4	0.349	1.04	0.03	2.49	0.25	0.01	4.37
2.572	4	0.4	0.59	0.05	7.70	0.30	0.01	3.70
2.572	4	0.6	0.25	0.04	17.78	0.87	0.02	2.34
2.572	4	0.75	0.17	0.03	16.10	0.59	0.02	3.04
2.572	2	0.9	0.22	0.03	12.84	0.30	0.04	13.01
2.572	1	1	0.12	0.05	45.03	0.35	0.04	10.72

Table D7: Uncertainty in RAO calculations from irregular waves

Speed (m/s)	Wave Height (m)	Frequency (rad/s)	Heave RAO (m)	Heave Uncertainty (m)	%Heave Uncertainty	Pitch RAO (deg)	Pitch uncertainty (deg)	%Pitch Uncertainty
0.514	1	0.28	1.12	0.10	8.78	0.37	0.06	17.26
0.514	1	0.32	1.54	0.13	8.23	0.33	0.03	10.09
0.514	1	0.36	1.80	0.15	8.08	0.36	0.03	8.00
0.514	1	0.4	0.86	0.08	9.59	0.37	0.03	7.62
0.514	1	0.44	0.47	0.06	13.29	0.47	0.04	7.56
0.514	1	0.48	0.53	0.06	12.21	0.54	0.04	7.57
0.514	1	0.52	0.53	0.06	12.23	0.62	0.05	7.57
0.514	1	0.56	0.50	0.06	12.63	0.69	0.05	7.57
0.514	1	0.6	0.46	0.06	13.48	0.77	0.06	7.57
0.514	1	0.64	0.40	0.06	14.92	0.82	0.06	7.57
0.514	1	0.68	0.31	0.06	17.89	0.85	0.06	7.56
0.514	1	0.72	0.23	0.05	23.58	0.90	0.07	7.56
0.514	1	0.76	0.16	0.05	33.81	0.94	0.07	7.56
0.514	1	0.8	0.15	0.05	34.49	0.87	0.07	7.56
0.514	1	0.84	0.17	0.05	30.73	0.74	0.06	7.57
0.514	1	0.88	0.19	0.05	27.86	0.60	0.05	7.56
0.514	1	0.92	0.20	0.05	26.70	0.46	0.03	7.56
0.514	1	0.96	0.21	0.05	25.16	0.28	0.02	7.58
0.514	1	1	0.21	0.05	25.35	0.15	0.01	8.58
0.514	1	1.04	0.20	0.05	26.71	0.17	0.01	7.65
0.514	1	1.08	0.16	0.05	32.60	0.23	0.02	7.61
0.514	1	1.12	0.12	0.05	43.35	0.22	0.02	7.59
0.514	1	1.16	0.09	0.05	59.15	0.20	0.02	7.63
0.514	1	1.2	0.10	0.05	53.21	0.20	0.02	7.69

0.514	1	1.24	0.08	0.05	66.81	0.16	0.01	7.60
0.514	1	1.28	0.06	0.05	91.13	0.12	0.01	7.61
0.514	1	1.32	0.05	0.05	109.63	0.10	0.01	8.11
1.543	1	0.28	1.11	0.10	8.79	0.67	0.08	11.40
1.543	1	0.32	1.23	0.11	8.58	0.43	0.04	9.16
1.543	1	0.36	1.23	0.11	8.64	0.39	0.03	7.97
1.543	1	0.4	0.89	0.08	9.46	0.36	0.03	7.63
1.543	1	0.44	0.52	0.07	12.43	0.41	0.03	7.58
1.543	1	0.48	0.49	0.06	12.82	0.48	0.04	7.57
1.543	1	0.52	0.50	0.06	12.60	0.55	0.04	7.57
1.543	1	0.56	0.50	0.06	12.66	0.66	0.05	7.57
1.543	1	0.6	0.47	0.06	13.16	0.71	0.05	7.57
1.543	1	0.64	0.41	0.06	14.56	0.79	0.06	7.57
1.543	1	0.68	0.34	0.06	16.75	0.86	0.07	7.56
1.543	1	0.72	0.26	0.05	21.06	0.94	0.07	7.56
1.543	1	0.76	0.20	0.05	26.33	0.98	0.07	7.56
1.543	1	0.8	0.18	0.05	28.94	0.95	0.07	7.56
1.543	1	0.84	0.17	0.05	31.24	0.90	0.07	7.57
1.543	1	0.88	0.15	0.05	35.04	0.83	0.06	7.56
1.543	1	0.92	0.16	0.05	32.39	0.67	0.05	7.57
1.543	1	0.96	0.18	0.05	29.41	0.48	0.04	7.57
1.543	1	1	0.18	0.05	29.46	0.26	0.02	7.89
1.543	1	1.04	0.14	0.05	37.44	0.13	0.01	7.70
1.543	1	1.08	0.12	0.05	43.35	0.13	0.01	7.64
1.543	1	1.12	0.12	0.05	43.23	0.18	0.01	7.59
1.543	1	1.16	0.20	0.05	26.94	0.28	0.02	7.61
1.543	1	1.2	0.35	0.06	16.33	0.31	0.02	7.65
1.543	1	1.24	0.23	0.05	23.24	0.24	0.02	7.62
1.543	1	1.28	0.18	0.05	29.32	0.18	0.01	7.59
1.543	1	1.32	0.11	0.05	46.72	0.16	0.01	7.57
1.543	1	1.36	0.08	0.05	64.73	0.14	0.01	7.60
1.543	1	1.4	0.06	0.05	82.93	0.11	0.01	7.61
1.543	1	1.44	0.06	0.05	82.81	0.09	0.01	7.63
1.543	1	1.48	0.07	0.05	78.71	0.11	0.01	7.63
1.543	1	1.52	0.05	0.05	96.14	0.10	0.01	7.59
1.543	1	1.56	0.04	0.05	139.86	0.10	0.01	7.57
2.572	1	0.28	1.25	0.11	8.55	2.15	0.17	8.11
2.572	1	0.32	1.28	0.11	8.52	0.97	0.08	7.91
2.572	1	0.36	1.27	0.11	8.58	0.58	0.05	7.73
2.572	1	0.4	1.01	0.09	9.07	0.41	0.03	7.61
2.572	1	0.44	0.68	0.07	10.73	0.40	0.03	7.62
2.572	1	0.48	0.54	0.07	12.09	0.45	0.03	7.58
2.572	1	0.52	0.55	0.07	11.99	0.55	0.04	7.57
2.572	1	0.56	0.52	0.06	12.31	0.61	0.05	7.57
2.572	1	0.6	0.47	0.06	13.15	0.71	0.05	7.57
2.572	1	0.64	0.39	0.06	14.95	0.78	0.06	7.57
2.572	1	0.68	0.32	0.06	17.49	0.83	0.06	7.56
2.572	1	0.72	0.28	0.06	19.45	0.91	0.07	7.56
2.572	1	0.76	0.27	0.06	20.07	0.97	0.07	7.56
2.572	1	0.8	0.26	0.05	20.77	0.99	0.08	7.56
2.572	1	0.84	0.21	0.05	25.41	0.95	0.07	7.57
2.572	1	0.88	0.18	0.05	28.88	0.83	0.06	7.57

2.572	1	0.92	0.14	0.05	38.24	0.59	0.04	7.56
2.572	1	0.96	0.05	0.05	93.97	0.31	0.02	7.59
2.572	1	1	0.05	0.05	101.83	0.16	0.01	8.39
2.572	1	1.04	0.07	0.05	71.61	0.16	0.01	7.76
2.572	1	1.08	0.09	0.05	55.08	0.13	0.01	7.78
2.572	1	1.12	0.12	0.05	44.94	0.15	0.01	7.58
2.572	1	1.16	0.13	0.05	41.11	0.14	0.01	7.71
2.572	1	1.2	0.15	0.05	34.51	0.08	0.01	8.38
2.572	1	1.24	0.14	0.05	37.45	0.12	0.01	7.62
2.572	1	1.28	0.10	0.05	53.77	0.12	0.01	7.57
2.572	1	1.32	0.07	0.05	68.62	0.11	0.01	7.58
2.572	1	1.36	0.07	0.05	75.99	0.12	0.01	7.61
2.572	1	1.4	0.08	0.05	61.71	0.12	0.01	7.59
2.572	1	1.44	0.09	0.05	55.05	0.10	0.01	7.64
2.572	1	1.48	0.07	0.05	77.93	0.08	0.01	7.73
2.572	1	1.52	0.06	0.05	90.75	0.08	0.01	7.59
2.572	1	1.56	0.05	0.05	95.65	0.10	0.01	7.60
2.572	1	1.6	0.05	0.05	109.45	0.11	0.01	7.83
2.572	1	1.64	0.04	0.05	130.15	0.11	0.01	7.89
3.086	1	0.28	1.12	0.10	8.78	2.82	0.22	7.95
3.086	1	0.32	1.16	0.10	8.72	1.30	0.10	7.77
3.086	1	0.36	1.15	0.10	8.79	0.78	0.06	7.67
3.086	1	0.4	1.11	0.10	8.82	0.49	0.04	7.58
3.086	1	0.44	0.93	0.09	9.34	0.45	0.03	7.61
3.086	1	0.48	0.64	0.07	10.96	0.49	0.04	7.58
3.086	1	0.52	0.51	0.06	12.48	0.55	0.04	7.57
3.086	1	0.56	0.47	0.06	13.20	0.62	0.05	7.57
3.086	1	0.6	0.41	0.06	14.54	0.65	0.05	7.57
3.086	1	0.64	0.38	0.06	15.50	0.74	0.06	7.57
3.086	1	0.68	0.32	0.06	17.68	0.83	0.06	7.56
3.086	1	0.72	0.31	0.06	17.90	0.88	0.07	7.56
3.086	1	0.76	0.31	0.06	18.20	0.91	0.07	7.57
3.086	1	0.8	0.26	0.05	21.22	0.90	0.07	7.56
3.086	1	0.84	0.23	0.05	23.68	0.84	0.06	7.57
3.086	1	0.88	0.15	0.05	34.90	0.56	0.04	7.57
3.086	1	0.92	0.07	0.05	71.19	0.43	0.03	7.58
3.086	1	0.96	0.05	0.05	99.97	0.41	0.03	7.58
3.086	1	1	0.11	0.05	45.16	0.52	0.04	7.67
3.086	1	1.04	0.12	0.05	43.99	0.27	0.02	7.59
3.086	1	1.08	0.10	0.05	49.74	0.19	0.01	7.59
3.086	1	1.12	0.13	0.05	40.46	0.18	0.01	7.58
3.086	1	1.16	0.16	0.05	32.98	0.14	0.01	7.70
3.086	1	1.2	0.16	0.05	32.16	0.14	0.01	7.82
3.086	1	1.24	0.15	0.05	35.42	0.15	0.01	7.59
3.086	1	1.28	0.15	0.05	34.75	0.17	0.01	7.57
3.086	1	1.32	0.13	0.05	41.23	0.14	0.01	7.57
3.086	1	1.36	0.09	0.05	57.66	0.11	0.01	7.61
3.086	1	1.4	0.08	0.05	63.05	0.08	0.01	7.61
3.086	1	1.44	0.07	0.05	75.77	0.07	0.01	7.61
3.086	1	1.48	0.07	0.05	77.88	0.09	0.01	7.67
3.086	1	1.52	0.06	0.05	80.74	0.09	0.01	7.59
3.086	1	1.56	0.06	0.05	88.41	0.10	0.01	7.60

