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D5.7: Doctoral theses

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Index

1. Introduction

This document collects the abstracts and the short descriptions of the Doctoral theses provided by the ESRs within the project STEP4WIND.

2. ESR 1: Likhitha Ramesh Reddy

2.1. Thesis title

The title of this thesis is: **Floating offshore substructure hydrodynamics: A numerical insight**

2.2. Delivery date (or expected delivery date)

The expected delivery date is December 2024

2.3. Abstract

Floating offshore wind technology is rapidly advancing, aiming to harness high-energy wind resources in deep-water areas that are beyond the reach of bottom-fixed solutions. Several pilot and demonstration projects have been deployed to test the feasibility of floating wind turbines, yielding promising results. For example, the Hywind Scotland floating array achieved a capacity factor of 54% over its first two years of operation, compared to an average of 40% for bottom-fixed offshore wind farms in the United Kingdom, and withstood major storms. Despite demonstrating significant potential, large-scale implementation of floating wind energy remains in its early stages. As of 2022, the global cumulative deployment of floating offshore wind turbines stood at a modest 128 MW, starkly contrasted with the over 35 GW of bottom-fixed offshore wind energy. However, this situation is expected to change significantly. In 2022, Crown Estate Scotland granted leases for 17 new offshore wind projects, 10 of which utilize floating technologies. Starting in 2030, the annual growth rate in offshore wind energy is anticipated to exceed 3 GW per year, and by 2040, the installation rate is expected to approach 10 GW per year.

To achieve full-scale commercialisation, it is important to reduce the levelised cost of energy (LCOE). Floating offshore substructures account for almost 30% of the total LCOE. Consequently, design optimization and standardization are critical for reducing the LCOE of these substructures. A crucial design aspect is the accurate prediction of hydrodynamic loading on the substructures, essential for the precise estimation of the Fatigue Limit State (FLS) and Ultimate Limit State (ULS) to ensure a safe and optimized design of the floater. Most current modeling approaches rely on potential flow theory, Morison's equation, or a combination of both. However, these tools consistently under-predict hydrodynamic loading by about 20% due to their limitations to linear or weakly non-linear analysis. As turbine capacity increases and the target water depth becomes deeper, nonlinear hydrodynamic effects become more significant, especially under extreme conditions that have become more frequent in recent years. This thesis aims **to improve the non-linear hydrodynamics of industrial tools for the optimisation and standardisation of floating offshore substructures**.

Mid-fidelity hydrodynamics: Floating offshore wind turbines experience different operating conditions, such as wind and wave inflow characteristics. Understanding the effect of wind and wave characteristics, as well as system parameters, is crucial for system optimisation. In this part, a sensitivity analysis is performed with various modelling input parameters (like wind and wave inflow conditions, hydrodynamic coefficients, etc.) using a Morris screening approach (Elementary effects). Simulations of the IEA15MW floating offshore turbine atop a Volturn US-S semisubmersible and NREL 5MW floating offshore turbine atop a Hywind spar buoy and DeepCwind semisubmersible are performed using the mid-fidelity aero-hydro-servo-elastic time domain tool, OpenFAST, to identify the significant parameters. The significant parameters are ranked based on the 10-minute damage equivalent loads obtained from OpenFAST simulations. This study provides valuable insight into design-driving input parameters, characterising substructure-specific wind-wave influence.
All the selected input variables in the sensitivity study are associated with the operating conditions of floating offshore wind turbines, except for drag coefficients. In other words, drag coefficients can be tuned to achieve more accurate results. In this section, a case study is conducted using wind-site metocean data to explore the impact of different drag coefficient values. This section aims to understand the domain of operating conditions that significantly impact the drag coefficients' uncertainty.

High-fidelity hydrodynamics:

High-fidelity tools like Computational Fluid Dynamics (CFD) are proved to accurately capture non-linear hydrodynamics, including viscous effects. Nonetheless, FSI simulations of complex geometries are expensive and cannot be implemented as an industrial solution. Therefore, there is a need to either improve the computational efficiency of CFD models or improve the existing engineering models to account for non-linear and viscous effects. This thesis focuses on the latter. In this part, a CFD model is set up in OpenFOAM for a DeepCwind and Volturn US-S semisubmersible and validated against experimental data. While these models performed close to the experimental results. Further, the drag coefficients and added mass coefficients are extracted from the CFD force time-series output.

Improved mid-fidelity hydrodynamics: This part aims to improve the non-linear hydrodynamics of the mid-fidelity tools using high-fidelity data.

2.4. Index

Introduction
This chapter provides a broad motivation for the research, exploring the role of floating offshore wind in battling climate change and challenges hindering the growth of floating offshore wind. In this chapter, the research objective, research questions and thesis structure are also presented.

Part I **MID-FIDELITY HYDRODYNAMICS**

Part I explores the importance of modelling input variables concerning different turbine and structural loads. Further, the impact of drag coefficients at different wind and wave characteristics is assessed so that one can understand when the accuracy of the drag coefficient is important.

- Chapter 1 **State-of-the-art low fidelity hydrodynamic modelling -** This chapter presents an overview of FOWT dynamics and its theory. Different low/mid-fidelity numerical models are explored.
- Chapter 2 **Significant Parameter Analysis -** In this chapter, a sensitivity analysis is performed with different wind and wave parameters and hydrodynamic coefficients on different turbine and floating substructure configurations. It helps to understand the most important variables for different FOWTs.
- Chapter 3 **Impact of hydrodynamic drag coefficients -** This chapter further explores the influence of the only tunable property considered in Chapter 3, i.e., the drag coefficients (because wind and wave inflow conditions are not user-dependent). The focus is on understanding which outputs are most affected by the uncertainty in drag coefficients.

Part II **HIGH-FIDELITY HYDRODYNAMICS**

Part II explores using high-fidelity hydrodynamics to tune drag coefficients, which is otherwise done through experiments. In this part, a high-fidelity technique, CFD, is first set up and validated to obtain hydrodynamic coefficients eventually.

- Chapter 1 **State-of-the-art high-fidelity hydrodynamic modelling -** This chapter provides insight into the theoretical aspects of Navier-Stokes-based solvers.
- Chapter 2 **CFD-determined hydrodynamic coefficients -** This chapter describes the multiphase flow solver used to run fluid-structure interaction simulations of the floating substructure. It also dives into details of the computational domain, meshing and numerical schemes used. In the end, the CFD setup is validated with experimental test results. This chapter further explains how CFD can be used to obtain hydrodynamic coefficients

Part III **IMPROVED MID-FIDELITY HYDRODYNAMICS**

Part III focuses on integrating the high-fidelity data obtained in Part II into the low-fidelity solver used in Part I.

- Chapter 1 **Time domain simulations with CFD-derived drag coefficients:** Through this chapter, a method to input CFD-derived drag coefficients to a low-fidelity solver is identified and tested by forming time domain simulations. This chapter generalises the process by processing a viscous correction model that can be used for all design load cases.

Global Conclusions

This part presents an overview of the thesis' conclusions and new insights. It provides an outlook for relevant future investigations.

