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Dynamic analyses on multiple arrays of floating offshore wind farm using OC5-DeepCwind floater with shared moorings

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Abstract. Mooring system design is critical for the deployment of floating offshore wind farms (FOWF). As the pursuit of offshore wind energy ventures into deeper waters, the application of floating structures is becoming increasingly feasible. Ensuring the stability and efficiency of these structures through robust mooring systems is essential. The paper examines various mooring configurations, evaluates their resilience against a range of environmental conditions, and develops optimized designs tailored for FOWF scenarios. A leap forward for exploiting wind resources in offshore environment setting is represented by FOWFs, which differ from fixed installations by being tethered to the ocean floor, providing the necessary buoyancy and stability for operation in deepwater locales. The key goal of this paper is to design and evaluate mooring systems that maintain both the stability and functional effectiveness of FOWFs, with considerations for environmental loads, coupled dynamic analyses, feasibility, and performance resilience. The paper also investigated existing mooring approaches in the context of FOWFs, analyzed environmental factors affecting mooring performance, used computational simulations to appraise diverse mooring concepts, evaluated the performance of various mooring arrangements, and suggested advancements in mooring solutions suitable for FOWFs. The results showed that the shared mooring systems with taut lines are feasible for 2, 4, 6 and 8 turbines in multiple arrays of FOWF in terms of stability and efficiency. The paper concluded that shared mooring systems are a viable and promising solution for FOWFs in offshore settings at water depths of 200 m.

Keywords: coupled dynamic analysis; floating offshore wind farms; mooring line failure; shared mooring

1. Introduction

In recent years, global warming has emerged as a pressing concern, urging world leaders to address the escalating air pollution and extreme weather events attributed to greenhouse gas (GHG) emissions. The relentless march of industrial and technological progress, aimed at enhancing human civilization, has only exacerbated these challenges (Cozzi and Gould 2021, Wright 2023).

The oil and gas industry, predominantly influential in the energy sector, faced significant upheaval during the 2020-2021 period due to the COVID-19 pandemic-induced lockdowns

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worldwide and uncertainties surrounding OPEC+ production cuts. These events resulted in supply glut volatility, cyclical oil price instability, reduced oil demand, and necessitated a recalibration of global economies. Thus, ensuring access to secure, reliable, and affordable energy becomes imperative, as it underpins sustainable living standards and fosters societal well-being, including prolonged health and prosperity.

According to GWEC (2023), the total new global installations of offshore wind market will have a strong growth from 11% to 23% by 2027 with CAGR of 15%. With such a promising growth rate, the floating offshore wind power will be contributing over 7% to global energy supply. Currently, there are four commercial floating offshore wind farm projects successfully installed and are operational worldwide, namely, Hywind Scotland (Aliyar *et al.* 2022, Mackinnon and Afewerki 2022), WindFloat Atlantic (Lucas *et al.* 2022), Floatgen BW Ideol (Pham *et al.* 2019), and Kincardine Offshore Wind Farm (Edwards *et al.* 2023). Research studies by Xu *et al.* (2024) and Edwards *et al.* (2023) investigated that the development of global floating offshore wind turbines and farms are still in their early stages and have not yet fully accomplished widespread commercial viability, primarily due to the challenges of cost controls across all aspects from design until execution to operation and maintenance, government initiatives and incentives and people skillsets.

Research works were done on case scenarios such as multiple floating offshore wind turbines (FOWTs) sharing on a single anchor point by Xu *et al.* (2024) with multiple loadings from different directions connecting to different FOWTs, and Liang *et al.* (2023) highlighting on the shared mooring line that connects two bodies of FOWTs in an array of four wind turbines in FOWF. From those research works, they can be concluded that both the shared anchors and mooring lines have been simulated for the design configuration of an array with two wind turbines and resulted with benefitting the FOWF with optimizing the mooring systems and reducing the number of anchors. They used this novel solution to tackle the high expenditure costs for developing FOWF. They discovered that having shared anchor points in the mooring system reduced both the number and length of the needed mooring lines. Review of the literature suggests that no research has been carried out to study on the development of FOWF with combined configuration of sharing mooring lines and anchors to improve the efficiency of FOWF with 6 or 8 wind turbines. There is a need to study by establishing the relationship of sharing mooring system and its stationkeeping performance for 2 wind turbines and to further studies on what are the effects and performances to the shared mooring lines and shared anchors with more complexities of 6 and 8 wind turbines in multiple arrays of FOWF. It is also a worth to consider on what will happen to the large complexities of multiple FOWTs in an array with failure scenarios of a shared line broken and damage to the shared anchor in the offshore Malaysian water.