3.086	1	1.6	0.04	0.05	120.64	0.10	0.01	7.80
3.086	1	1.64	0.04	0.05	144.15	0.09	0.01	8.08
3.086	1	1.68	0.03	0.05	153.09	0.08	0.01	7.63
3.086	1	1.72	0.02	0.05	208.96	0.07	0.01	8.41
3.086	1	1.76	0.02	0.05	207.72	0.08	0.01	7.76
0.514	2	0.28	1.14	0.05	4.37	0.60	0.03	5.37
0.514	2	0.32	1.45	0.06	4.21	0.41	0.02	4.41
0.514	2	0.36	1.38	0.06	4.31	0.35	0.01	4.01
0.514	2	0.4	0.74	0.04	5.20	0.40	0.02	3.84
0.514	2	0.44	0.54	0.03	6.16	0.50	0.02	3.79
0.514	2	0.48	0.55	0.03	6.01	0.57	0.02	3.79
0.514	2	0.52	0.54	0.03	6.06	0.64	0.02	3.79
0.514	2	0.56	0.52	0.03	6.21	0.71	0.03	3.79
0.514	2	0.6	0.47	0.03	6.57	0.77	0.03	3.79
0.514	2	0.64	0.41	0.03	7.28	0.83	0.03	3.78
0.514	2	0.68	0.32	0.03	8.73	0.89	0.03	3.78
0.514	2	0.72	0.24	0.03	11.47	0.93	0.04	3.78
0.514	2	0.76	0.16	0.03	16.22	0.95	0.04	3.78
0.514	2	0.8	0.16	0.03	16.03	0.90	0.03	3.79
0.514	2	0.84	0.18	0.03	14.39	0.79	0.03	3.79
0.514	2	0.88	0.21	0.03	12.84	0.64	0.02	3.79
0.514	2	0.92	0.20	0.03	13.20	0.46	0.02	3.78
0.514	2	0.96	0.22	0.03	12.16	0.28	0.01	3.82
0.514	2	1	0.24	0.03	11.23	0.16	0.01	5.14
0.514	2	1.04	0.23	0.03	11.68	0.20	0.01	3.82
0.514	2	1.08	0.18	0.03	14.60	0.24	0.01	3.91
0.514	2	1.12	0.12	0.03	21.62	0.21	0.01	3.86
0.514	2	1.16	0.10	0.03	25.97	0.22	0.01	3.90
0.514	2	1.2	0.13	0.03	20.60	0.22	0.01	3.89
0.514	2	1.24	0.12	0.03	21.66	0.19	0.01	3.86
0.514	2	1.28	0.09	0.03	30.26	0.16	0.01	3.85
0.514	2	1.32	0.08	0.03	32.94	0.13	0.01	4.42
0.514	2	1.36	0.07	0.03	36.69	0.13	0.01	4.05
0.514	2	1.4	0.05	0.03	54.53	0.10	0.00	4.09
1.543	2	0.28	1.13	0.05	4.38	0.85	0.04	4.64
1.543	2	0.32	1.22	0.05	4.35	0.55	0.02	4.14
1.543	2	0.36	1.18	0.05	4.36	0.48	0.02	3.93
1.543	2	0.4	0.91	0.04	4.74	0.40	0.02	3.86
1.543	2	0.44	0.62	0.04	5.68	0.39	0.01	3.83
1.543	2	0.48	0.55	0.03	6.03	0.49	0.02	3.79
1.543	2	0.52	0.51	0.03	6.29	0.53	0.02	3.79
1.543	2	0.56	0.50	0.03	6.32	0.61	0.02	3.79
1.543	2	0.6	0.48	0.03	6.54	0.71	0.03	3.79
1.543	2	0.64	0.41	0.03	7.24	0.80	0.03	3.78
1.543	2	0.68	0.34	0.03	8.46	0.90	0.03	3.78
1.543	2	0.72	0.27	0.03	10.29	0.94	0.04	3.78
1.543	2	0.76	0.22	0.03	12.06	0.96	0.04	3.78
1.543	2	0.8	0.20	0.03	13.59	0.98	0.04	3.79
1.543	2	0.84	0.18	0.03	15.04	1.02	0.04	3.78
1.543	2	0.88	0.14	0.03	18.78	0.90	0.03	3.79
1.543	2	0.92	0.14	0.03	18.95	0.71	0.03	3.79
1.543	2	0.96	0.15	0.03	18.14	0.51	0.02	3.80

1.543	2	1	0.13	0.03	20.71	0.25	0.01	4.35
1.543	2	1.04	0.11	0.03	23.91	0.16	0.01	3.82
1.543	2	1.08	0.11	0.03	23.26	0.14	0.01	4.08
1.543	2	1.12	0.16	0.03	16.42	0.22	0.01	3.85
1.543	2	1.16	0.25	0.03	11.03	0.23	0.01	3.93
1.543	2	1.2	0.21	0.03	12.95	0.15	0.01	4.29
1.543	2	1.24	0.18	0.03	15.06	0.15	0.01	4.10
1.543	2	1.28	0.14	0.03	18.91	0.13	0.00	3.89
1.543	2	1.32	0.11	0.03	23.51	0.13	0.00	3.82
1.543	2	1.36	0.09	0.03	27.57	0.14	0.01	3.86
1.543	2	1.4	0.09	0.03	28.54	0.12	0.00	3.85
1.543	2	1.44	0.07	0.03	35.68	0.09	0.00	3.91
1.543	2	1.48	0.06	0.03	41.88	0.08	0.00	3.83
1.543	2	1.52	0.06	0.03	44.94	0.07	0.00	4.01
1.543	2	1.56	0.05	0.03	51.99	0.07	0.00	4.09
1.543	2	1.6	0.04	0.03	64.84	0.09	0.00	4.04
1.543	2	1.64	0.03	0.03	87.25	0.09	0.00	4.36
2.572	2	0.28	1.10	0.05	4.41	1.24	0.06	4.67
2.572	2	0.32	1.14	0.05	4.43	0.65	0.03	4.03
2.572	2	0.36	1.16	0.05	4.41	0.51	0.02	3.87
2.572	2	0.4	0.91	0.04	4.75	0.36	0.01	3.86
2.572	2	0.44	0.70	0.04	5.32	0.41	0.02	3.91
2.572	2	0.48	0.60	0.03	5.74	0.50	0.02	3.80
2.572	2	0.52	0.56	0.03	5.93	0.57	0.02	3.79
2.572	2	0.56	0.51	0.03	6.24	0.64	0.02	3.79
2.572	2	0.6	0.46	0.03	6.70	0.71	0.03	3.79
2.572	2	0.64	0.39	0.03	7.50	0.77	0.03	3.79
2.572	2	0.68	0.32	0.03	8.81	0.86	0.03	3.79
2.572	2	0.72	0.28	0.03	9.78	0.95	0.04	3.78
2.572	2	0.76	0.26	0.03	10.69	0.98	0.04	3.78
2.572	2	0.8	0.23	0.03	11.66	1.05	0.04	3.79
2.572	2	0.84	0.18	0.03	14.71	0.99	0.04	3.79
2.572	2	0.88	0.15	0.03	17.78	0.85	0.03	3.80
2.572	2	0.92	0.12	0.03	22.11	0.66	0.03	3.78
2.572	2	0.96	0.07	0.03	38.78	0.38	0.01	3.82
2.572	2	1	0.07	0.03	38.22	0.21	0.01	4.59
2.572	2	1.04	0.09	0.03	27.63	0.17	0.01	4.01
2.572	2	1.08	0.10	0.03	25.56	0.11	0.01	4.46
2.572	2	1.12	0.11	0.03	22.68	0.14	0.01	3.90
2.572	2	1.16	0.14	0.03	18.72	0.15	0.01	4.03
2.572	2	1.2	0.15	0.03	16.98	0.10	0.00	4.26
2.572	2	1.24	0.13	0.03	20.32	0.11	0.00	4.00
2.572	2	1.28	0.09	0.03	27.27	0.10	0.00	3.84
2.572	2	1.32	0.08	0.03	30.55	0.10	0.00	3.85
2.572	2	1.36	0.08	0.03	34.05	0.09	0.00	3.98
2.572	2	1.4	0.09	0.03	29.11	0.09	0.00	3.87
2.572	2	1.44	0.12	0.03	22.25	0.09	0.00	3.96
2.572	2	1.48	0.10	0.03	26.60	0.09	0.00	3.87
2.572	2	1.52	0.06	0.03	39.52	0.08	0.00	3.95
2.572	2	1.56	0.05	0.03	49.54	0.09	0.00	4.08
2.572	2	1.6	0.05	0.03	54.99	0.09	0.00	4.42
2.572	2	1.64	0.04	0.03	57.67	0.10	0.00	3.86

3.086	2	0.28	1.24	0.05	4.28	1.60	0.07	4.67
3.086	2	0.32	1.06	0.05	4.52	0.79	0.03	4.01
3.086	2	0.36	1.11	0.05	4.43	0.52	0.02	3.93
3.086	2	0.4	1.12	0.05	4.45	0.50	0.02	3.80
3.086	2	0.44	0.89	0.04	4.80	0.43	0.02	3.91
3.086	2	0.48	0.66	0.04	5.42	0.52	0.02	3.80
3.086	2	0.52	0.54	0.03	6.08	0.57	0.02	3.80
3.086	2	0.56	0.47	0.03	6.64	0.63	0.02	3.79
3.086	2	0.6	0.44	0.03	6.93	0.70	0.03	3.79
3.086	2	0.64	0.37	0.03	7.79	0.80	0.03	3.79
3.086	2	0.68	0.33	0.03	8.50	0.84	0.03	3.78
3.086	2	0.72	0.30	0.03	9.31	0.92	0.03	3.78
3.086	2	0.76	0.29	0.03	9.53	1.02	0.04	3.79
3.086	2	0.8	0.24	0.03	11.27	1.01	0.04	3.79
3.086	2	0.84	0.18	0.03	15.10	0.84	0.03	3.80
3.086	2	0.88	0.11	0.03	24.23	0.52	0.02	3.81
3.086	2	0.92	0.06	0.03	46.13	0.41	0.02	3.82
3.086	2	0.96	0.05	0.03	50.38	0.39	0.01	3.83
3.086	2	1	0.12	0.03	20.92	0.48	0.02	4.00
3.086	2	1.04	0.12	0.03	22.50	0.23	0.01	3.79
3.086	2	1.08	0.10	0.03	27.01	0.16	0.01	3.97
3.086	2	1.12	0.13	0.03	20.42	0.17	0.01	3.87
3.086	2	1.16	0.16	0.03	16.75	0.14	0.01	4.05
3.086	2	1.2	0.16	0.03	16.21	0.14	0.01	4.03
3.086	2	1.24	0.18	0.03	14.92	0.14	0.01	3.89
3.086	2	1.28	0.15	0.03	17.04	0.14	0.01	3.83
3.086	2	1.32	0.12	0.03	21.88	0.12	0.00	3.83
3.086	2	1.36	0.10	0.03	26.15	0.10	0.00	3.93
3.086	2	1.4	0.10	0.03	27.08	0.07	0.00	3.89
3.086	2	1.44	0.09	0.03	29.48	0.07	0.00	3.84
3.086	2	1.48	0.08	0.03	32.68	0.08	0.00	3.80
3.086	2	1.52	0.07	0.03	35.75	0.10	0.00	3.89
3.086	2	1.56	0.06	0.03	40.56	0.11	0.00	3.99
3.086	2	1.6	0.06	0.03	44.51	0.12	0.00	4.04
3.086	2	1.64	0.05	0.03	53.14	0.10	0.00	3.92
3.086	2	1.68	0.04	0.03	68.03	0.09	0.00	3.92
3.086	2	1.72	0.03	0.03	75.91	0.10	0.00	4.63
3.086	2	1.76	0.03	0.03	88.66	0.10	0.00	4.09
3.086	2	1.8	0.03	0.03	96.87	0.09	0.00	4.43
0.514	4	0.28	1.15	0.03	2.18	0.90	0.02	2.24
0.514	4	0.32	1.27	0.03	2.20	0.63	0.01	2.24
0.514	4	0.36	1.05	0.03	2.56	0.53	0.01	1.96
0.514	4	0.4	0.72	0.02	2.68	0.53	0.01	1.97
0.514	4	0.44	0.62	0.02	2.90	0.54	0.01	1.90
0.514	4	0.48	0.60	0.02	2.88	0.60	0.01	1.90
0.514	4	0.52	0.58	0.02	2.89	0.68	0.01	1.90
0.514	4	0.56	0.55	0.02	3.01	0.75	0.01	1.94
0.514	4	0.6	0.50	0.02	3.20	0.81	0.02	1.92
0.514	4	0.64	0.42	0.02	3.56	0.88	0.02	1.90
0.514	4	0.68	0.34	0.01	4.25	0.94	0.02	1.91
0.514	4	0.72	0.24	0.01	5.68	0.98	0.02	1.90
0.514	4	0.76	0.17	0.01	7.76	0.97	0.02	1.90