3. ESR 2: Ricardo Pinto Elisbão Martins Amaral

3.1. Thesis title

The title of this thesis is: **Impact of a moving rotor on wind turbine wakes**

3.2. Delivery date (or expected delivery date)

The extected delivery date is 28 February 2025

3.3. Abstract

As of mid-2023, Europe had 32 GW of offshore wind power installed capacity set to grow five times by 2030, should the countries achieve the ambitious installation targets. Most of the offshore wind turbines installed so far were built on fixed-bottom substructures, since they are more cost-competitive than floating offshore wind turbines (FOWTs) for water depths below 50-60 m. However, harvesting wind energy in locations with water depths higher than 60 m and more than 60 km away from the shore has the potential to supply the world's total electricity demand several times by 2040. At these locations, FOWTs are more cost-competitive which makes the technology a serious candidate to support the energy transition. As a result, floating offshore wind farms are already under operation, deployment and auction, with 10 GW of capacity expected in Europe by 2030. More than ever, it is necessary to have a holistic and in-depth understanding of FOWTs, their physics and the way they interact with each other, which can differ materially from their fixed-bottom counterparts, since the rotor is free to move. Engineering models widely used for wind turbine load design are based on the blade-element momentum theory (BEMT) and rely on assumptions that, while being reasonable for bottom-fixed turbines, may break down for FOWT. On a similar note, engineering wake models that do not intrinsically solve the time-varying nature of the wake, may miss wake disturbances caused by the platform motion in a FOWT. Even the dynamic wake meandering model that does capture this time-dependency, assumes that a base stationary wake is convected as a passive scalar subjected to large scale ambient turbulent structures, thus capturing only one of the wake meandering processes. These large scale structures are responsible for the low-frequency content of the wake spectra, with periods of up to 1 h. The other mechanism relates to wake shear layer instabilities, which is a topic that has been investigated over the past two decades. This thesis investigates the impact that the rotor motion induced by the floating platform has on the wake evolution by means of high-fidelity large-eddy simulations with an actuator-line model of the rotor. Prior to the core simulations, the simulation setup is validated against experimental data, both for the wake and turbine loads. Afterwards, simple sinusoidal platform motions are investigated under laminar flow in order to isolate and highlight the physical phenomena triggered specifically by the floating motion. Once these phenomena are reasonably understood, layers of complexity are added in order to bring the simulation conditions closer to normal operation. In particular, instead of having single-frequency prescribed motions, these become described by a spectrum over a relevant range of frequencies. In addition to that, the flow becomes turbulent, through the injection of a Mann box, at different turbulence intensity levels. This will allow one to assess whether previously identified floating-specific wake phenomena are relevant or not, as a function of the inflow conditions.

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Description of the potential differences between floating offshore wind turbines and fixed-bottom wind turbines in terms of performance and wake behaviour.

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2.2 High-fidelity methods . . . .

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2.2.1 Large-eddy simulations . . . .

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2.2.2 Actuator-line model . . . .

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2.2.3 Turbulence modelling . . . .

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2.2.4 YALES2 . . . .

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2.3 Wind turbine models . . . .

Description the turbine models that were simulated.

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5.4 Wake meandering . . . .

4. ESR 3: Deepali Singh

4.1. Thesis title

The title of this thesis is: Data-driven surrigates in wind-energy: Applications to offshore wind turbine workflows.

4.2. Delivery date (or expected delivery date)

Expected delivery date is December 2024.

4.3. Abstract

The global demand for energy is increasing, pushing advancements in the renewable energy sector. By 2028, global renewable energy capacity is expected to surpass 7000 GW, with significant growth in solar and wind energy. Offshore wind capacity grew by 16% in 2022 and is projected to reach 380 GW in the next decade. Floating offshore wind turbines (FOWTs) offer the potential to unlock vast energy resources from deep offshore regions. According to the IEA offshore wind outlook, about 70% of the offshore wind potential is in deep water sites. FOWTs also benefit from high-quality wind conditions, as demonstrated by the Hywind Scotland wind farm that produced power at a 54% capacity factor in the first five years of its operation. Despite the current challenging economic conditions and supply-chain delays, the Global Wind Energy Council (GWEC) still estimates about 10.9GW of floating wind energy production by 2030. The design of FOWTs presents new technological, economic, and financial challenges, necessitating complex and costly numerical simulations. The quantities of interest derived from the simulations are often very difficult to model using generalizable, parametric, physics based approaches. Especially in case of floating wind turbines, the response dynamics, extreme and fatigue loads are functions of the geometry and type of the floating substructure, along with the wind turbine. Developing a separate model for every foundation type is impractical. Data-driven models provide a big advantage in this sense as they can infer complex relations between the inputs and quantities of interest, solely on the basis of data pairs.

The primary research focus of this thesis is the use of data-driven models, known as surrogates, to simplify and accelerate various engineering workflows for all wind turbines, with a special focus on FOWTs. The thesis covers three broad topics:

- Probabilistic load surrogates for site analysis: The first part presents a data-driven probabilistic surrogate modeling framework for short-term damage equivalent load prediction based on 10-minute statistics of the environmental conditions as input. The novel methodology minimizes the training costs associated with training the surrogate by eliminating the need for seed repetitions, while quantifying the uncertainty in the loads as a result of the stochastic wind and wave conditions. Probabilistic estimates of the loads can also be useful in defining more conservative safety factors as we move towards reliability based engineering to reduce material costs.

- **Surrogate for floater design optimization** (With ESR 4): The second part introduces a surrogate model that maps the geometric parameters of a semi-submersible foundation to the corresponding hydrodynamic matrix elements in a frequency domain solver, which is ultimately a part of a bigger optimization framework.

- **Data-driven time series modeling of wind turbine loads:** This part aims to model the complete load time series as a function of the inflow conditions on a floating wind turbine.

4.4. Index

Part I- Introduction

This section provides a broad context for the motivation of doing this research. The urgent need to develop breakthrough renewable energy technology to counter the effects of climate change is presented. Wind energy has evolved significantly in recent years, with a current shift towards newer technologies like floating wind turbines (FOWTs). These innovations play a crucial role in the current energy mix, particularly in offshore sites where traditional fixed-bottom turbines are not feasible. At the same time, it is prudent to leverage the rapid advances in other sectors, such as machine learning and data science to accelerate some of the engineering processes involved in designing such complex megastructures. This section also presents the research question, the research objectives and the outline of the thesis.

Part II- Uncertainty matters: Surrogate models for wind turbine loads

This part is focused on the novel probabilistic surrogate modeling framework for site-specific load prediction. All offshore wind turbines experience cyclic hydrodynamic and aerodynamic loads in response to the fluctuating metocean conditions. For floating wind turbines, there is an additional dependence on the type of floating substructure. Calculating fatigue loads for such complex systems is computationally expensive as it requires simulating several thousand load cases encompassing various operational scenarios. Although certification requires standard aero-servo-hydro-elastic engineering tools, data-driven surrogate models can potentially reduce the computational costs associated with site analysis. The surrogates are designed to map the 10-minute statistics of the environmental conditions at potential sites to the 10-minute damage equivalent loads on the wind turbine tower and blades. In this study, we explore data-driven probabilistic surrogates in particular. Traditional load surrogate modeling entails performing seed repetitions per training data point to consider the uncertainty associated with the stochastic site conditions properly. For floating wind turbines, this could inflate the training costs. Probabilistic surrogates have the advantage of being able to predict the most likely response, given certain site conditions, without requiring seed repetitions, thereby limiting the computational cost of training. Additionally, they provide a corresponding uncertainty estimate, enabling more informed decision-making. In this section, surrogates for onshore, fixed-bottom offshore and floating wind turbines are developed. The onshore and offshore monopile cases of the IEA-10MW reference wind turbine are used for the study. The simulations for these cases are performed with OpenFAST. For the floating wind turbine, the data-driven models are trained on damage equivalent loads calculated from BHawC-OrcaFlex coupled aero-servo-hydro-elastic simulations of a modified geometry of the commercial, 6MW Hywind Scotland spar-buoy wind turbine. Relevant features characterizing the site are identified, and their ranges are defined based on site conditions acquired from the ERA5 reanalysis models. This part presents a motivation for using probabilistic models, a theoretical overview of the various probabilistic approaches, details about the simulation setup, and finally, the results are presented.

Part II- Surrogate based design optimization

This part presents a surrogate-assisted optimisation approach to speed up the substructure analysis in the preliminary design phase. The approach consists of replacing the radiation-diffraction analysis in a frequency domain analysis model for floating wind turbines with a data-driven surrogate model predicting the hydrodynamic coefficients for parameterised substructure geometries. This procedure is compared with the reference approach of estimating the hydrodynamic coefficients via radiation-diffraction analysis. A representative use case of assessing the trade-off between minimizing the capital cost and reducing the wave-induced nacelle acceleration standard deviation for a semi-submersible substructure is presented. A multi-output implementation of the XGBoost model is used in order to include the correlation between the targets. The surrogate model is shown to capture the trade-off between the two objective functions, and the optimal designs identified with the surrogate model generally follow the same trend as those obtained with the reference model. However, relying on the surrogate model for performing the analysis of the substructure introduces local minima in the objective function that cause a discrepancy between the optimal designs identified with the surrogate model and those identified with the reference model.