The purpose of this research is to study the effects of an array with 2 wind turbines and more complexities of 6 and 8 wind turbines in multiple arrays of FOWF on the performance of mooring system with the combination of shared mooring lines and shared anchor points. Then, the failure scenarios were analyzed to assess the efficiency, operability, and robustness of the shared mooring system. The research was undertaken by carrying out simulation analyses by using the industry software for mooring analysis, OrcaFlex and hydrodynamic response in OrcaWave, while the modeler for FOWT floating structure in DNV Sesam Genie module.

2. Literature review

2.1 Types of floaters used in FOWT

FOWT has become a pivotal technology for harnessing wind energy in deepwater regions, where traditional fixed-bottom turbines are impractical. The evolution of FOWT involves the development of various types of floaters, each with unique design principles, advantages, and challenges. This section delves into the different types of floaters used in FOWT, focusing on spar-buoy, semi-submersible, and tension-leg platforms, and relates these to the OC5 semi-submersible platform.

Spar-buoy platforms are renowned for their stability in deep waters due to their deep draft structure, which provides substantial ballast. This design effectively counteracts the turbine's overturning moments caused by wind and waves. Ma *et al.* (2015) conducted dynamic response analyses on spar-type FOWT, demonstrating their robustness under wind-wave-induced motions. The spar-buoy's deep draft ensures minimal vertical and horizontal movement, making it ideal for stable power generation.

Semi-submersible platforms offer a versatile and balanced solution between stability and ease of deployment. These platforms consist of multiple columns connected by horizontal pontoons, which provide buoyancy and stability. Zhao *et al.* (2020) examined the effects of second-order hydrodynamics on large semi-submersible FOWTs, highlighting their capability to withstand harsh ocean conditions while maintaining operational stability. Semi-submersibles are particularly favored for their ability to be towed to the site fully assembled, reducing installation costs and time.

Tension-leg platforms (TLPs) are anchored to the seabed by vertical tendons, providing excellent nonlinear stability with minimal horizontal motion. This design is beneficial in maintaining the turbine's vertical position, crucial for optimal wind energy capture. However, TLPs are complex and costly to install due to the tensioned mooring system. Zhao *et al.* (2022) explored the dynamic response of semi-submersible platforms with TLP characteristics, showing that TLPs can effectively reduce platform motion and enhance stability.

The OC5 project focuses on the validation and enhancement of floating wind turbine designs, specifically the semi-submersible platform. The OC5 semi-submersible is designed to improve upon the OC4 platform by incorporating lessons learned from previous iterations and enhancing stability and performance under various environmental loads. Ariffin and Ali (2021) conducted numerical studies on the stability of the OC5, highlighting improvements in dynamic response and mooring efficiency. The semi-submersible design of OC5 benefits from the stability provided by its multi-column structure and horizontal pontoons. This design minimizes the vertical and horizontal motions, ensuring the turbine operates efficiently even in rough sea conditions. Ferri *et al.* (2022) optimized the mooring system of a 10 MW semi-submersible FOWT, demonstrating the potential for reducing costs and improving performance through shared mooring lines and anchors.

2.2 Array pattern in floating offshore wind farms

FOWTs have gained significant attention due to their potential to harness wind energy in deep waters (Ji *et al.* 2016; Majhi *et al.* 2013). Multiple used of FOWT in an array pattern of these turbines are called as Floating Offshore Wind Farm (FOWF), which is a critical aspect that influences the overall performance and efficiency of the energy harvesting process (Ambühl *et al.* 2014, Xu and Guedes Soares 2023).