0.514	4	0.8	0.18	0.01	7.43	0.91	0.02	1.89
0.514	4	0.84	0.21	0.01	6.46	0.83	0.02	1.89
0.514	4	0.88	0.23	0.01	6.02	0.67	0.01	1.95
0.514	4	0.92	0.23	0.01	6.03	0.50	0.01	1.97
0.514	4	0.96	0.24	0.01	5.94	0.31	0.01	1.90
0.514	4	1	0.24	0.01	5.84	0.19	0.01	2.67
0.514	4	1.04	0.22	0.01	6.26	0.16	0.00	2.36
0.514	4	1.08	0.18	0.01	7.52	0.19	0.00	2.05
0.514	4	1.12	0.14	0.01	9.64	0.19	0.00	2.03
0.514	4	1.16	0.13	0.01	9.90	0.21	0.00	2.11
0.514	4	1.2	0.17	0.01	7.74	0.23	0.00	2.13
0.514	4	1.24	0.17	0.01	7.68	0.22	0.00	2.06
0.514	4	1.28	0.16	0.01	8.46	0.23	0.00	2.12
0.514	4	1.32	0.14	0.01	9.52	0.21	0.01	2.54
0.514	4	1.36	0.09	0.01	14.61	0.17	0.00	2.33
0.514	4	1.4	0.06	0.01	21.35	0.13	0.00	2.28
0.514	4	1.44	0.05	0.01	25.43	0.10	0.00	2.22
0.514	4	1.48	0.04	0.01	31.77	0.09	0.00	2.19
1.543	4	0.28	1.18	0.03	2.17	1.02	0.02	2.14
1.543	4	0.32	1.14	0.03	2.20	0.78	0.02	2.13
1.543	4	0.36	1.08	0.02	2.24	0.63	0.01	1.97
1.543	4	0.4	0.89	0.02	2.43	0.51	0.01	2.00
1.543	4	0.44	0.68	0.02	2.77	0.50	0.01	1.93
1.543	4	0.48	0.62	0.02	2.84	0.53	0.01	1.91
1.543	4	0.52	0.56	0.02	2.96	0.59	0.01	1.91
1.543	4	0.56	0.52	0.02	3.11	0.66	0.01	1.96
1.543	4	0.6	0.48	0.02	3.28	0.76	0.01	1.93
1.543	4	0.64	0.41	0.01	3.66	0.80	0.02	1.90
1.543	4	0.68	0.33	0.01	4.33	0.88	0.02	1.91
1.543	4	0.72	0.26	0.01	5.34	0.96	0.02	1.90
1.543	4	0.76	0.22	0.01	6.20	1.01	0.02	1.90
1.543	4	0.8	0.19	0.01	7.06	1.00	0.02	1.89
1.543	4	0.84	0.14	0.01	9.51	0.91	0.02	1.89
1.543	4	0.88	0.13	0.01	10.33	0.80	0.02	1.93
1.543	4	0.92	0.16	0.01	8.59	0.68	0.01	1.94
1.543	4	0.96	0.16	0.01	8.45	0.43	0.01	1.91
1.543	4	1	0.15	0.01	8.94	0.26	0.01	2.30
1.543	4	1.04	0.13	0.01	10.18	0.15	0.00	2.41
1.543	4	1.08	0.17	0.01	7.77	0.17	0.00	1.97
1.543	4	1.12	0.27	0.01	5.21	0.26	0.01	1.95
1.543	4	1.16	0.23	0.01	5.94	0.22	0.00	2.16
1.543	4	1.2	0.18	0.01	7.38	0.12	0.00	3.25
1.543	4	1.24	0.18	0.01	7.53	0.11	0.00	3.00
1.543	4	1.28	0.14	0.01	9.09	0.12	0.00	2.72
1.543	4	1.32	0.11	0.01	11.58	0.12	0.00	2.51
1.543	4	1.36	0.12	0.01	11.23	0.14	0.00	2.25
1.543	4	1.4	0.11	0.01	11.63	0.14	0.00	2.07
1.543	4	1.44	0.09	0.01	14.93	0.11	0.00	2.05
1.543	4	1.48	0.08	0.01	15.53	0.12	0.00	1.94
1.543	4	1.52	0.07	0.01	18.55	0.11	0.00	2.12
1.543	4	1.56	0.06	0.01	22.61	0.10	0.00	2.67
1.543	4	1.6	0.05	0.01	26.98	0.11	0.00	2.76

2.572	4	0.28	1.19	0.03	2.16	1.10	0.03	3.11
2.572	4	0.32	1.15	0.03	2.20	0.77	0.02	2.12
2.572	4	0.36	1.05	0.02	2.30	0.51	0.01	1.92
2.572	4	0.4	0.92	0.02	2.40	0.48	0.01	2.00
2.572	4	0.44	0.77	0.02	2.59	0.53	0.01	2.03
2.572	4	0.48	0.66	0.02	2.76	0.53	0.01	1.94
2.572	4	0.52	0.58	0.02	2.90	0.61	0.01	1.92
2.572	4	0.56	0.52	0.02	3.12	0.61	0.01	1.97
2.572	4	0.6	0.45	0.02	3.41	0.70	0.01	1.93
2.572	4	0.64	0.40	0.01	3.73	0.82	0.02	1.91
2.572	4	0.68	0.31	0.01	4.50	0.87	0.02	1.91
2.572	4	0.72	0.27	0.01	5.07	0.92	0.02	1.90
2.572	4	0.76	0.25	0.01	5.48	0.98	0.02	1.90
2.572	4	0.8	0.21	0.01	6.39	0.98	0.02	1.89
2.572	4	0.84	0.15	0.01	8.68	0.92	0.02	1.90
2.572	4	0.88	0.11	0.01	12.39	0.75	0.01	1.97
2.572	4	0.92	0.09	0.01	14.53	0.59	0.01	1.95
2.572	4	0.96	0.09	0.01	15.42	0.37	0.01	1.93
2.572	4	1	0.08	0.01	16.19	0.21	0.01	2.57
2.572	4	1.04	0.13	0.01	10.07	0.23	0.01	2.29
2.572	4	1.08	0.16	0.01	8.28	0.19	0.00	2.17
2.572	4	1.12	0.13	0.01	9.85	0.15	0.00	2.01
2.572	4	1.16	0.15	0.01	8.58	0.14	0.00	2.32
2.572	4	1.2	0.16	0.01	8.30	0.11	0.00	2.83
2.572	4	1.24	0.17	0.01	7.96	0.10	0.00	2.58
2.572	4	1.28	0.15	0.01	8.97	0.11	0.00	2.69
2.572	4	1.32	0.11	0.01	12.04	0.09	0.00	2.80
2.572	4	1.36	0.11	0.01	12.18	0.10	0.00	2.61
2.572	4	1.4	0.13	0.01	10.00	0.13	0.00	2.05
3.086	4	0.28	1.17	0.03	2.17	1.30	0.05	3.55
3.086	4	0.32	1.15	0.03	2.19	0.97	0.02	2.11
3.086	4	0.36	1.04	0.02	2.26	0.60	0.01	2.01
3.086	4	0.4	0.96	0.02	2.40	0.45	0.01	1.96
3.086	4	0.44	0.82	0.02	2.52	0.58	0.01	2.02
3.086	4	0.48	0.71	0.02	2.63	0.56	0.01	1.93
3.086	4	0.52	0.62	0.02	2.83	0.61	0.01	1.92
3.086	4	0.56	0.46	0.02	3.38	0.61	0.01	1.97
3.086	4	0.6	0.41	0.02	3.63	0.70	0.01	1.94
3.086	4	0.64	0.35	0.01	4.16	0.79	0.02	1.91
3.086	4	0.68	0.29	0.01	4.74	0.82	0.02	1.91
3.086	4	0.72	0.29	0.01	4.82	0.91	0.02	1.90
3.086	4	0.76	0.25	0.01	5.61	0.85	0.02	1.93
3.086	4	0.8	0.20	0.01	6.74	0.90	0.02	1.89
3.086	4	0.84	0.15	0.01	9.05	0.76	0.01	1.92
3.086	4	0.88	0.09	0.01	15.11	0.49	0.01	2.03
3.086	4	0.92	0.05	0.01	26.68	0.35	0.01	2.14
3.086	4	0.96	0.07	0.01	18.39	0.35	0.01	1.96
3.086	4	1	0.13	0.01	9.89	0.41	0.01	2.21
3.086	4	1.04	0.13	0.01	10.44	0.25	0.01	2.09
3.086	4	1.08	0.10	0.01	12.46	0.16	0.00	1.95
3.086	4	1.12	0.13	0.01	10.26	0.17	0.00	1.99
3.086	4	1.16	0.15	0.01	8.89	0.14	0.00	2.35

3.086	4	1.2	0.15	0.01	8.50	0.13	0.00	2.61
3.086	4	1.24	0.18	0.01	7.28	0.15	0.00	2.18
3.086	4	1.28	0.18	0.01	7.36	0.14	0.00	2.40
3.086	4	1.32	0.16	0.01	8.24	0.13	0.00	2.41
3.086	4	1.36	0.13	0.01	9.85	0.10	0.00	2.50
3.086	4	1.4	0.10	0.01	12.48	0.08	0.00	2.22
3.086	4	1.44	0.09	0.01	13.64	0.08	0.00	2.00
3.086	4	1.48	0.08	0.01	15.98	0.08	0.00	1.96
3.086	4	1.52	0.07	0.01	17.65	0.08	0.00	2.24
0.514	6	0.28	1.13	0.02	1.47	0.79	0.02	2.55
0.514	6	0.32	1.14	0.02	1.57	0.56	0.01	1.79
0.514	6	0.36	0.95	0.02	2.18	0.49	0.01	1.80
0.514	6	0.4	0.71	0.02	2.25	0.49	0.01	1.39
0.514	6	0.44	0.64	0.01	2.06	0.50	0.01	1.27
0.514	6	0.48	0.63	0.01	1.87	0.58	0.01	1.30
0.514	6	0.52	0.59	0.01	1.91	0.66	0.01	1.34
0.514	6	0.56	0.55	0.01	2.00	0.72	0.01	1.27
0.514	6	0.6	0.48	0.01	2.17	0.79	0.01	1.29
0.514	6	0.64	0.42	0.01	2.41	0.86	0.01	1.29
0.514	6	0.68	0.33	0.01	2.90	0.89	0.01	1.28
0.514	6	0.72	0.23	0.01	3.87	0.95	0.01	1.27
0.514	6	0.76	0.17	0.01	5.10	0.93	0.01	1.28
0.514	6	0.8	0.18	0.01	4.95	0.86	0.01	1.47
0.514	6	0.84	0.20	0.01	4.55	0.75	0.01	1.86
0.514	6	0.88	0.21	0.01	4.51	0.62	0.01	2.18
0.514	6	0.92	0.20	0.01	4.45	0.42	0.01	2.82
0.514	6	0.96	0.22	0.01	4.33	0.27	0.01	3.78
0.514	6	1	0.21	0.01	4.52	0.19	0.01	2.87
0.514	6	1.04	0.18	0.01	5.10	0.13	0.00	2.44
0.514	6	1.08	0.16	0.01	5.62	0.15	0.00	1.92
0.514	6	1.12	0.14	0.01	8.24	0.16	0.00	2.62
0.514	6	1.16	0.15	0.01	6.12	0.19	0.00	1.30
0.514	6	1.2	0.17	0.01	5.19	0.22	0.01	2.43
0.514	6	1.24	0.16	0.01	5.61	0.20	0.01	2.88
0.514	6	1.28	0.13	0.01	6.71	0.17	0.00	2.34
1.543	6	0.28	1.17	0.02	1.46	1.08	0.02	2.04
1.543	6	0.32	1.14	0.02	1.46	0.66	0.01	1.65
1.543	6	0.36	1.05	0.02	1.62	0.59	0.01	1.69
1.543	6	0.4	0.89	0.02	1.93	0.52	0.01	1.41
1.543	6	0.44	0.73	0.01	1.91	0.49	0.01	1.32
1.543	6	0.48	0.64	0.01	1.87	0.54	0.01	1.32
1.543	6	0.52	0.59	0.01	1.93	0.61	0.01	1.36
1.543	6	0.56	0.54	0.01	2.03	0.70	0.01	1.27
1.543	6	0.6	0.49	0.01	2.15	0.75	0.01	1.30
1.543	6	0.64	0.39	0.01	2.54	0.82	0.01	1.29
1.543	6	0.68	0.31	0.01	3.05	0.85	0.01	1.28
1.543	6	0.72	0.25	0.01	3.62	0.93	0.01	1.27
1.543	6	0.76	0.20	0.01	4.46	0.96	0.01	1.27
1.543	6	0.8	0.18	0.01	4.82	0.97	0.01	1.43
1.543	6	0.84	0.16	0.01	5.67	0.93	0.02	1.68
1.543	6	0.88	0.15	0.01	6.25	0.82	0.02	1.85
1.543	6	0.92	0.17	0.01	5.18	0.61	0.01	2.16