Part III- Digital twins: Surrogates for load time series prediction

Recursive neural networks, autoregressive models and long short-term memory recurrent neural networks (LSTM) are used to build surrogate models to forecast time-series blade loads for both fixed and floating offshore wind turbines. The aim of the surrogate models is to generate load forecasts inexpensively and accurately such that they can be used in a model predictive controller. The 6MW Hywind Scotland floating wind turbine with a modified tower geometry is used for this study. The simulations to obtain the ground truth time series are performed with BHawC coupled with OpenFast. Several data encoding approaches are evaluated to find a suitable latent representation of the complex information from the inflow turbulence grid to feed as input to the surrogate. The main challenge with this application is that the only information available to the surrogate in terms of the state of the ocean is the wave elevation at the origin. During operation, a wind turbine with catenary mooring lines can move several meters away from the initial location. Therefore, the wave elevation values at the origin have a chance of losing correlation with the loads on the wind turbine. The tower bottom loads are especially susceptible to noise from the stochastic hydrodynamic loading that the surrogate has no information about. We also explore probabilistic time series modeling approaches to attach a confidence interval to the load predictions.

5. ESR 4: Matteo Baudino Bessone

5.1. Thesis title

The title of this thesis is: Assessing the relevance of trade-offs in floating wind farm design.

5.2. Delivery date (or expected delivery date)

The expected delivery date is November 2024.

5.3. Abstract

Floating offshore wind farms are complex multi-disciplinary systems whose development, design, and realization involves a wide range of stakeholders. To these days, wind farm subcomponents are largely designed independently by several organizations with limited interactions, in a so-called partitioned or sequential design approach.

In contrast, recent research effort has shown the advantage of applying Multidisciplinary Design, Analysis, and Optimization (MDAO) techniques to the design of conventional offshore wind systems. MDAO consists in coupling models pertaining to different disciplines within an overarching workflow, that emulates the design process of a complex multidisciplinary system. By coupling the workflow with an optimization algorithm, the whole system can be optimized, leveraging on the trade-offs between different subcomponents to yield an improved design than a sequential design approach.

However, developing and implementing an MDAO approach for a complex subsystem such as a floating wind farm is no easy task. First, in real world wind farms different stakeholders undertake the design of the farm components, imposing a barrier on the circulation of information, and thus on the application of high-level MDAO approaches. Furthermore, the computational effort and time required to run MDAO workflow increase significantly with respect to going through the design workflow a limited number of times. It becomes then important to identify those trade-offs that have a larger impact on the KPI of the floating wind farm, so that effort is concentrated in including them in the design process.

This research involves the development of an MDAO workflow emulating the design of a floating wind farm, and the application of such a framework to identify those trade-offs that have the highest potential in reducing the Levelised Cost of Energy (LCoE) for floating wind farms.

5.4. Index

1. Introduction

1.1 Why floating wind?
This section provides a brief excursion on the drivers for floating wind and the current status of development

1.2. Functional and practical partitions in a floating wind farm project
This section introduces a ‘blank’ Design Structure Matrix (DSM), where the rows and columns elements are based on the functionality of the floating wind farm subcomponent, and mirror existing industry partitions. The DSM relies on the pilot wind farms of Hywind Scotland and Kincardine as references for subcomponents and supply chain cateogorisation.

1.3 Why a systems engineering approach (may) be needed and why it is not a 'magic wand'.
In this section, the DSM is populated, showing the several trade-offs and couplings that can be exploited by adopting a multidisciplinary design analysis and optimisation (MDAO) approach. The two different matrices (for Hywind Scotland spar buoys

and for Kincardine semi-submersibles) introduce the concept of quantitative trade-offs in dimensioning subcomponents and categorical trade-offs between concepts". Adopting an MDAO approach would allow accounting for all these trades which are overlooked by a sequential desing approach, and thus achieve improved floating wind farm designs. However, assessing couplings is time-consuming and requires coordination between different functional groups within a stakeholder or between various stakeholders in the industry.

1.4 Main research question

In this section, the considerations expressed in the previous section are reiterated, leading to the need to understand which trade-offs are significant and which can be overlooked, explicitly formulating the main research question for this thesi**s.**

1.5 Limitations and context for the main research question.

In this section, the limitation to the main research questions are expressed. In particular, to make the problem manageable, we look at a subset of couplings:

1. Couplings between designs and logistics, as these are generally overlooked in the academic literature
2. Couplings in the (regular) layout definition, as these are different than in bottom fixed offshore wind , and not addressed in the literature.

Following these considerations, three sub-questions are formulated, one for each trade-off analysed:

1. Flaoting substructure concept selection (trades among substructure capital costs, installation, and maintenance costs)
2. Substructure sizing and accessibility (trades between substructure capital costs and maintenance costs)
3. Floating wind farm layout definition (trades among AEP, infield cables costs, and moorings costs)

The section follows with the realisation that it is necessary to assess more than one floating wind farm realisation, as floating wind farm projects will be executed with different project boundary conditions. Trade-offs might be insignificant for certain project boundary conditions, and relevant in others. This consideration leads to the introduction of the design drivers, as external drivers that can affect the relevance or irrelevance of a trade-off.

1.6 Summary of the layout of the report.

2. Methodology to assess trade-offs relevance.

2.1 Overarching approach.

In this section the overarching approach adopted to assess the trade-offs relevance is described- The strength of MDAO in assessing 'trade-offs in dimensioning' is highlighted, and it is further explained how MDAO is used to set a common comparison base to assess 'trade-offs between concepts' in this thesis. Furthermore, the approach adpopted to emulate the MDAO and the sequential design approach to a gfloating wind farm is described, with high-level Extended Design Structure Matrix (XDSM) showing both approaches. Having defined the MDAO and sequential design workflows, the floarting wind farm design process is emulated with the MDAO and sequential approach for several case studies obtained by combining different design drivers and the reuslting optimal wind farms are compared in terms of LCoE.

2.2 Design drivers and case studies.

This section summarises the criteria for selecting the design drivers, and introduces qualitative the case-studies analysed in the research.

2c. Criteria for relevance of a trade-off.

This section introduces the criteria adopted to define whether a trade-off is relevant or not, i.e. "A trade-off is relevant when accounting for it leads to a wind farm configuration with a lower LCoE than the one obtained with a sequential design approach", and outlines the reason why LCoE is selected as the metric for this study.

3. The MDAO framework.

3.1 Overarching description of the MDAO workflow.

This section provides a detailed XDSM for the wind farm with semi-submersibles and spar buoys.

3.2 Description of each functional analysis block.

This section details the content of each analysis block in the optimisation workflow:

- Substructure analysis
- AEP
- Infield cables with cables installation and maintenance

- Installation logistics
- Maintenance logistics
- Financial analysis

3.3 Verification of the functional analysis blocks.
This section provides the verification of each analysis block, independently:
'- Substructure analysis
- AEP
- Electrical BOS
- Weather delay function for installation and O&M modules

3.4 Verification of the MDAO workflow LCoE prediction.
In this section the share of each subcomponent to the total life-cycle cost of the wind farm is compared with publicly available references.

4. Results

4.1 Case studies description.
This section provides the summary of all the parameters provided as input to the MDAO workflow to set up the various case studies.

4.2. Trade-offs in floating substructure concept selection.
This section highlights In which project conditions does accounting for trade-offs in substructure concept selection lead to a solution with a lower LCoE than a sequential design approach, how significant is the LCoE reduction, and what are the main drivers for LCoE reduction.

4.3 Trade-offs in substructure sizing and accessibility.
This section highlights In which project conditions does accounting for trade-offs between substructure sizing and accessibility lead to a solution with a lower LCoE than a sequential design approach, how significant is the LCoE reduction, and what are the main drivers for LCoE reduction.

4.4 Trade-offs in floating wind farm layout definition.
This section highlights In which project conditions does accounting for trade-offs in wind farm layout definition lead to a solution with a lower LCoE than a sequential design approach, how significant is the LCoE reduction, and what are the main drivers for LCoE reduction.