The array patterns in FOWF are primarily determined by the type of floating foundations used (Wang *et al.* 2019, Whittaker *et al.* 2020). The three main concepts for floating foundations are spar-buoy, semi-submersible, and TLP (Song *et al.* 2016, Stanisic *et al.* 2019). Variants on these also exist, including the mounting of multiple turbines onto a single floating foundation (Girón *et al.* 2014, Jin *et al*. 2020). The choice of array pattern is influenced by factors such as water depth, wind and wave conditions, and the specific dynamics of the floating platforms (Kakanda *et al*. 2022, Righetti *et al*. 2020).

As the water depth increases, traditional fixed offshore wind turbines become costlier to install and more difficult to construct in deep waters (Xu *et al.* 2019, 2020). In contrast, floating offshore wind turbines are not limited by water depth and can simplify unit lifting (Timmington and Efthimiou 2022, Zhang and Liu 2023). A fixed-bottom turbine will get very expensive in deeper water because of the non-linear power law scaling of support structure costs with water depth. With that comparison of FOWT in shallow water or deepwater, floating systems cost is relatively insensitive to water depth (Lozon and Hall 2023, Xu *et al*. 2024).

The optimization of the floating support structure is of great importance in the preliminary phase of the design process (Goldschmidt and Muskulus 2015, Liang *et al*.,2024). Various numerical tools and optimization approaches have been used for the conceptual design of the support structure for FOWT and FOWF (Hall *et al.* 2022, Liang *et al.* 2023). However, there are limitations preventing the convergence to an optimal floating support structure (Girón *et al*. 2014, Kakanda *et al.* 2022).

There are several challenges that need to be addressed to study the accurate behaviour of floating platforms operating under combined wind-wave environmental conditions (Hannan *et al.* 2021, Jacobson *et al*. 2018, McKenna *et al*. 2021, Quirapas and Taeihagh 2021). With the current technological advancements, the offshore floating multi-turbine platform can be a potential solution to harness the abundant offshore wind resource. Future work should focus on addressing these challenges and further optimizing the design and operation of floating offshore wind farms (BP Energy 2021, Nian *et al*. 2019, Qureshy and Dincer 2020).

In the realm of FOWF, researchers have extensively studied array patterns comprising 2, 3, and 4 FOWTs, specifically those with shared mooring lines (Chemineau *et al.* 2023, Hall *et al.* 2022, Zhang and Liu 2023). However, configurations involving 6 and 8 FOWTs have not been explored in the existing literature. This absence of research on these specific configurations presents a significant research gap. Therefore, these unexplored configurations could be considered for a sensitivity case study in this research endeavor. This approach could potentially yield valuable insights into the optimization of array patterns in FOWTs.

2.3 Theories used in mooring analysis

The theories of mooring analysis are pivotal components in the design of offshore wind turbines, especially for floating offshore wind turbines. These theories integrate several fundamental concepts, including the Morison equation, potential flow theory, and linear Airy wave theory. The Morison equation, a semi-empirical formula, is used to estimate the force exerted by a fluid on a submerged body, such as a mooring line. Ji *et al.* (2016) employed this equation in their comprehensive dynamic analysis of a Floating Production Storage and Offloading (FPSO) system with mooring lines and risers. Their research underscores the significance of considering the dynamic interaction between the mooring lines and the floating structure during the design and analysis process.

Potential flow theory, a simplification of fluid dynamics, is frequently used in the analysis of unsteady, incompressible flow around a body. Jin *et al.* (2020) implemented this theory in their study of multi-floater-mooring systems in regular and irregular waves, demonstrating its utility in intricate hydrodynamic analyses. The linear Airy wave theory, a linear approximation to the propagation of surface waves on a fluid, is extensively used in offshore engineering to model wave behaviour. Zhang and Liu (2023) applied this theory in their coupled dynamic analysis on floating wind farms with shared mooring under complex conditions, emphasizing its relevance in the analysis of offshore wind farms.