1.543	6	0.96	0.16	0.01	5.69	0.43	0.01	2.53
1.543	6	1	0.15	0.01	6.36	0.28	0.01	2.16
1.543	6	1.04	0.13	0.01	6.78	0.18	0.00	1.97
1.543	6	1.08	0.19	0.01	4.88	0.18	0.00	1.62
1.543	6	1.12	0.26	0.01	4.51	0.22	0.00	2.05
1.543	6	1.16	0.19	0.01	4.79	0.18	0.00	1.47
1.543	6	1.2	0.19	0.01	4.80	0.14	0.01	3.89
1.543	6	1.24	0.18	0.01	4.87	0.11	0.01	5.22
1.543	6	1.28	0.15	0.01	5.90	0.11	0.00	3.27
1.543	6	1.32	0.14	0.01	6.67	0.14	0.00	2.26
1.543	6	1.36	0.13	0.01	7.06	0.16	0.00	2.26
1.543	6	1.4	0.11	0.01	8.04	0.15	0.00	2.30
1.543	6	1.44	0.10	0.01	8.64	0.13	0.00	2.33

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Chapter 5

Towing analysis using OpenFAST: Paper D

5.1 Motivation and Aim

The previous paper presents two new methodologies for analysing the towing behaviour of semi-submersible FOWT platforms. The hybrid approach combining the potential-flow method with the Morison equation-based method demonstrates notable effectiveness. However, this method was implemented in Orcaflex, a well-known but closed-source and costly software. Similarly, the alternative method employed SEACAL, which is also closed-source. Given this context, utilising a free open-source tool for FOWT towing analysis becomes imperative and OpenFAST emerges as a viable solution.

OpenFAST possesses the capability to model Morison elements and integrate them with potential flow-based methodologies, thus facilitating the modelling of towing operations. Despite its capability, this method requires intricate adjustments in input files to simulate bodies moving with a forward speed. This paper outlines two approaches utilising OpenFAST, comparing with experimental data, all of which are presented within this paper. The objectives of this paper are:

1. **Developing a free and open-source implementation of the previously developed hybrid method**

   OpenFAST, being one of the widely used numerical tools, is very effective for analysing FOWTs. The method developed in this paper would help the research community to further develop the presented work and improve the solutions.

2. **An exploratory analysis examining the impact of wind**

   As a specialised tool for wind turbines, OpenFAST possesses the capability to incorporate wind effects in its simulations. This allows researchers to analyse the motion and loads not only of the floater but also of the wind turbine structure. An exploratory investigation analysing the towing operations in the presence of wind has been performed and added. Three different wind speeds were analysed and compared to towing without the presence of wind. The results and compared and discussed.

3. **An opportunity to analyse multi-physics phenomena combining the effects of wind and current.**

   This method also aids in performing structural calculations like strength checks and fatigue of the wind turbine while towing. This particular capability remains untested in the study presented, necessitating further research; however, it serves as a starting point.

An analysis of floating wind turbine towing operations using OpenFAST

Published in

Journal of Physics: Conference Series, ISSN: 1742-6596

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D.1. Introduction

Floating Offshore Wind Turbines (FOWTs) are gaining momentum worldwide, with a robust pipeline of floating wind farm projects expected to be delivered over the coming decade [1]. Most of the research has been focused on developing innovative floating wind turbine designs suited for various wind farm locations recently and research on installation and operational phases is lacking [2]. A few pilot-scale projects are already operational in certain locations around the globe and the focus is slowly shifting to large-scale wind farms. Many marine operations are required during the installation operations concerning FOWTs and optimised towing operations are crucial for installation, O&M (Operation and Maintenance) and decommissioning activities [2].

While towing, a FOWT is subjected to various environmental factors like wind, waves and current and it is important to understand and analyse the behaviour of FOWTs while towing in various metocean conditions. Semi-submersibles offer full construction and assembly at the quay and can towed to the farm locations using tugs and installed without the use of expensive heavy-lift vessels [2]. OpenFAST is a dedicated open-source wind turbine analysis tool developed by the National Renewable Energy Laboratory (NREL), United States of America, which can be used for aero-hydro-servo-elastic simulations of offshore (fixed-bottom and floating) and onshore wind turbines [3].

OpenFAST has the capability to model blade and tower deflections, as well as calculate the loads and moments at different connection points, such as the blade and tower roots. It can also simulate the motions and hydrodynamic response of the full FOWT system subject to various metocean conditions. These capabilities are favourable for analysing the seaworthiness as well as the structural integrity of the FOWT system while towing. Additionally, OpenFAST is free and open-source which is advantageous, considering the fact that many of the numerical tools used for the analyses of marine operations are expensive and closed-source. Generally, OpenFAST is used for analysing FOWTs in installed conditions. Two new methods for analysing the towing operation of a fully assembled FOWT using OpenFAST are described in this paper. These methods include the modification of the various input files for running OpenFAST for achieving the desired results.

The DeepCwind [4] semi-submersible has been chosen for the analysis. A fully-assembled FOWT system is analysed with the wind turbine set to a parked-feathered condition, which is ideal for towing [5]. A forward-speed effect is simulated by applying a

current with a speed equal to the towing speed while constraining the platform. The platform is constrained using two methods, in the first method the surge motion of the platform is set to zero and in the second method, by using a mooring line modified into a towing line in the Moordyn module of OpenFAST. Using the modified OpenFAST files, the hydrodynamic response of the platform is simulated in head-sea conditions. The simulation results are compared against the experimental data obtained from a towing test campaign conducted at the Maritime Research Institute Netherlands (MARIN). Both the methods are compared and the advantages and disadvantages are discussed.

D.2. Methodology

For the presented study, the analyses were performed using the DeepCwind platform which supports a NREL 5MW wind turbine [6]. Usually, OpenFAST is used for the analysis of FOWTs in installed condition i.e., with mooring lines attached. This is the operating condition of the FOWT, but during the installation operations, the FOWT system is usually towed to the wind farm location using large ocean-going tugs. In this condition, the mooring lines are not connected and the wind turbine is in a parked-feathered condition [5].

By modifying the input files to include a forward speed effect, OpenFAST can be used for analysing towing operations. The parked-feathered condition can be set up by changing the pitch angle of the blades to 90 degrees and disabling the generator rotational degree of freedom inside the Elastodyn module of OpenFAST. Two different methods (Figure 1) for simulating the towing process are described and analysed in this paper. The results are compared against the data obtained from an experimental campaign conducted at Maritime Research Institute Netherlands (MARIN).

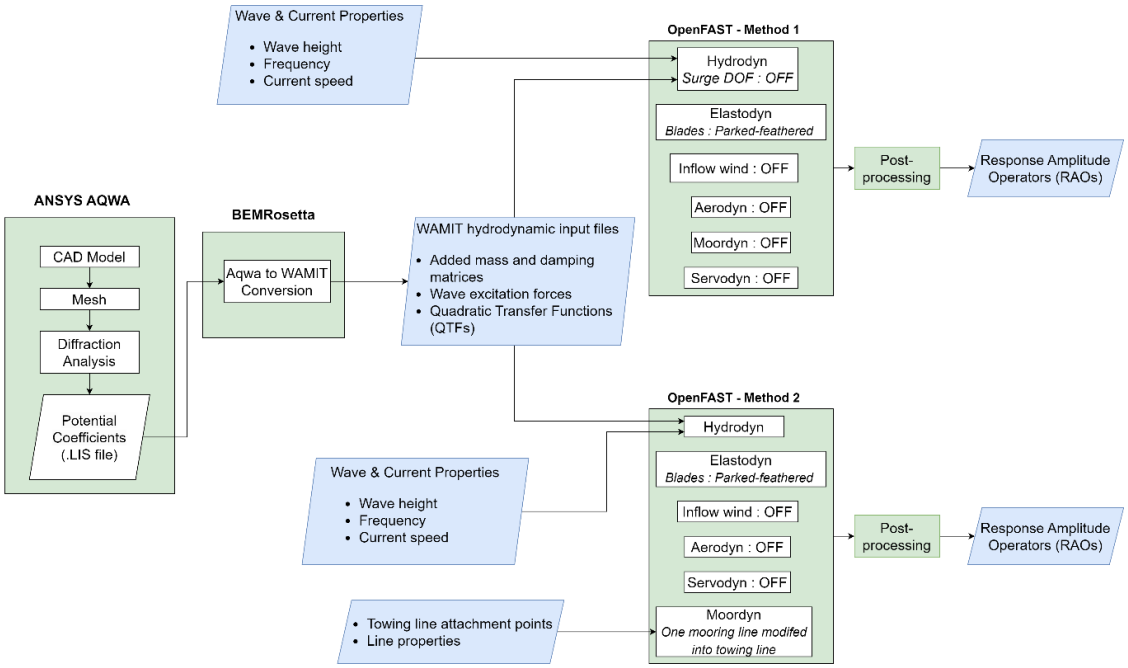


Figure 1: OpenFAST for towing analyses, Methods 1 and 2

OpenFAST has various modules inside its framework to analyse the effects of wind, waves and current, depending on the wind turbine, as well as a module for controlling the turbine operations. Hydrodyn, the hydrodynamic solver of OpenFAST, requires a database of the hydrodynamic properties of the floater while analysing floating wind turbines. The input files required for the analysis of the DeepCwind FOWT in installed condition are supplied by NREL [7]. This will not be sufficient as the draught at which the FOWT is usually towed is lower than the installation draught, in order to reduce the fluid-drag during towing. A draught of 10 m was used for the towing operation. The hydrodynamic characteristics of the FOWT system at the towing draught need to be generated for these simulations. These input files are usually generated using WAMIT [8], which is a commercial hydrodynamic analysis suite and OpenFAST is capable of reading WAMIT files only. As WAMIT was not available, the hydrodynamic database of the platform at towing draught was simulated using a student version of the commercial hydrodynamic tool, Ansys Aqwa [9] and converted into WAMIT files using the tool, BEMRosetta [10] and provided as input for Hydrodyn. These input files consist of the added mass and damping matrices, the wave excitation forces and the Quadratic Transfer Functions (QTFs) which are utilised by Hydrodyn during hydrodynamic calculations. To account for viscous effects, Morison elements were modelled along the columns, pontoons and braces, in the Hydrodyn input file and the drag and inertia coefficients supplied by NREL were used for simulations [7].

As it is not possible to impose a forward speed on the floating body in OpenFAST, in both approaches the towing was simulated by constraining the FOWT system and applying a current, which has a speed equal to the speed of towing. The wave frequencies were replaced with encounter frequencies to include the forward speed effect. Even though wind can be included in the simulations, for the presented study, wind was not considered, as wind was not included in the experimental campaign used for the validation of the simulation results. The Aerodyn module, which is the aerodynamics solver of OpenFAST has also been disabled and the wind speed was set to zero, to simulate a still air condition. The major difference in the approaches is in the method used for constraining the FOWT system in the incoming flow. In Method 1, the body was constrained by setting the surge degree of freedom (DOF) as zero and this was set inside the Elastodyn input file of OpenFAST. In Method 2, the body was constrained using a towing line which was a modified mooring line, set up inside Moordyn (Version 1), the mooring simulation module of OpenFAST. In the installed condition, the DeepCwind platform has three mooring lines. Two of them were removed and the mooring line attachment points and the line properties of the remaining line were modified to represent a towing line. The modified OpenFAST input files corresponding to the various encounter frequencies and wave heights were generated using an automated Python script and the simulations were performed.