4.5 Results summary.

5. Conclusions

5.1 Wrapping up main conclusions.

5.2 Limitations of current work.

5.3 Recommendations for future work.

6. ESR 5: Felipe Miranda Novais

6.1. Thesis title

The title of this thesis is Model Testing of Floating Offshore Wind Turbines

6.2. Delivery date (or expected delivery date)

The expected delivery date for this thesis is December 2024

6.3. Abstract

The complex dynamics involved in Floating Offshore Wind Turbines (FOWTs) result from the combined interactions of the turbine, wind, current, and waves. A deep understanding of the physics involved in these systems is crucial for the development of the industry, which is still in its early stages. Given the few available FOWTs prototypes deployed, the limited reliability of the currently available simulation models and the prohibitive computational cost of high-fidelity tools in testing multiple load cases, an alternative has been to resort to model testing.

When performing model experiments of FOWTs, two different kinds of facilities can be used. A wind tunnel is preferred when the goal of the test campaign is to investigate the aerodynamic phenomena if the objective is to understand the hydrodynamics or the overall coupled dynamics, a wave basin approach is preferred. In the absence of physical means to emulate a specific environmental condition, hybrid methodologies can be used, where one of the subsystems, either the rotor or the platform, is physically downscaled whilst the other uses an actuator system imposing the quantity of interest, either forces or motion, on the model.

This work comprises a series of wind tunnel experiments conducted at two different facilities, each with unique setups. Firstly, the methodology to develop a brand-new setup is presented, and the experimental device designed based on the dimensions of the open-jet section of the Delft University of Technology is used to conduct experiments utilizing imposed motions for single and coupled degrees-of-freedom to experimentally investigate the aerodynamics of the wind turbine rotor when subject to floater motions. A limitation in the aforementioned study is the rotor maintains a constant blade pitch angle and rotational speed during its operation, a simplified scenario compared to the state-of-the-art wind turbines deployed in the open sea, which are equipped with controllers capable of adjusting the rotor operating parameters according to the inflow conditions. To overcome the limitation of previous studies, another experiment is conducted at the boundary layer section of the GVPM wind tunnel at Politecnico di Milano, where the existing device is capable of controlling both the blade pitch angle and the rotor speed. Now, a turbine with an active controller is set under harmonic motion and the unsteady aerodynamic effects are investigated with the presence of rotor operation parameter variations.

Finally, an investigation into the differences between the main testing methodologies is presented. This includes a collection of data from prior experiments conducted in a wind tunnel at Politecnico di Milano, using a hardware-in-the-loop approach, as well as wave basin experiments performed at the Maritime Research Institute Netherlands, which involved setups with both a real wind turbine and hybrid scale models. A quantitative and qualitative analysis is conducted in the context of differences between utilizing each kind of approach, also focusing on the strengths and limitations of using each method. The main outcome of this thesis is a conjunction of lessons learned from the work performed with data involved in all the different facilities and using different methods, serving as a guideline for future model testers on how to exploit the most out of their experiments.

6.4. Index

Chapter 1: Development of a Wind Tunnel Experimental Model for the Delft University of Technology.

The introductory chapter presents the methodology used to develop a 1:148 scale model of the reference wind turbine DTU 10 MW. The process of defining the scaling parameters is explained and linked to the facility and the hexapod, a 6 degree-of-freedom actuator device used to impose motions. An investigation is conducted into the testing capabilities of the setup, not only for single harmonic motions but also for full load cases based on real sea conditions and different platform motions. The scaling methodology is discussed, and a FAST simulation model developed for the turbine is presented, comparing the simulations to the thrust and torque of the real turbine. Finally, the validation of the rotor is conducted, with a comparison shown between testing the fully mounted rotor in two different wind tunnels, one at Politecnico di Milano and the other at Delft University of Technology.

Chapter 2: Wind Tunnel Experiment at the Open-Jet Facility Section at Delft University of Technology.

Utilizing the setup previously described in Chapter 1, the subsequent part of this thesis aims to describe the test campaign conducted at the Delft University of Technology. The first section details all the facilities involved and the setup mounted, with special attention given to the sensor chains of the rotor, integration with the hexapod, data acquisition systems, and the control of the entire experimental apparatus. The methodology used to derive the measured forces is presented, and static tests are compared to experimental measurements to validate the setup and analyze variations in thrust and torque between repetitive samples. The process for defining the test matrix is explained and linked to the setup's capabilities. Firstly, results of the measurements for single degrees-of-freedom are shown and analyzed. Secondly, some coupled degrees-of-freedom measurements are presented. Lastly, fully coupled 6 degrees-of-freedom motions extracted from simulations considering realistic sea-state and platform motions are imposed. A conclusion is then presented, highlighting the main limitations of the experiment as well as the main outcomes.

Chapter 3: Wind Tunnel Experiment at the Boundary Layer Section of the Politecnico di Milano.

At Politecnico di Milano, an existing experimental apparatus, commonly used by joint research efforts as a benchmark for cross-comparison of aerodynamic numerical codes, is employed. The experiment builds upon the work presented in Chapter 2. Given that the current setup allows for rotor speed and blade pitching capabilities, the goal is to work with the same imposed harmonic motions, focusing this time exclusively on pitch motion, but this time with an active controller to investigate unsteady aerodynamic phenomena. The setup is thoroughly described, and the methodology for experimentally implementing the ROSCO open-source controller is presented. Finally, the numerical results are compared to simulations, and the main experimental results are discussed, including the challenges of implementing a controller for wind tunnel testing.

Chapter 4: A Critical Comparison Between Wind Tunnel Hardware-in-the-Loop Testing and Wave Basin Testing Methodologies.

Nowadays, various techniques for performing experiments with floating offshore wind turbines are available, each with its strengths and limitations. Accurately reproducing the aerodynamics and hydrodynamics in an experimental facility is challenging, and each approach may be more suitable for a specific goal or used in conjunction to overcome experimental limitations and exploit the advantages of each method synergistically. This section aims to present a critical comparison between wave basin and wind tunnel techniques, focusing specifically on the setups developed by the Maritime Research Institute Netherlands (MARIN) and the Politecnico di Milano. Previous chapters focused exclusively on wind tunnel testing methodologies, specifically using an open-loop approach, where the hexapod movements are predetermined before each test. Now, a wind tunnel hardware-in-the-loop approach is employed, where aerodynamic load measurements are fed to the hydrodynamic numerical internal model to set the movement point. Additionally, two different wave basin methodologies are used: one with a full physical turbine and a wind generator device, and another utilizing a winch actuator system. Experimental results from both facilities are compared to numerical models, and a discussion is presented concerning their main shortcomings. Potential sources of uncertainty in each method and their strengths are also highlighted.

7. ESR 6: Alejandro Jiménez del Toro

7.1. Thesis title

The title of this thesis is: **The role of phase transition kinetics and flow directionality on the intimate contact development of carbon fibre reinforced polyphenylene sulphide in automated fibre placement.**

7.2. Delivery date (or expected delivery date)

The delivery date of this thesis is 01/03/2024.

7.3. Abstract

Offshore floating wind energy holds significant potential for enhancing green energy production across coastal regions of the European Union. By deploying floating wind turbines in deep waters, anchored to the seabed, this technology offers a viable solution for harnessing wind resources where traditional bottom-fixed offshore wind farms fall short. Regardless of the type of wind farm, one key strategy to improve energy output per turbine is by increasing the rotor diameter, which allows for greater power generation from each unit. This drive towards larger rotors necessitates the design and manufacture of longer wind turbine blades. To achieve the required structural integrity while minimizing the weight of the blades, carbon fibre composites have emerged as a preferred material choice. These composites offer a combination of high stiffness and low density, making them ideal for large-scale blades. However, they also present challenges, particularly in compressive strength due to fibre misalignment

This thesis explores the potential of automated fibre placement (AFP), an additive manufacturing technology currently used in aerospace, for manufacturing wind turbine blade spar caps with carbon fibre-reinforced thermoplastic composites. AFP not only ensures precise fibre alignment, addressing the critical issue of misalignment in large structures, but also leverages the advantages of carbon fibre reinforced thermoplastic composites (CFTP). The AFP places unidirectional CFTP tapes in successive layers up to the completion of the part. The material is heated up to the processing temperature and compacted under a roller to achieve consolidation. These materials enable in-situ consolidation (ISC), i.e. the part is fully consolidated under the compaction roller. This allows to produce the final part as the tapes are placed, eliminating the need for additional post-processing, and offer inherent welding capabilities, which can simplify assembly and enhance structural integrity. Moreover, thermoplastics facilitate easier recycling compared to traditional thermosetting composites, making them a more sustainable option for large-scale wind turbine blades.