D.3. Experimental results

An experimental campaign was conducted at MARIN to analyse the towing performance of FOWTs in the seaway. A 1:50 model of the fully-assembled DeepCwind platform was used for the campaign and various towing speeds, wave heights and frequencies were tested in the Concept Basin at MARIN. A towing cable was designed according to classification society (Det Norske Veritas) rules [11]. The details of the towline can be found in Table 1. The full tow line length could not be applied in the basin, whereupon the length was reduced to 135 m in the model tests. The towing configuration and the details of the platform can be found in Figure 2, Figure 3 and Table 2 respectively. One end of the cable was attached to the model and the other end to a stiff rod connected to a carriage, which pulls the model according to the towing speed. The tow point was fixed at the same level as the centre of gravity of the model to avoid unbalanced moments due to the tow line pull. A spring, which represents the stiffness of the towing cable was also connected to the towing line. The motion of the platform was captured using an optical tracking camera and the tension on the line was

recorded using a dynamometer connected to the towing line. The tests were performed in head-sea conditions and the motions of the platform along with the towing loads were extracted and analysed.

Table 1: Towline Properties

Property	**Value**
Length	900 m
Modulus of Elasticity	9.16E+10 Pa
Rope diameter	0.09 m
Stiffness	647.5 KN/m

Initially, the natural frequencies of the platform in heave, roll and pitch were found out using decay tests in calm water. Subsequently, calm water towing tests were performed for towing speeds ranging from 0.514 m/s to 3.086 m/s (1 to 6 knots) to ascertain the drag loads in calm water. Later, towing tests were performed with various speeds in head regular waves of various heights and frequencies. The details of the towing tests in regular waves can be found in Table 3. The tests were performed for two towing configurations: one column forward and two columns forward and using a bridle. For comparison and validation with OpenFAST, only the results of the one-column-forward configuration are presented in the present work.

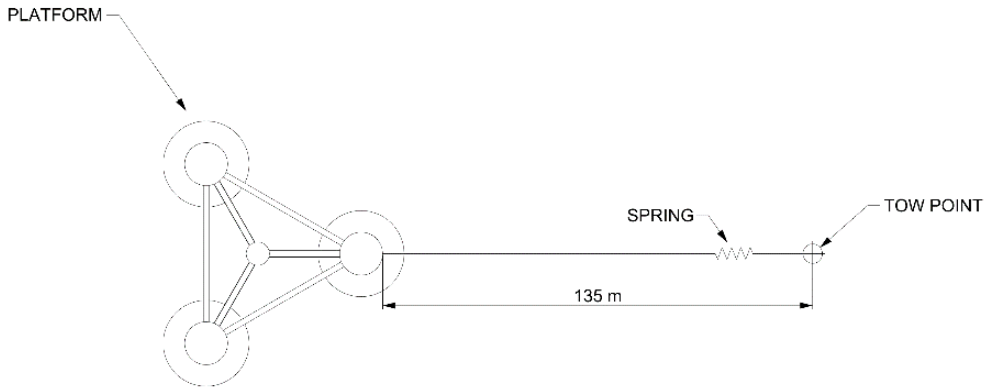


Figure 2: Towing Configuration



Figure 3: Platform Model

Table 2: Platform properties

Property	Unit	Required	Realised
Draught	[m]	10	10
Mass	[ton]	10357.1	10410.3
LCG	[m]	-0.009	-0.01
TCG	[m]	0.017	0.02
VCG	[m]	12.159	12.09
Kxx	[m]	33.854	30.54
Kyy	[m]	34.073	31.01
Kzz	[m]	36.326	31.13
Ixx	[tm2]	1.19E+07	9.71E+06
Iyy	[tm2]	1.20E+07	1.00E+07
Izz	[tm2]	1.37E+07	1.01E+07

Table 3: Test matrix

Speed (m/s) [kn]	Wave Height (m)	Wave Period (s)	Case
1.029 [2]	1	6.28	1
	2	6.98	2
	4	8.38,10.47,15.71,18,20.94	3-7
2.058 [4]	1	6.28	1
	2	6.98	2
	4	8.38,10.47,15.71,18,20.94	3-7

D.4. Comparison of results

D.4.1. Decay tests

The decay tests were performed for ascertaining the natural frequencies of heave, roll and pitch motions. Decay test simulations were performed using OpenFAST also and the comparison is shown in Figure 4. The calculated natural frequencies and their comparison with the simulation are listed in Table 4.

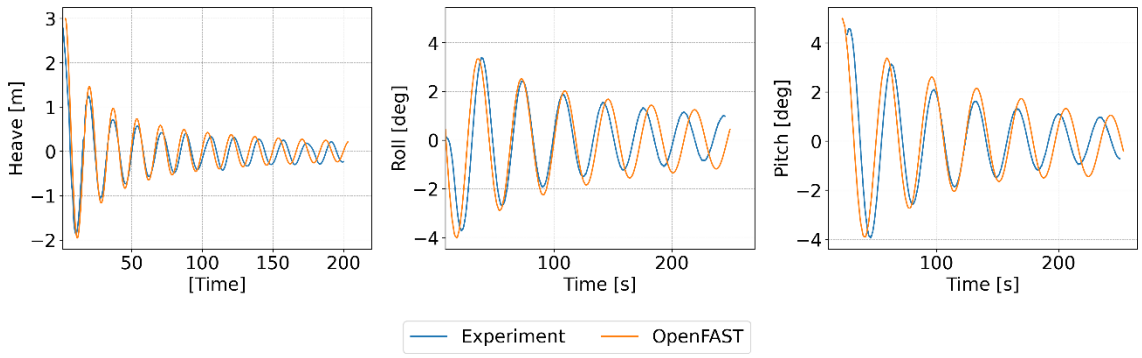


Figure 4: Decay tests

Table 4: Natural frequencies

	Experiment	OpenFAST
Heave	17s	16.8 s
Roll	35s	36s
Pitch	35s	36s

D.4.2. Towing in calm water

The towing tests in calm water correspond to the fluid drag encountered by the FOWT system during towing. The mean tow force is plotted against the mean tension on the towing line calculated using Moordyn (Method 2). The comparison can be found in Figure 5. It can be observed that there is good agreement at low speeds but there are some deviations at higher speeds.

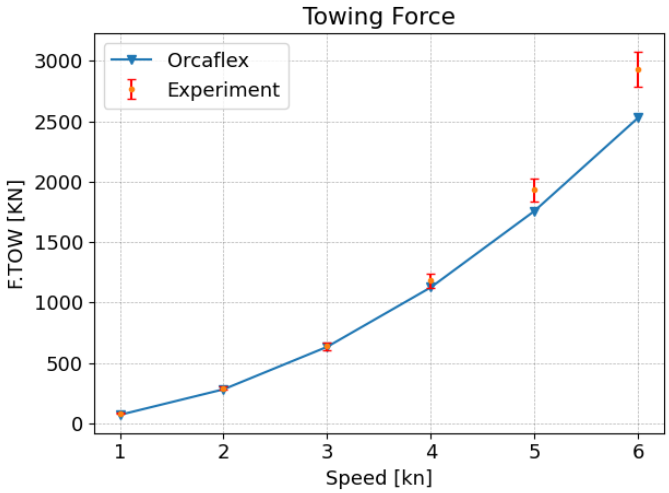


Figure 5: Drag Comparison

D.4.3. Towing in regular waves

D.4.3.1 Motions of the platform

To refine motion predictions and ascertain towing requisites during towing operations, a comprehensive understanding of the Floating Offshore Wind Turbine (FOWT) system's behaviour in regular waves is imperative. The tests mentioned in Table 3, provided the response of the FOWT system in head waves of various heights and frequencies. In OpenFAST, the response of the system was simulated using both methods and compared with the experimental results. One of the examples of such a comparison is shown in Figure 6. The roll motion was observed to be very low during the experiments, so only heave and pitch motion responses are presented.

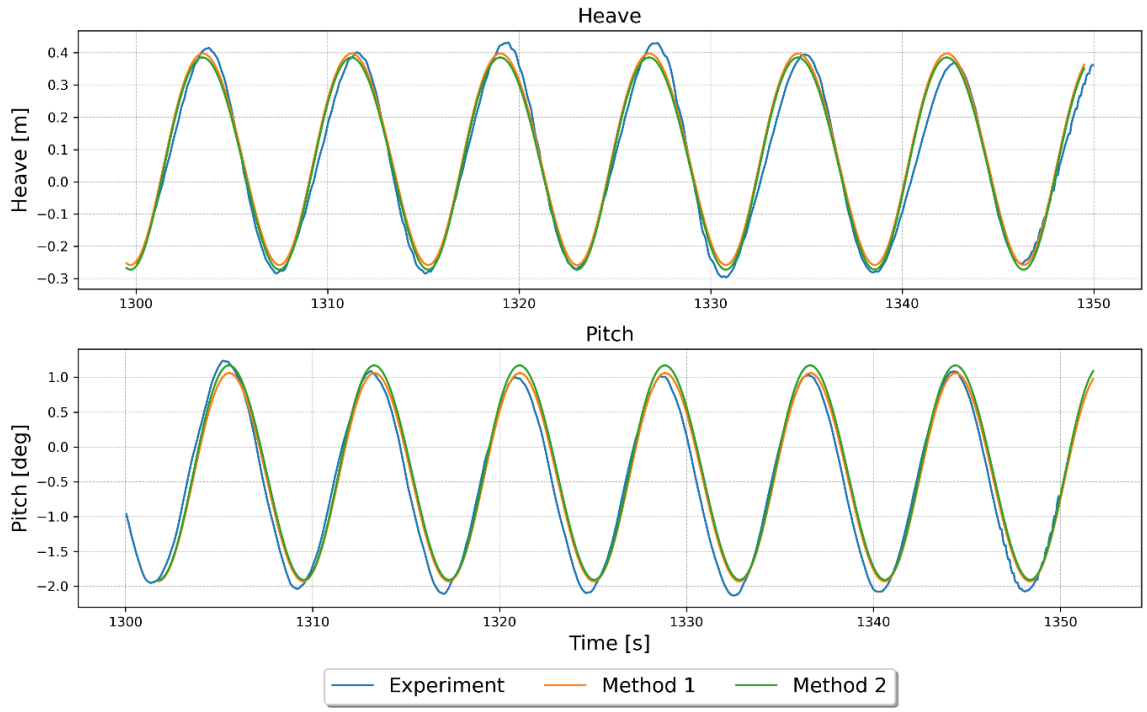


Figure 6: H = 4 m, ω = 8.38 rad/s, Speed = 1.029 m/s

Similar to the analysis shown above, the response of the FOWT system in all the test cases was analysed and post-processed using Python scripts and the Response Amplitude Operators (RAOs) were calculated. The calculated RAOs are plotted and shown in Figure 7 and Figure 8.

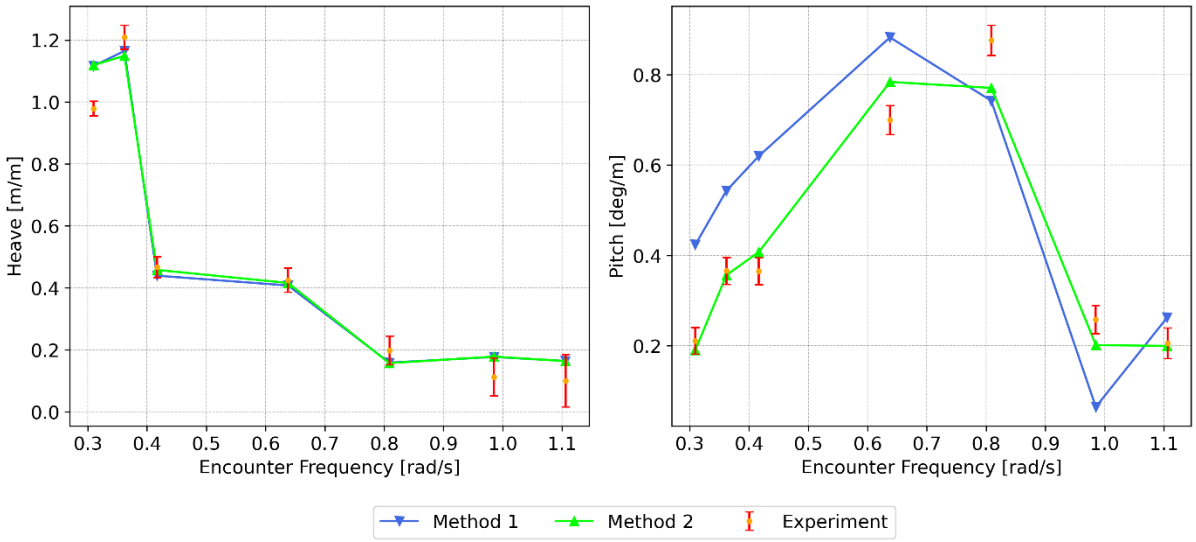


Figure 7: Heave and Pitch RAOs, Towing Speed = 1.029 m/s

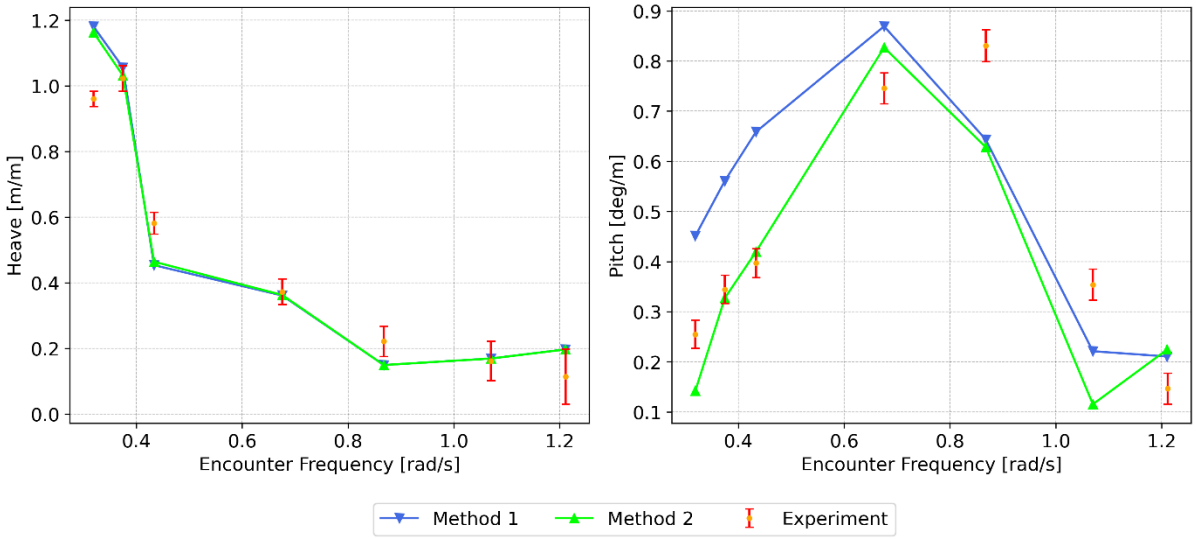


Figure 8: Heave and Pitch RAOs, Towing Speed = 2.058 m/s

D.4.3.2 Towing forces and bollard pull

The tension on the towing line while towing the FOWT system was recorded during the tests. This metric represents the towing force necessary to tow the platform under specific wave conditions mentioned in Table 3. In this section, the loads on the towing line are calculated using OpenFAST (Method 2) and presented. Another important aspect is the added resistance encountered by the FOWT system in waves. It affects the operational aspects such as speed, fuel consumption and manoeuvrability of the vessel and its estimation is crucial. Added resistance is a second-order phenomenon and is obtained by subtracting the total drag in calm water from the total drag in a wave system. This value is normalised by the square of the wave amplitude and plotted against the ratio of the wavelength to the length of the platform.

The total drag is also plotted for the various test cases mentioned in Table 3. The results can be found in Figure 9 and Figure 10.

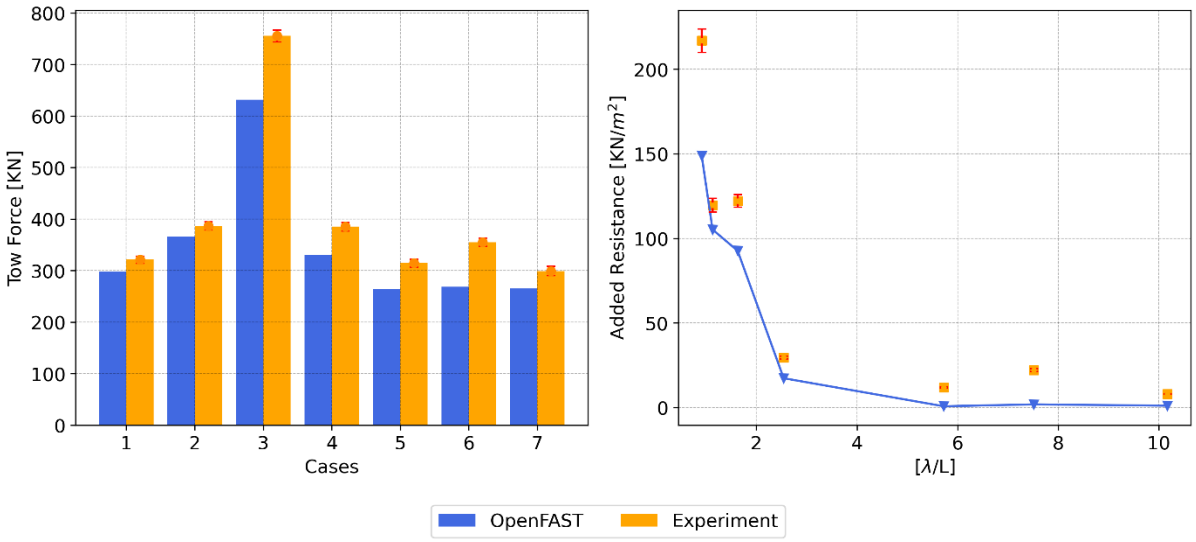


Figure 9: Towing force and added resistance in waves, Towing speed = 2kn

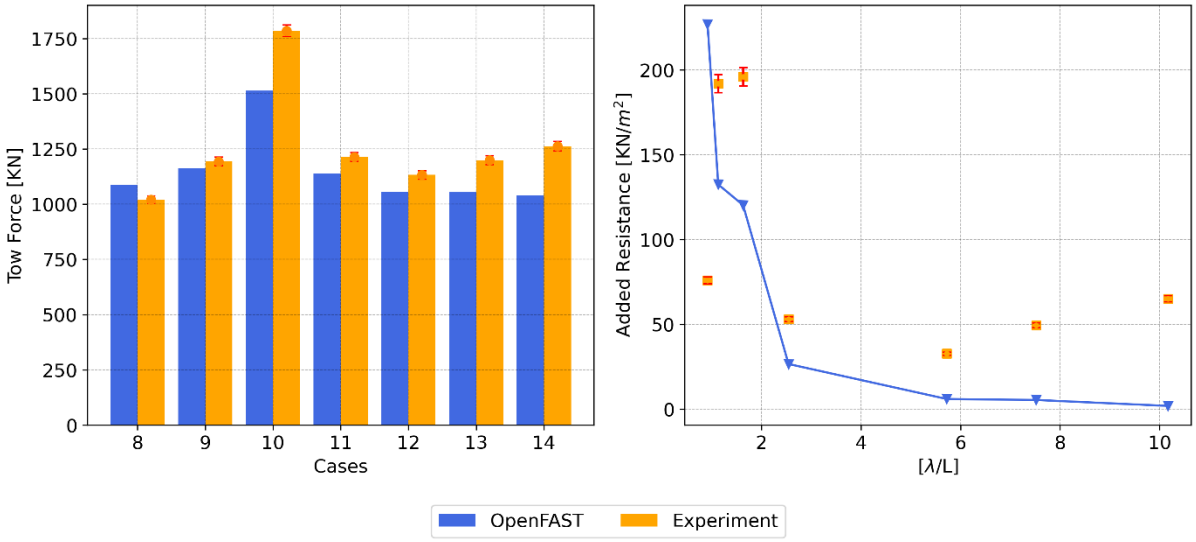


Figure 10: Towing force and added resistance in waves, Towing speed = 4kn

D.5. Discussion

This paper examines the application of OpenFAST in scrutinising the towing operations involving Floating Offshore Wind Turbines (FOWTs). Two different analysis approaches are detailed herein, with their respective outcomes presented in the preceding sections. Regarding the prediction of motion responses, both methods display satisfactory accuracy in heave motion predictions across varying speeds. However, significant disparities arise in predicting pitch motion, with Method 2 showcasing better alignment with experimental results. The

discrepancy in the accuracy of Method 1's pitch motion predictions is a result of the absence of surge-pitch coupling effects, as the surge motion is constrained in the first method. This can be back tested by simulations without restricting surge, which show significant pitch motions. Still, Method 1 cannot be completely dismissed and further research is required to improvise this method. Consequently, Method 2 emerges as a more practically viable and advantageous option for towing simulations utilising OpenFAST. It can also be observed that the pitch prediction was better at a lower speed (1.029 m/s) compared to the higher speed (2.058 m/s). Further exploration is warranted to assess if these discrepancies stemmed from inaccuracies within the OpenFAST input and whether refinement could be achieved through calibration using additional experimental data.

Method 2 offers a distinct advantage as it provides the opportunity to model the towing line and the tension on the line while towing. Using this method, the tension on the line was predicted with good accuracy for lower towing speeds in calm water, but higher towing speeds show an under-prediction (around 26% for 3.09 m/s). This may be improved by calibrating the drag coefficients defined while modelling the Morison elements. The effects of other non-linear phenomena also remain to be checked. In regular waves, the simulation and experiment show good agreement for the calculation of the tow force. The prediction of the total towing force exhibited generally acceptable accuracy across most frequencies with an average error of around 13% and 9% for 1.029 m/s and 2.058 m/s respectively. It is demonstrated that the highest added resistance is encountered when wavelengths are small compared to the length of the platform.

D.6. Conclusion and further work

The numerical methods described in the paper come in handy as an efficient numerical solution for investigating FOWT towing operations. Among these methods, Method 2 emerges as a better approach due to its capability to dynamically model the entire FOWT system alongside the towing cable. This modelling capacity not only yields more accurate predictions of the motion RAOs but also provides a more precise estimation of towing forces. The determination of towing forces holds paramount importance, determining the bollard pull and guiding the selection of an appropriate tug vessel and the optimal towing line for safe and efficient operations.

Although these approaches demonstrate commendable efficiency and alignment with experimental results, particularly in head waves, further validation is necessary for diverse

headings. This validation process requires additional experimental data to fortify the methodology's reliability and accuracy. Other metocean factors like wind and current were not included in the presented study, but they can also be included in Hydrodyn and analysed using OpenFAST. For this analysis, the towing speed must be added to the wind and current speeds before the simulation.

Expanding the scope of analysis, the response of the FOWT system in irregular waves remains unexplored, promising to be an area of future investigation using the versatile capabilities of OpenFAST. This analysis would yield insights into the additional resistance in distinct sea states, offering valuable considerations for planning long towing operations.

In summary, while the numerical methods presented in this paper showcase notable efficacy in FOWT towing analysis, avenues for future research involve the validation of methodologies across diverse wave headings, inclusion of non-linear hydrodynamic effects, inclusion of wind and current effects, exploration of FOWT responses in irregular waves using OpenFAST, and addressing the challenge of modelling bridles for comprehensive towing simulations.

Code availability

The OpenFAST setup and the code used for the simulations are uploaded to:

https://doi.org/10.5281/zenodo.14264026

Acknowledgement

This research work has received funding from STEP4WIND, a European Industrial Doctorate programme, granted under the H2020 Marie-Curie Innovative Training Network initiative (H2020-MSCA-ITN-2019, grant agreement 860737).