Despite its potential, AFP/CFTP lacks applicability due to the low placement speeds at which it currently has to operate to deliver parts with acceptable quality. This is due to the fact that ISC is largely hindered by the high viscosity of the thermoplastic matrix. Viscosity refers to the ability of the polymer and the composite to flow under shear load which, in this case, is applied by the compaction roller. The high viscosity of the thermoplastic hinders its flowability through the fibre bed into the surface of the tape, which leads to a lack of matrix at the surface of both plies. The lack of matrix at the interface can lead to voids, which have detrimental effects on the final part. The process of generating a resin rich surface via resin and composite flow capable of further bonding with the substrate layer is known as intimate contact (IC) development and has been identified as the rate limiting factor to achieve ISC in AFP/CFTP. Thus, studying the role of viscosity and flow directionality in the intimate contact development of CFTP in AFP can lead to the improvement of such technologies.

Viscosity largely depends on temperature, which has extensively been studied in literature for AFP/CFTP, and refers to the increase of mobility of the polymer chains due to a higher temperature, easing the flow, thus lowering the viscosity. In addition, it also depends on the degree of crystallinity of the semicrystalline thermoplastics. Semicrystalline polymers are of major interest for CFTP materials for high performance applications. Their microstructure consists of amorphous and ordered regions, the latter being called crystals. Two relevant temperatures can be identified for these thermoplastics, the glass transition and the melting temperature. Below the glass transition temperature, the amorphous phase is solid; whereas above it, it melts and becomes

mobile. The melting temperature is higher than the glass transition one, and identifies the stability limit for the crystals. Above it, the crystals melt and the whole polymer is molten. Below it, the crystals' are stable and they can be formed, i.e. crystallisation, or destroyed, i.e. melting. Thus, between the glass transition temperature and the melting temperature, the polymer consists of a molten amorphous phase with solid crystals in it. It is known that the presence of crystals significantly increases viscosity in thermoplastics, yet its role has not been studied for AFP/CFTP. Hence, the crystallisation and melting kinetics, i.e. phase transition kinetics, of the a CFTP in AFP and their effect on IC development studied in this thesis. The researched composite is CF reinforced polyphenylene sulphide (CF/PPS), due to its relatively low viscosity and still high performance properties.

The desired flow of polymer and the composite are those which lead to an effective bond between tape and substrate by generating a resin-rich surface and flattening the surface roughness. These are called percolation flow and squeeze flow, respectively. The former refers to the flow on matrix within a static fibre bed and it can be longitudinal or transversal to the fibre direction. This flow is responsible to wet resin poor areas and create a resin-richer surface. The later describes the cooperative movement of fibres and matrix upon compaction. Due to the inextensibility of the fibres in the longitudinal direction, it develops in the transverse one, widening the tape. Squeeze flow is responsible for flattening the surface roughness. It is the combination of both flows that allows to reach a successful IC, yet their development is largely uneven. Percolation flow is largely hindered in TP composites due to their high viscosity, leaving squeeze flow as the preferred one. Hence, tape widening is largely observed in AFP/CFTP while percolation is not. Thus, strategies to promote percolation flow and evaluating its impact on IC development are studied.

The findings of this thesis contribute to optimizing AFP for the production of carbon fibre-reinforced thermoplastic parts, offering insights into how intimate contact development is influenced by the CF/PPS phase transition kinetics and flow modes. By enhancing the understanding of these processes, this work supports the creation of lighter, stronger, and more sustainable composite structures across various industries, ultimately improving the efficiency and viability of offshore floating wind energy farms.

7.4. Index

This thesis researchers the role that phase transition kinetics and flow modes have on the intimate contact development in laser-assisted automated fibre placement for carbon fibre reinforced polyphenylene sulphide composites.

Chapter 1 introduces wind turbine blades and their structural components, focusing on AFP and CFTP, particularly PPS and CF/PPS. The challenges associated with these technologies and the motivations for this work are presented, including discussions on phase transition kinetics, flow modes, and relevant characterization techniques. The current state of the art is reviewed, research gaps are identified, and the objectives of this thesis are outlined.

Chapter 2 studies the melting kinetics of PPS and CF/PPS using fast scanning calorimetry (FSC). Key phenomena include the variation of melting temperature with heating rate for both isothermal and non-isothermal crystals, the impact of temperature and time on melt memory, and the effect of fibre reinforcement on matrix melting kinetics. A melting kinetics model is developed from experimental data for both materials, which will be integrated into a melting and crystallisation model in Chapter 4.

Chapter 3 examines the non-isothermal crystallisation kinetics of PPS and CF/PPS using FSC and differential scanning calorimetry (DSC). The combination of these techniques allows for analysis across a wide range of heating and cooling rates, enhancing the representativeness of the experimental data for developing a crystallisation model. Both melt and cold crystallisation are studied to account for nucleation effects. A parallel Velisaris-Seferis model is chosen to represent the simultaneous development of primary and secondary crystallisation of PPS. The crystallisation kinetics models will be integrated into the phase transition kinetics model in Chapter 4.

Chapter 4 combines the melting kinetics model (Chapter 2) and the crystallisation kinetics model (Chapter 3) into a phase transition kinetics model for PPS and CF/PPS. The CF/PPS model is validated against experiments using static laser and laser-assisted tape placement equipment. Validation of the PPS model is not possible with laser heating, as PPS is transparent to the infrared laser available in our facilities.

Chapter 5 applies the developed phase transition kinetics model to evaluate its influence on the intimate contact development of thermoplastic composites. The focus is on the temperature range between the glass transition and melting points. Laser-assisted AFP with a self-heated tool is used to produce samples under varying heating and cooling rates, processing temperatures, and placement speeds. Crystallisation and melting during heating and cooling are modelled using the phase transition kinetics model from Chapter 4, and their effects on IC development are studied. The final degree of crystallinity is measured by DSC and compared to the model's predictions for validation. Surface and cross-sectional microscopy are used to assess the degree of intimate contact.

Chapter 6 synthesizes the key findings of this thesis, focusing on the impact of phase transition kinetics and flow modes on intimate contact development in AFP of carbon fibre-reinforced polyphenylene sulphide composites. The chapter summarizes the outcomes of each previous chapter and discusses their implications for producing lighter, stronger, and more sustainable composite structures, particularly in wind turbine blade manufacturing. It also addresses research limitations, such as model validation challenges, and offers recommendations for future work, including refining models and exploring new materials or techniques. This chapter provides a concise roadmap for further research and potential industrial applications.

8. ESR 7: Huzaifa Syed

8.1. Thesis title

The title of this thesis is: **Optimization Of Dynamic Cable Configuration For FOWT's And Farms**

8.2. Delivery date (or expected delivery date)

The delivery date for this thesis is: December 2024.

8.3. Abstract

The global transition to sustainable energy has underscored the importance of offshore wind power as a critical component in achieving renewable energy targets. Floating offshore wind turbines (FOWTs) have emerged as a significant innovation, enabling the harnessing of wind energy in deeper waters where wind resources are more abundant and consistent. This thesis focuses on the optimization of dynamic cable configurations for FOWTs, which are essential for transmitting electricity from turbines to the grid while enduring the challenging marine environment. Using the open-source software MoorDyn, coupled with Open-FAST. steep wave dynamic cable configurations for different environmental scenarios are modelled and validated against industry-standard tool OrcaFlex. The primary configuration explored is the steep wave configuration, known for its ability to mitigate fatigue and mechanical stresses in dynamic environments. The results demonstrate that this approach provides accurate predictions of the structural behaviour of dynamic cables, offering a reliable and cost-effective tool for dynamic cable modelling in offshore wind applications. The thesis explores cost optimization strategies for the lazy wave dynamic cable configuration, a widely used design in floating wind farms. Utilising the OpenMDAO framework integrated with OrcaFlex and the COBYLA (Constrained Optimization BY Linear Approximations) algorithm, the research identifies configurations that reduce costs while maintaining high performance and reliability. The findings indicate that optimised lazy wave configurations with optimum number of Buoyancy modules can significantly lower installation and maintenance expenses, thereby improving the economic viability of offshore wind projects. The thesis further investigates the feasibility and optimization of suspended cable systems for deep-water FOWTs. Detailed case studies reveal that suspended cables, supported by buoyancy modules, can be effectively deployed in deep-water environments, offering advantages such as reduced cable tension and enhanced durability. These insights provide valuable guidelines for the design and implementation of suspended cables in challenging offshore conditions. A comprehensive trade-off analysis examines the impact of marine growth on deep-water suspended cables. Marine growth, which increases drag and weight on submerged structures, poses significant challenges to the longevity and performance of dynamic cables. The analysis compares the economic feasibility and reliability of optimising cables for the start of their operational life versus the end of their life, considering the effects of marine growth. It was found that optimising for the end of life, where marine growth is most impactful, can provide a more economically viable and reliable solution for maintaining cable integrity. The study also emphasises the importance of selecting appropriate buoyancy sizes and implementing effective maintenance strategies to ensure long-term cable performance and reduce lifecycle costs.