Appendix A

A1. Numerical tools used in the study

a. **OpenFAST (Version 2.4.0 & 3.5.0)**

OpenFAST (Open-source Field Operation and Analysis Software Tool) is an advanced, open-source simulation software developed by the National Renewable Energy Laboratory (NREL) to analyse the dynamic behaviour of wind turbines. Designed to support both offshore and onshore wind turbines, OpenFAST simulates the combined aerodynamic, structural,

hydrodynamic, and control responses under a range of operating and environmental conditions. This functionality makes OpenFAST an invaluable tool for researchers, engineers, and designers working on optimizing wind turbine performance, lifespan, and efficiency.

OpenFAST is based on a modular, multi-physics approach that integrates various physical domains (aerodynamics, structural dynamics, hydrodynamics, and control systems) into a coupled simulation. This approach enables it to handle the complex interactions between components and forces that wind turbines encounter. The underlying theory of OpenFAST relies on solving the coupled nonlinear equations of motion that represent these interactions.

The important modules in OpenFAST include:

1. **AeroDyn**: Simulates the aerodynamic loads on wind turbines. AeroDyn calculates the forces acting on turbine blades due to wind, providing essential inputs for analysing turbine dynamics, load distribution, and energy capture. AeroDyn primarily uses BEM (Blade-Element Momentum Theory), a method that divides turbine blades into small elements to calculate lift and drag forces on each segment, allowing for detailed analysis of aerodynamic forces along the blade span.

2. **Hydrodyn**: Models the hydrodynamic forces acting on floating platforms, including wave loads, currents, and marine growth. It uses a combination of potential flow theory, using precomputed wave radiation and diffraction solutions from WAMIT and Morison's equation for drag and inertia forces on slender members.

3. **ServoDyn**: The module used to model and simulate the control and actuation systems for wind turbines. It plays a crucial role in simulating turbine responses to environmental inputs by accounting for control mechanisms and drivetrain dynamics, making it essential for realistic, comprehensive wind turbine simulations. ServoDyn models wind turbine control systems, including blade pitch and generator torque control, enabling simulations of standard control strategies like collective pitch control (CPC) or individual pitch control (IPC) used in modern turbines.

4. **SubDyn**: The structural dynamics module, specifically designed to model the dynamic behaviour of the support structures for offshore wind turbines, such as jackets, monopiles, and semi-submersibles. It provides a detailed analysis of these substructures, capturing their dynamic response to both wave and wind loads. SubDyn uses a finite-element approach to simulate the complex structural behaviour of multi-

member substructures, accounting for elements such as joints, beams, and masses, which are crucial in offshore wind turbine foundations.

5. **ElastoDyn**: Models the structural response of the wind turbine components, including the tower, blades, nacelle, and hub, by simulating their dynamic behaviour under operational loads. ElastoDyn represents the turbine blades and tower as flexible bodies with multiple modes of deformation. This allows it to simulate bending, torsion, and coupled dynamics under various load conditions.
6. **Moordyn**: Models the mooring system and aids the analysis of floating wind turbines (explained in detail in the next section)

These modules work together, as shown in Figure 11, to compute the structural and dynamic response of the turbine under various loading conditions, with ElastoDyn handling the coupling between structural components.

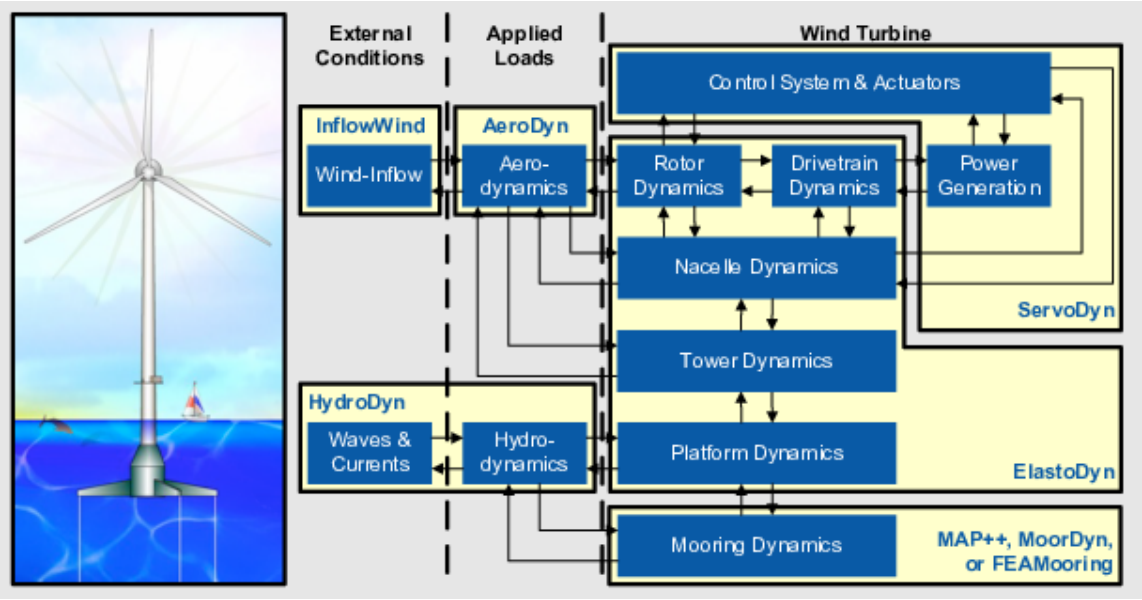


Figure 11: Workflow of OpenFAST [3]

b. Moordyn (version V1)

Special focus is given to Moordyn, which is the main module used for the research work presented in the paper. MoorDyn is an open-source mooring line dynamics model developed by the National Renewable Energy Laboratory (NREL). Designed specifically for simulating the dynamics of mooring systems in offshore wind, wave, and floating platform applications, MoorDyn can model flexible, multi-segment mooring lines subject to forces from the

environment. This software is a key component in analysing the stability and response of floating structures, particularly floating offshore wind turbines (FOWTs), under various sea conditions. It can be used as a standalone tool or as part of coupled simulation platforms like OpenFAST, where it provides detailed mooring line dynamics for the overall floating structure.

MoorDyn models the mooring lines as a series of discrete mass nodes and connecting segments, which allow it to capture the complex nonlinear behaviour of flexible mooring lines under dynamic loads. The theory behind MoorDyn is based on the lumped-mass approach, where each segment of the mooring line is represented by discrete masses that move independently. This approach allows the software to account for the weight, elasticity, drag, and inertial forces acting on each mooring line segment. The motion of each node in the mooring line is governed by Newton's second law of motion. The tension force between each pair of connected nodes is determined by the segment's elastic properties. These forces are calculated at each time step for each node, and the resulting positions and velocities are updated accordingly.

Workflow in MoorDyn

1. **Defining Mooring System Parameters**: Users input the mooring system's properties, including line material, diameter, elasticity, damping and segment length, which define the characteristics of each node and segment.
2. **Environmental Condition Setup**: Environmental forces such as wave height, frequency, current speed, and direction are specified, which determine the hydrodynamic loading on the mooring lines.
3. **Simulation and Time-Stepping**: MoorDyn applies the forces calculated for each segment at each time step, solving the differential equations of motion to determine each node's position, velocity, and acceleration over time. It uses explicit time integration for real-time dynamic simulations.
4. **Output Analysis**: MoorDyn outputs time series data for each mooring line's tension, position, and orientation, enabling detailed analysis of mooring line behaviour under varying environmental conditions.

Appendix B

Exploratory analysis - The effect of wind while towing using OpenFAST

The methodology outlined above allows for an investigation into the effects of wind on towing operations for FOWTs. To conduct this analysis, the AeroDyn and InflowWind modules of OpenFAST have been activated to incorporate aerodynamic loads induced by wind. An important step in the analysis is the addition of towing velocity to the wind velocity to accurately capture the effect of wind.

In this study, the specified conditions, as detailed in the table below (Table B1), were used to model the towing scenario under the influence of wind. A constant uniform wind with a vertical variation in wind velocity according to the power law has been used for the simulations. White noise waves were used in the simulations and the results are compared and analysed in both the time domain and frequency domain. To ensure reliable statistical results, time-domain simulations were conducted for the DNV recommended duration of 3 hours [12]. These simulation results are also compared to experimental data from towing tests conducted without wind, providing valuable insights into the additional effects introduced by aerodynamic forces during towing operations.

Table B1: Simulation parameters while towing in wind conditions

Towing speed (m/s)	Wind speed (m/s)	Wave height (m)	Blade condition
1.54	0	2	Parked - Feathered
1.54	10	2	Parked - Feathered
1.54	20	2	Parked - Feathered
1.54	30	2	Parked - Not Feathered

First the heave and pitch motions and the tension on the line are plotted and analysed in the time domain. The time series data is analysed and shown in the figure below (see Figure B1, Figure B2, Figure B3).

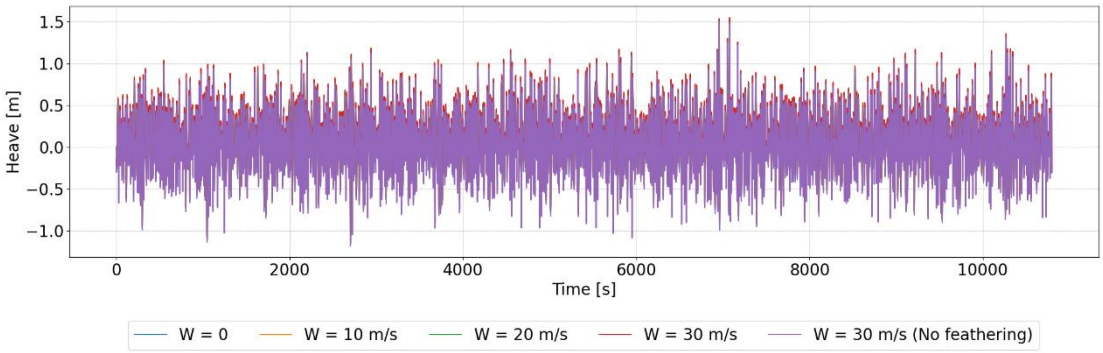


Figure B1: Heave response (time-domain)

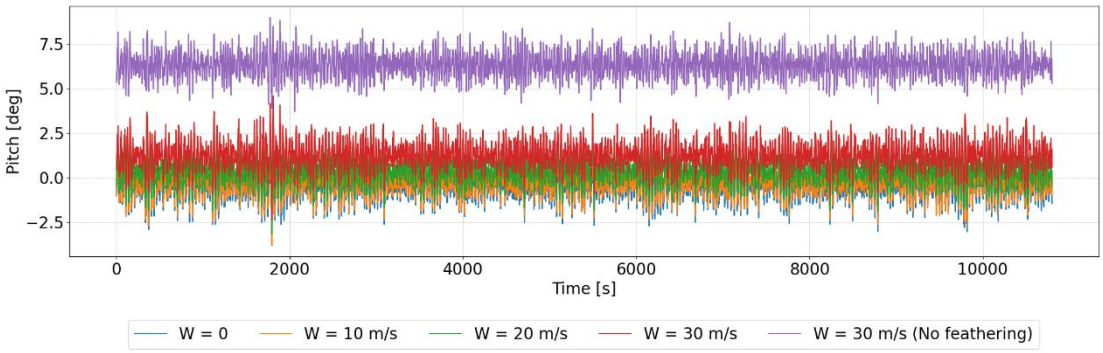


Figure B2: Pitch response (time-domain)

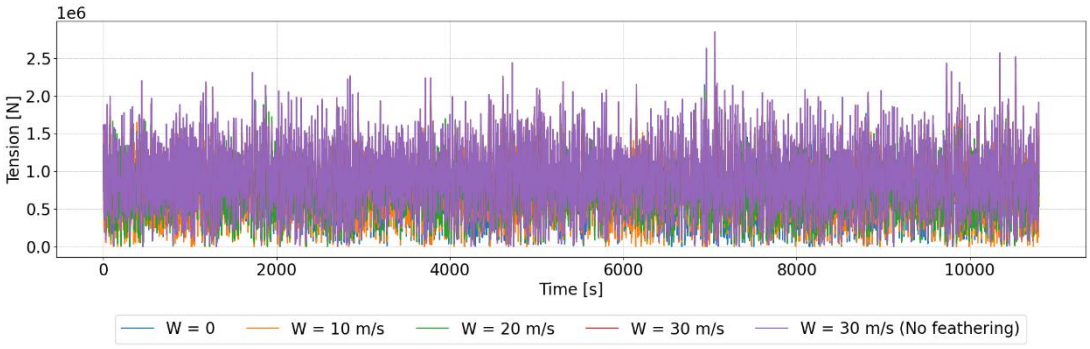


Figure B3: Towing line tension response (time-domain)

The time domain results shows that the heave is not much affected by a constant wind, but the wind provides a constant mean pitch angle to the platform. The platform performs pitch oscillations with respect to this mean pitch angle. The wind affects the drag values also. Table B2 shows the mean pitch angle and mean towing line force while towing under different wind speeds. The heave and pitch RAOs have been plotted and presented in Figure B4. The RAOs are compared against the experimental results of towing without the influence of wind.