8.4. Index

1. Introduction

This section provides an overview of the global shift towards renewable energy, emphasising the critical role of offshore wind power in addressing climate change and reducing carbon emissions. The motivation behind the research is to address the unique challenges posed by floating platforms, particularly in the design and optimization of dynamic cables. The section also discusses the increasing demand for reliable and cost-effective solutions in offshore wind energy, setting the stage for the research focus on dynamics. The primary objectives of the thesis include the optimization of dynamic cable configurations for FOWTs to enhance reliability, performance, and economic viability. It outlines the specific goals of the research, such as modelling dynamic cables using advanced simulation tools, optimising cable designs to reduce costs, and investigating the impact of environmental factors like marine growth.

2. Literature Review.

This section introduces various types of dynamic cable configurations used in floating offshore wind farms, including the Simple catenary, steep wave, lazy wave, Tethered lazy wave, and suspended, configurations. It explores the engineering principles behind these configurations, explaining how they are designed to withstand the dynamic movements of floating platforms and harsh marine environments. The section also reviews recent advancements in cable materials and construction techniques that enhance durability and performance. Challenges such as cable fatigue, mechanical stresses, and installation complexities are discussed, along with potential solutions and innovations. This review provides a background for the subsequent chapters on modelling and optimising dynamic cables. It also examines the current market trends and future projections for floating offshore wind technology, highlighting the rapid growth and increasing investment in this sector. Identifying the key challenges facing the floating offshore wind industry, particularly in relation to dynamic cable design and optimization. Issues such as cable fatigue, installation complexities, and the impact of marine growth are discussed in detail.

3. Modelling Methodology of Dynamic Cable Configurations Using MoorDyn

The modelling of dynamic cable configurations for floating offshore wind turbines (FOWTs) is a critical aspect of ensuring the reliability and efficiency of power transmission in offshore wind farms. This section outlines the methodology used to model dynamic cable configurations, specifically focusing on the integration of MoorDyn with OrcaFlex, validated through a series of simulations and analyses. The chosen configuration for this study is the steep wave configuration, which is known for its effectiveness in managing the mechanical stresses and fatigue that cables endure in dynamic marine environments. The modelling approach involved defining the physical properties of the cable, such as its stiffness, mass, and damping characteristics, as well as the environmental conditions, including wave height, wind speed, and current velocity. The simulations were conducted under various scenarios to assess the cable’s performance and durability across different operational conditions. The results were validated against the outputs from OrcaFlex, demonstrating a high degree of correlation, which confirms the reliability of the modelling approach. In conclusion, the study highlights the effectiveness of the steep wave configuration in managing the complex dynamics of floating offshore wind turbines. The combination of MoorDyn and OrcaFlex offers a powerful tool set for modelling and optimising dynamic cable configurations, ensuring their reliability and efficiency in offshore wind applications. These findings contribute significantly to the design and operational strategies for floating offshore wind farms, providing a solid foundation for future research and development in this field.

4. Cost Optimization of Lazy Wave Dynamic Cable Configuration for Floating Offshore Wind Turbines

This chapter emphasises the economic significance of optimising dynamic cable configurations in offshore wind farms. It discusses the high costs associated with cable installation, maintenance, and replacement, highlighting the need for cost-effective solutions. The section explores the potential savings that can be achieved through optimization, including reduced material usage, minimised installation time, and extended cable lifespan. It also considers the broader economic implications for the offshore wind industry, such as improving the competitiveness of floating wind projects and facilitating their wider adoption. The importance of balancing cost with performance and reliability is a key theme in this discussion. It also details the methodology used for optimising the lazy wave dynamic cable configuration, focusing on the integration of the OpenMDAO framework with OrcaFlex and the COBYLA algorithm. The methodology is designed to identify configurations that minimise costs while maintaining high performance, providing a practical approach to achieving economic efficiency in offshore wind projects. This methodological framework is critical for the case studies that follow. Different configurations of the lazy wave dynamic cable are analysed, with the optimization process identifying the most cost-effective designs. The results demonstrate significant reductions in installation and maintenance costs, along with improvements in cable performance and reliability. The section also discusses the sensitivity of the optimization outcomes to various parameters, such as water depth, platform motion, and environmental loads. These case studies provide concrete examples of how optimization can lead to tangible benefits in offshore wind projects, offering valuable insights for industry practitioners.

5. Suspended Cables for Deep Water Floating Offshore Wind Turbines

This chapter introduces the concept of suspended cable systems, which are used to connect floating offshore wind turbines in deep-water environments. The section explains the design principles behind suspended cables, including their use of buoyancy modules to maintain cable shape and reduce tension. It also discusses the advantages of suspended cables in deep water, such as their ability to accommodate large vertical motions and their potential for reducing mechanical stresses. The introduction for a detailed analysis of the feasibility and optimization of suspended cables, highlighting their relevance to the future development of deep-water offshore wind projects. It further provides a comprehensive analysis of the feasibility of using suspended cable systems in deep-water offshore wind farms. The study examines various factors that influence feasibility, including water depth, seabed conditions, and environmental forces such as waves and currents. The section also discusses the technical challenges associated with suspended cables, such as managing cable tension and preventing excessive sagging. Case studies of existing projects are reviewed to illustrate best practices and lessons learned. The feasibility analysis is crucial for understanding the practical considerations and potential obstacles in deploying suspended cables in real-world scenarios. It elaborates on the optimization strategy used in earlier chapters for suspended cable configurations, focusing on enhancing their durability and performance in deep-water environments. The discussion includes techniques for optimising the placement of buoyancy modules, adjusting cable geometry, and selecting appropriate materials to withstand harsh marine conditions. The section also considers the trade-offs between different design options, such as balancing cable flexibility with the need for stability and strength. Optimization case studies are presented to demonstrate the practical application of these techniques, providing insights into how suspended cables can be effectively designed for deep-water offshore wind farms. This section builds on the feasibility studies to offer solutions for overcoming technical challenges. The case studies highlight the design choices, installation processes, and operational performance of these systems, providing valuable insights into their practical applications. The section also discusses the challenges encountered during installation and operation, along with the strategies used to address them. Lessons learned from these case studies are summarised, offering guidance for future projects. This practical perspective complements the theoretical analysis and optimization techniques discussed earlier, bridging the gap between theory and real-world application.

6. Trade-off Analysis of Marine Growth on Deep Water Suspended Cables

This chapter examines the impact of marine growth on suspended cables in deep-water offshore wind farms. Marine growth, which includes the accumulation of organisms such as barnacles, algae, and mussels on submerged structures, can significantly increase the weight and drag on cables, affecting their performance and lifespan. The section discusses the biological and environmental factors that contribute to marine growth and the challenges they pose for cable maintenance and reliability. Case studies and experimental data are reviewed to illustrate the effects of marine growth on cable dynamics and structural integrity. Understanding this impact is essential for developing strategies to mitigate the negative effects of marine growth. The aim is to provide a trade-off analysis comparing the optimization of cables for the start of their operational life versus the end of their life, considering the cumulative impact of marine growth. The analysis explores different design strategies and maintenance approaches, evaluating their effectiveness in maintaining cable performance over time. The section discusses the advantages and disadvantages of optimising for start-of-life conditions, where cables are initially free of marine growth, versus end-of-life conditions, where significant growth has occurred. The findings offer insights into the most cost-effective and reliable strategies for managing marine growth, balancing the need for initial performance with long-term durability.

9. ESR 8: Rahul Chitteth Ramachandran

9.1. Thesis title

The title of this thesis is: **Installation and decommissioning of Large Floating Offshore Wind Farms: The role of towing operations**

9.2. Delivery date (or expected delivery date)

The delivery date of this thesis was: 31 December 2023

9.3. Abstract

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.

9.4. Index

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:

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 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 is published in the Journal of Marine Science and Engineering.

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 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 will be presented at the Deepwind 2024 conference in Norway and has been submitted to the Journal of Physics.

10. ESR 9: Omer Khalid

10.1. Thesis title

The title of this thesis is: Techno-economic assessment for robotics-driven inspection of floating offshore wind farms

10.2. Delivery date (or expected delivery date)

The delivery date for this thesis was: August 2024

10.3. Abstract

The floating offshore wind farm (FOWF) industry is poised for substantial growth, necessitating efficient operations and maintenance (O&M) practices to overcome challenges such as restricted weather windows, long-distance logistics, and the need for precise maneuvering and high-quality data acquisition. This thesis explores integrating robotic systems into FOWF-specific O&M from a techno-economic perspective, revealing several key insights. Advancements in battery technology enhance the potential of battery-powered remotely operated vehicles (ROVs) and unmanned aerial vehicles (UAVs) for autonomous offshore logistics, with ROVs showing promise for underwater cable inspection and burial despite challenges in increasing their technological readiness levels (TRLs) and operational range. Autonomous surface vehicles (ASVs) offer improved safety and efficiency for longer missions and harsh weather conditions, while advanced sensors and data acquisition technologies, such as thermographic cameras, provide feature-rich data as compared to traditional visual inspections. AI and data-driven approaches can improve resource management and asset availability through automated data gathering and retrieval, and modular designs of climbing robots and UAVs equipped with mission-specific sensors can further aid various inspection tasks.

This thesis explores the use of the WOMBAT tool, and devises a cost estimation framework for an offshore multi-robot platform (MRP) inspecting a 1.5GW FOWF highlighting potential cost and inspection time reductions. Furthermore, key variables are identified that impact operational expenditure (OPEX) and time-to-completion, suggesting initial utilization of fewer MRPs to balance costs and inspection duration. Simulations incorporating unmanned surface vehicles (USVs), ROVs, and UAVs for FOWF inspections indicate long-term cost savings from early adoption of higher autonomy levels, with real options analysis (ROA) emphasizing flexible investment approaches to adapt to market dynamics. The ROA demonstrates the strategic advantage of adopting higher autonomy levels earlier in a project's lifecycle, emphasizing the importance of flexible investment approaches in the face of market and technological uncertainties.

Performance evaluation using visible and thermal imaging shows significant benefits, with thermal imaging effectively identifying deeper structural erosion and combined imaging modalities assessing damage severity. A model-based systems engineering (MBSE) framework for deploying robotics-driven FOWF inspections integrates system requirements with software and hardware design, facilitating end-to-end traceability and coherence. Identifying potential deployment roadblocks, such as system requirements and architecture, along with prioritizing risk mitigation efforts through failure modes and effects analysis (FMEA), underscores the importance of advanced robotics and systems engineering methodologies. This thesis supports the integration of these methodologies to enhance the integrity and reliability of FOWF infrastructure, and hence, contributing to the overall economical and environmental sustainability efforts.

10.4. Index

Chapter 2: Applications of robotics in floating offshore wind farm operations and maintenance: Literature review and trends

Abstract: Marine operations required to transfer technicians and equipment represent a significant proportion of the total cost of offshore wind. The profile of sites being considered for floating offshore wind farms (FOWFs), e.g., further from the shore and in harsher environments, indicates that these costs need to be assessed by taking into account the maintenance requirements and restricted weather windows. There is an immediate need to investigate the potential use of robotic systems in the wind farm's operations and maintenance (O&M) activities, to reduce the need for costly manned visits. The use of robotic systems can be critical, not only to replace repetitive activities and bring down the levelised cost of energy but also to reduce the health and safety risks by supporting human operators in performing the desired inspections. This paper provides a review of the state of the art in the applications of robotics for O\&M of FOWFs. Emerging technology trends and associated challenges and opportunities are highlighted, followed by an outline of the agenda for future research in this domain.

Chapter 3: Cost-benefit assessment framework for robotics-driven inspection of floating offshore wind farms

Abstract: Operations and maintenance (O\&M) of floating offshore wind farms (FOWFs) poses various challenges in terms of greater distances from the shore, harsher weather conditions and restricted mobility options. Robotic systems have the potential to automate some parts of the O&M leading to continuous feature-rich data acquisition, operational efficiency, along with health and safety improvements. There remains a gap in assessing the techno-economic feasibility of robotics in the FOWF sector. This paper investigates the costs and benefits of incorporating robotics into the O\&M of a FOWF. A bottom-up cost model is used to estimate the costs for a proposed multi-robot platform (MRP). The MRP houses unmanned aerial vehicle (UAV) and remotely operated vehicle (ROV) to conduct the inspection of specific FOWF components. Emphasis is laid on the most conducive O\&M activities for robotization, and the associated technical and cost aspects. The simulation is conducted in WOMBAT, where the metrics of the incurred operational expenditure (OPEX) and inspection time are calculated and compared with those of a baseline case consisting of crew transfer vessels, rope-access technicians and divers. Results show that the MRP can reduce the inspection time incurred but this reduction has dependency on the efficacy of the robotic system and the parameterization (e.g., cost elements, inspection rates) of the FOWF. Conversely, the increased MRP day-rate results in a higher annualized OPEX. Residual risk is calculated to assess the net benefit of incorporating the MRP. Furthermore, sensitivity analysis is conducted to find the key parameters influencing the OPEX and the inspection time variation. A key output of this work is a robust and realistic framework which can be used for cost-benefit assessment of the MRP systems for specific FOWF activities.

Chapter 4: Informed decision-making for investment in robotics-driven inspection of floating offshore wind farms: A real options approach

Abstract: The inspection and maintenance of floating offshore wind farms presents significant challenges due to their remote locations and harsh environments. Utilizing robotics can be an effective solution for enhancing the efficiency and safety of these operations. There is an increased focus on the deployment of autonomous robotic systems for inspecting the critical components of floating offshore wind farms, such as the turbine blades, mooring lines, and export cables. However, the integration of robotic systems for offshore inspection involves significant upfront investments, extended deployment timelines, and uncertainties arising from the technology readiness levels of such systems. An informed investment approach based on the insights derived from extensive cost assessment can allay these concerns. This research focuses on the devising of an informed investment decision-making process, leveraging real options analysis as the basis. Four different scenarios ranging from no autonomy to full-scale autonomy have been simulated in a cost model and the option values associated with various decision paths have been calculated. The model aims to determine the optimal investment approach and timing for the deployment of robotic inspection systems in a way to lower the incurred costs for each decision path. Results show that the transition to full-scale autonomy earlier in the project's lifecycle can save up to 24% in the incurred costs.

Chapter 5: UAV-based automated detection of wind turbine blade damages: Sequential evaluation of model training with thermal analysis

Abstract: Automated inspection of wind turbine blades using unmanned aerial vehicles have been gaining traction in recent years. It can help to identify defects at an earlier stage resulting in preventive maintenance and mitigating risks of turbine downtime and catastrophic failures. In this work, we present a sequential evaluation of model training with thermal analysis applied on the imagery dataset acquired from an operational wind farm. A convolutional neural network has been trained to conduct binary classification on the visible (RGB) images while temperature differential analysis is conducted on the thermal images. The outputs

from the two techniques are evaluated in terms of their detection performance and computational cost. Results demonstrate that the model training can result in effective detection with a precision of up to 76%, although a sparse training dataset can limit the performance of the model. Furthermore, applying thermal differential analysis on the detected damaged regions can help in identifying most of the defects that have penetrated the blade surface.