Table B2: Mean pitch and tension values while towing under the influence of wind

Wind speed (m/s)	Mean Pitch (deg)	Mean Tension (KN)
0	-0.46	688
10	-0.28	720
20	0.36	800
30	1.28	927
30 (No feathering)	6.33	1398

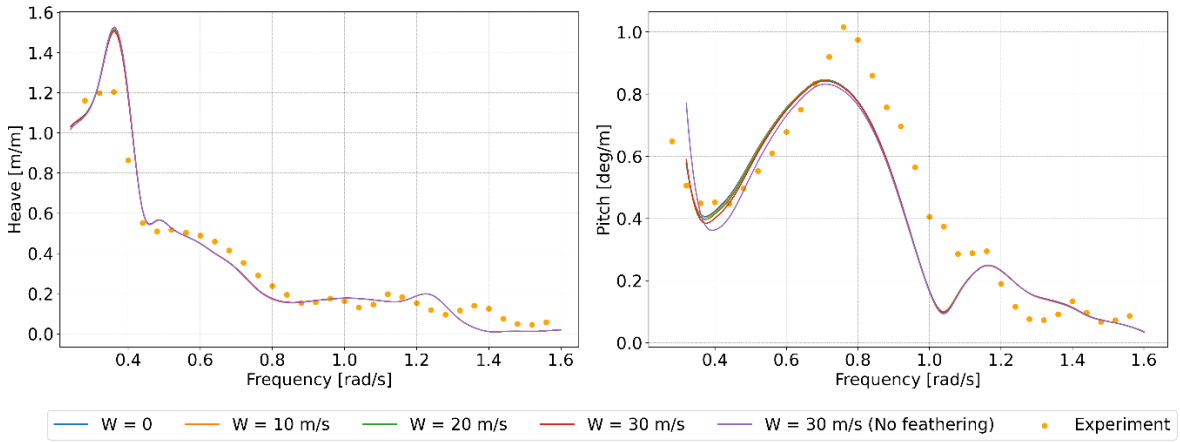


Figure B4: Heave and pitch RAOs

Discussion

It has been observed that wind velocity significantly influences both the pitch motions and the total drag on the platform during towing under wind conditions. This analysis brings the study closer to real-life towing scenarios where both wind and waves are present. A mean pitch angle arises due to the steady wind acting on the platform and the total drag increases in the presence of wind. While the RAOs show minimal variation, the pitch motions oscillate about a particular trimming condition during towing, reflecting the impact of wind on the platform's dynamics. The feathering of the wind turbine also has a significant impact on the mean pitch as well as the drag. This established the fact that the wind turbines must be kept in feathered condition while towing tow avoid unnecessary additional drag.

Further analyses incorporating wind spectra and experimental validations are necessary to gain a deeper understanding of the effects of wind. However, for basic towing assessments, the presented conditions are adequate and can serve as preliminary evaluations before initiating towing operations.

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Chapter 6

Conclusions and further work

This section provides the main findings of the research work along with recommendations for future work.

6.1 Conclusions

The presented research work analyses the FOWT-related towing operations in depth and derives valuable insights from the experimental tests and the ensued numerical simulations. The presented empirical studies, experimental analyses and the development of numerical approaches present a comprehensive framework pivotal for the optimisation and enhancement of towing procedures within the domain of floating offshore wind. The conclusions are divided into two categories: direct conclusions, which summarize findings immediately evident from the work, and derived conclusions, which analyse the broader implications of the insights gained.

Direct conclusions:

- Identifying the strictest limiting factor is important and this determines the environmental limits for towing. In the analyses mentioned in Chapter 3, the acceleration at the nacelle (1 m/s^2) was identified to be the strictest limiting factor. Due to this, a significant wave height (Hs) limit of 1.5 m applies to the investigated towing operation. Enhancing the acceleration limit at the nacelle would have increased the system's towability, particularly in higher Hs during towing operations. Identifying the limiting factors, improving the design and raising such limits would enable faster towing and towing in rougher wave conditions.

- The acceleration at the nacelle is a FOWT-specific towing limit identified during the research work. There might be several comparable constraints linked to FOWTs, such as dynamic loads impacting turbine structures during towing, potentially leading to

fatigue damage at blade roots and tower-transition piece/platform connections. The existing towing operation guidelines set by classification societies and regulatory bodies should be revised to accommodate these limiting factors.

- The second most stringent requirement would be the bollard pull capacity of tug vessels. A 400 ton bollard pull is required for towing the Innwind semi-submersible platform at the installation draught, at a speed of 5 knots in calm sea conditions. Post-arrival at the designated site, considerable time is usually allocated to ballasting the platform to its installation draught. Opting to tow at installation draught could potentially reduce offshore time by avoiding ballasting operations, especially for large FOWTs. However, the primary challenge remains securing a tug with high bollard pulls and since the installation draught of the platform is 18 m, it necessitates a deep-water port for the construction and assembly of the FOWT system.

- Towing tests performed using the DeepCwind semi-submersible platform demonstrated that the use of a bridle minimises fluid-induced motions. Phenomena like pitch-induced wave runups, emergence of heave plates above water surface, sprays and splashes were observed during towing. These phenomena are highly non-linear and should be expected while towing floating wind turbines. Using a bridle improves the course-keeping of the towed platform and is recommended to be used while towing FOWTs.

- Two numerical analysis approaches were assessed in the thesis. The first method is usually used for the analysis of ships with forward speed but novelly adopted for FOWTs. The difference here is that while analysing ships usually only viscous roll damping is included additionally. This is not the case for FOWTs as viscous pitch and heave damping also play major roles and must be accounted for and included during the simulations. The second approach is commonly used in the offshore industry for analysing offshore structures. The implementation of both these approaches is explained, analysed and compared in Chapter 4.

    - Method I - A frequency domain forward-speed approach: This approach was able to give accurate predictions of heave and pitch responses at low towing speeds (0.514 m/s – 1.542 m/s). At higher speeds and larger wave heights (> 2 m) the simulation deviates from the experimental results.

  - Method II - A time-domain hybrid approach using potential flow methods combined with Morison equation: This approach was able to accurately predict the hydrodynamic response and towing loads of the platform for the tested towing speeds (0.514 m/s – 3.084 m/s) and wave heights (1 m - 6 m). The simulations agreed well with the experimental results.

  Method II provides a direct prediction of the towing loads and motions of towed platforms in various wave conditions. This is advantageous compared to Method I, which requires external viscous damping coefficients, which are usually calculated using model tests or CFD simulations. This is not practical because model tests are not always feasible due to costs and time constraints and CFD simulations are usually time-consuming and computationally intensive. However, Method I calculates the RAOs directly in the frequency-domain, so no further post-processing is required compared to Method II.

- Accounting for viscous effects is crucial while simulating the response of floating platforms while towing. In the first method, this is achieved using Morison elements distributed along the columns, pontoon and braces of the model. They calculate the viscous force using the Morison equation for the tested wave conditions. In the second method, viscous damping coefficients are calculated from decay tests and introduced in the simulation. Depending on the availability of resources, the right hydrodynamic tool can be used to implement these methods.

- In the presented work commercial numerical tools were used for calculations initially. These numerical tools are expensive and closed-source and for further developing the research work a free and open-source numerical tool is essential. A novel approach for analysing FOWT towing by implementing the hybrid method in OpenFAST is presented in Chapter 5. This method provides good prediction of platform motions and towing loads and agrees well with the experimental results obtained from the experimental campaign. To develop further research, this method is recommended.

Derived conclusions:

- There are several overlaps between the floating wind industry, the oil and gas industry and the fixed-bottom wind industry and they are explained in detail in Chapter 2. Expertise and knowledge in many domains can be adopted from those

industries to meet the challenges faced during the commercialisation of floating wind. Learning from the challenges faced and solutions found by these industries in the early stages would help accelerate the development of floating wind technology.

- It is important to consider the installation, O&M and decommissioning processes in the design phase itself for the practical realisation of the concept designs.
- Farm-level deployments with large wind turbines (> 15MW) help reduce costs but invite challenges due to high bollard pull requirements and prolonged installation durations. Tugs with high bollard pull (>300 tons) are rare and need to be developed and built.
- Whilst bigger turbines have driven cost-saving for offshore wind in the past the same may not be true for floating wind due to the required vessel capabilities being impractical. Further research is required to find the limiting size of the turbine and the platform beyond which wet towing becomes impractical.
- Wet towing was employed during the construction of all the floating wind farms existing around the world and so far, it has been unavoidable. The towing operations for semi-submersibles need to be analysed specifically due to the fact that they are highly sensitive to wave conditions.
- The framework presented in Chapter 3 acknowledges several identified phenomena influencing towing operations, yet there could be other unaccounted factors. This thesis delves into the hydrodynamic motion and explores towing limits based on motion criteria and bollard pull. Upon selecting the most suitable numerical model, it can be integrated into the framework to optimise towing operations.
- While planning the construction of large floating wind farms, an iterative study must be performed using the mentioned framework to find the optimised towing characteristics applicable to the selected floater. This ensures the efficient utilisation of available weather windows, enabling fast and safe towing of the platforms to the farm location, consequently saving both time and costs.

6.2 Future recommended work

- The thesis highlights the significance of considering viscous effects in the analysis of towing operations. The hybrid method that incorporates the Morison equation can

account for viscous effects and provide good motion predictions. In the second method, a correction for viscous effects is introduced, but the method is good only at low speeds and low wave heights. Predictions using high-fidelity tools like Computational Fluid Dynamics (CFD) are recommended to check if better predictions are feasible. CFD methods are also useful for analysing other nonlinear phenomena like FIMs, wave run-ups, green-water shipping etc. which were observed during the experimental campaign.

- During the towing of floating wind turbines, the blades are kept in a parked-feathered condition to minimise the wind loads while towing. As wind turbines get larger, the wind loads on the platform also increase. Consequently, the effect of wind on towing operations also needs to be analysed. Similarly, a significant part of the floater will be above the water surface while towing and the effect of wind loads on the stability and motions of the platform needs to be studied.

- The platform and the wind turbine structures are assumed to be rigid during the simulations mentioned in the thesis and this is not always true. Analysis using a flexible model is required to understand the effects of towing on the floater and the wind turbine structure. For long towing operations, fatigue checks are essential to ensure that the floater and the wind turbine structures are not damaged during the towing operation.

- The thesis focuses mainly on the heave, roll and pitch motions of the FOWT during towing. The sway and yaw motions of the FOWT-system determine the course-keeping of the platform while towing. It is also important to analyse the course-keeping and directional stability of FOWTs before commencing the towing operation to check whether additional supporting tugs are required while towing in rough seas.

- MoorDyn v1 was used in this study since only cases without bridles were analysed. However, MoorDyn v2 offers advanced capabilities for analysing towing using bridle, making it more suitable for future studies that require this level of detail. Consequently, future research should utilize MoorDyn v2 to allow for a comprehensive assessment of bridle effects on the performance and stability of the towed system.

- So far, only one FOWT is towed at a time during installation. While constructing large windfarms this will be time-consuming. Methods to tow multiple FOWTs together need to be developed to overcome this challenge.

- As wind turbines get larger, the bollard pull requirements also increase. It is important to design and build large tug vessels with high bollard pulls for the installation of large wind turbine structures.

- Since the floating wind industry is in its infancy, the classification society rules/guidelines are not fully developed. Numerous marine operations adhere to broad guidelines established for other offshore sectors during their execution. There is a crucial need to adapt and refine existing guidelines to suit the specific context of Floating Offshore Wind Turbines (FOWTs).

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