Chapter 6: Development of a systems engineering framework for the deployment of robotics-driven inspection of floating offshore wind farms

Abstract: Technological innovations in the marine sector often suffer from a slow uptake and struggle to achieve the technical and commercial readiness required for mass scale adoption. The use of robotic systems for the inspection of floating offshore wind farms is one such example. This paper aims to leverage model based systems engineering to conceptualise and assess the risks associated with such systems. The paper demonstrates how MBSE facilitates end-to-end traceability and coherence from system requirements through design, deployment, and operations. The methodology encompasses the identification of system requirements, relating them to software and hardware aspects of system design, and leveraging expert elicitation for estimating cost drivers based upon the COSYSMO model. Additionally, a Failure Mode and Effects Analysis (FMEA) is conducted to capture the inherent uncertainty at the sub-system level. Key findings highlight the holistic nature of system requirements, the effectiveness of MBSE in delineating software-hardware interfaces, and the identification of potential deployment roadblocks. The FMEA results provide crucial insights for prioritizing risk mitigation efforts and enhancing system reliability. This framework offers a structured approach to addressing the complex challenges in developing and deploying autonomous inspection systems for FOWFs, potentially leading to more cost-effective and efficient strategies.

11. ESR 10: Omar Ibrahim

11.1. Thesis title

The title of this thesis is: **Dedicated floating offshore wind to hydrogen: Coupling possibilities, system design, and techno-economic assessment**

11.2. Delivery date (or expected delivery date)

The delivery date for this thesis is December 2024

11.3. Abstract

To achieve the net-zero emissions goal, a major up-scale in green hydrogen needs to be achieved; this will also facilitate use of renewable electricity as a source of decarbonised fuel in hard-to-abate sectors such as industry and transport. Nearly 80% of the world's offshore wind resource is in waters deeper than 60 m, where bottom-fixed wind turbines are not feasible. This creates a significant opportunity to couple the high capacity factor floating offshore wind and green hydrogen. The focus of the thesis is dedicated around dedicated floating offshore wind solely for hydrogen production. This is investigated through three major topics; (i) coupling possibilities, (ii) system design, and (iii) techno-economic assessments.

For the coupling possibilities, three coupling configurations were examined; (i) centralised onshore electrolysis, (ii) decentralised offshore electrolysis, and (iii) centralised offshore electrolysis. The configuration design is based on variables including for: electrolyser technology; floating wind platform; and energy transmission vector (electrical power or offshore hydrogen pipelines). Offshore hydrogen pipelines are assessed as economical for large and distant farms. The decentralised offshore configuration, employing a semi-submersible platform could accommodate a proton exchange membrane electrolyser on deck; this would negate the need for an additional separate structure or hydrogen export compression and enhance dynamic operational ability. It is flexible; if one electrolyser (or turbine) fails, hydrogen production can easily continue on the other turbines. It also facilities flexibility in further expansion as it is very much a modular system. Alternatively, less complexity is associated with the centralised offshore typology, which may employ the electrolysis facility on a separate offshore platform and be associated with a farm of spar-buoy platforms in significant water depth locations.

For the system design, an islanded semi-submersible 15 MW floating offshore wind turbine system is developed and modelled for decentralised hydrogen production. The methodology proposed is based on removing the grid side converter, potentially saving costs and improving efficiency via fewer conversion steps. As the system is off-grid, there is no need to meet grid compliance requirements. This saves a control layer, compared to the classic route of electricity export. The scope emphasises on minimal equipment and innovative strategies for direct coupling. A future polymer electrolyte membrane electrolyser single cell and a 15 MW electrolyser system were developed and dynamically modelled in Matlab/Simulink. The entire numerical model is made freely available to the scientific community to facilitate collaborative research. Various control levels validated the model's dynamic response. The reference model was then interrogated to investigate relative sizing of components and the potential role of emerging technologies. Findings suggests heavy transformers might be replaced with a lighter power tapping solution. Despite the enhanced production efficiency oversizing an electrolyser might suggest, it was found it might not be justified from an economic perspective. Sizing of an integrated battery system was also investigated. Results suggest that even with several MWhs-sized batteries, they're insufficient to robustly support a steady hydrogen production at downtimes.

For the techno-economic assessment, it was attempted to answer the question if large-scale dedicated floating wind can offer a cost-competitive electrolytic hydrogen. This was conducted by examining different configurations: (i) centralised onshore, (ii) decentralised offshore with repurposed pipelines, (iii) decentralised offshore with new pipelines, (iv) centralised offshore with repurposed pipelines, and (v) centralised offshore with new pipelines. The analysis incorporated a generic bottom-up modelling approach, where a range of future projections of the levelised cost of energy from floating offshore wind is considered through

three time horizons: 2025, 2030, and 2050. The levelised cost of hydrogen (LCoH) is then estimated at 4 different generic offshore distances: 55 km, 100 km, 150 km, and 200 km, with a generic farm size of 2 GW. Results suggest that for 2025, the onshore configuration is deemed the most cost-competitive one. The decentralised offshore configuration with repurposed offshore pipelines can start competing at a 150 km offshore distance by 2030. By 2050, the latter would be arguably the most economical route for all floating offshore distances. The analysis suggests floating wind could contribute to potentially cost-efficient hydrogen with continuous developments in technologies, as well as robust policy frameworks dictating the future hydrogen demand.

11.4. Index

This five-chapter thesis presented as a thesis by publication investigates dedicated floating offshore wind as a route for hydrogen production, this includes for examining the coupling configurations, direct integration of an electrolyser on a floating wind turbine, and assessing the techno-economics of the potential coupling configurations. Except Chapter 1 (Introduction) and Chapter 5 (Conclusion), each chapter corresponds to a paper and can be read independently with corresponding appendices and references.

At the time of production of this thesis (August 2024) chapter 2 is published in an international journal following peer-review, while chapters 3 and 4 are currently under preparation for submission to an international journal. Accordingly, each chapter in this thesis closely resembles the published or submitted manuscripts bar some minor modifications including harmonising abbreviations and reducing repetition to improve the reading experience. The link between each chapter and a summary of chapters 2 to 5 are given as follows:

Chapter 2: Dedicated large-scale floating offshore wind to hydrogen: Assessing design variables in proposed typologies

This chapter aims to explore the coupling configurations between floating wind and hydrogen production and provide the reader with a suitable background to the thesis. This chapter includes an in-depth study of the system components, relevant on-ground projects, as well as proposing three main coupling routes. To simplify the assessment, this chapter undertakes a systems approach to break down the bigger system into individual system components. Perspectives on the possibility of having an onshore electrolysis versus offshore, with a comparison between high voltage cables and offshore pipelines are highlighted. These provide the background for further investigations documented in the following chapters. The chapter develops a framework for what to consider in each of the proposed three main coupling routes.

Chapter 3: A reference islanded 15 MW floating offshore wind turbine system dedicated for hydrogen production

Chapter 3 closely investigates one of the main coupling routes proposed in chapter 2, which is the decentralised offshore electrolysis route. This chapter presents a reference numerical model for a 15 MW off-grid floating offshore wind turbine producing only hydrogen in a decentralised configuration. System design variables were discussed, shedding light on the potential modifications required to the standard components in a (floating) offshore wind turbine system to transform it into a hydrogen producing one. Perspectives on integrating a battery system supporting a consistent hydrogen production with various sizing approaches are discussed. The direction of having large-scale electrolysis systems is explored to investigate how direct coupling with modern high rating wind turbines happens in a dedicated setting.

Chapter 4: Can dedicated floating wind achieve cost-efficient hydrogen?

Chapter 4 techno-economically investigated the route of producing hydrogen from dedicated large-scale floating offshore wind farms. The chapter examined the three main configurations (onshore centralised, offshore decentralised, as well as offshore centralised) that were proposed earlier in chapter 2. The offshore configurations considered both repurposed and new offshore pipelines as the hydrogen export vector. The modelling incorporated a generic bottom-up approach for promising levelised cost of energy (LCoE) anticipated for floating wind potential sites. Perspectives on which coupling route might be competitive in different horizons (2025, 2030m and 2050) are discussed. The analysis suggests floating wind could contribute to potentially cost-efficient hydrogen with continuous developments in technologies, as well as robust policy frameworks dictating the future hydrogen demand.