Time series domain analysis provides detailed information on the temporal response of mooring systems, capturing dynamic interactions over time. This method is particularly useful for understanding the behaviour of mooring systems under transient and extreme environmental conditions. Ambühl *et al*. (2014) conducted an extrapolation of extreme response for different mooring line systems of floating wave energy converters. Their research offered valuable insights into how these systems behave under severe environmental stresses, contributing to the development of more resilient mooring designs. Similarly, Tabeshpour and Abbasian (2021) performed a numerical time-domain analysis on a semi-submersible platform with sensitivities scenarios of optimum mooring configuration using JONSWAP spectrum. Their study showcased the utility of time-domain analysis in understanding the complex dynamic responses of optimum mooring configurations.

Song *et al.* (2016) investigated the dynamic characteristics between waves and a floating cylindrical body connected to a tension-leg mooring system, revealing the need for sophisticated models to accurately simulate the dynamic behaviour of mooring systems under realistic environmental conditions. This highlights the importance of time series domain analysis in capturing the nuances of mooring system dynamics.

3. Modeling and Analysis for FOWF

This study involves computational modelling and analysis focused on the hydrodynamic responses and dynamic coupled interactions of mooring configurations within FOWF. This section outlines the implemented model, which utilizes dynamic analysis software to simulate environmental loads and floating platform behaviour. It then details the specific mooring configurations studied and the simulations performed to evaluate their effectiveness and performance. The simulation case studies would begin by having a single FOWT model of experimental OC5 DeepCwind floating semisubmersible 5MW wind turbine, while having to station-keeping with a typical mooring system of individual mooring lines and anchors. The case studies will iterate with more complexity of multiple FOWTs and various combinations of shared mooring lines and shared anchor points using the environmental data of offshore Malaysian water. The failure scenarios were selected and simulated based on the failure to the highly tension loaded of a shared mooring line broken and damage to the shared anchor.

3.1 Modelling of FOWT

Computational modelling and analysis were performed for hydrodynamic of the global responses, mooring analysis and dynamic coupled analysis for the combined effects within the system. The simulation case studies of shared mooring system were repeated by varying certain key parameters to identify the effectiveness of the proposed mooring configuration with combinations of shared mooring lines and shared anchors. The modelling of semisubmersible floating offshore wind model is based on the Offshore Code Comparison, Collaboration, Continued, with Correlation (OC5) project under the International Energy Agency (IEA), which the research focused on the validation of offshore wind models (OC5, OC4 and OC3) by comparing the simulated responses of the floating platform to physical wind wave model test and actual measurements. The floating semi-submersible system was tested by the DeepCwind consortium in 2013 at the Maritime Research Institute Netherlands (MARIN) offshore wave basin under combined wind and wave loading (Robertson *et al*. 2017).

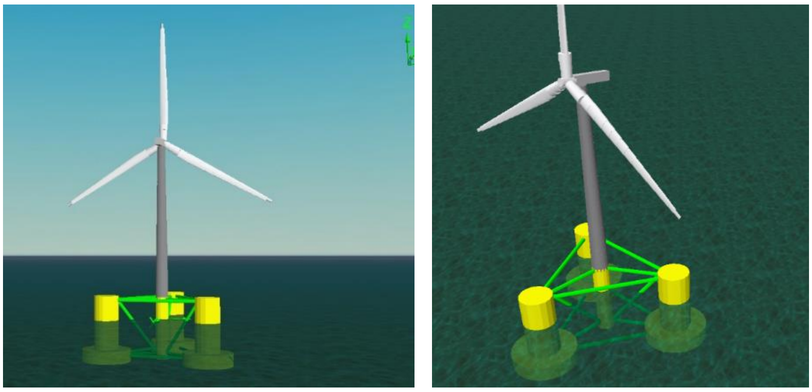


Fig. 1 OC5-DeepCwind FOWT model in OrcaFlex

The OC5 semisubmersible FOWT system design (as shown in Fig. 1) was used throughout the study for the numerical simulations. The key configuration details of OC5 semisubmersible FOWT were extracted, while the other parameters in which the model was referenced to the OC4 semisubmersible DeepCwind system (Robertson *et al*. 2014, Robertson *et al*. 2017).

3.2 Design environmental criteria

The site locations for the FOWT were simulated in offshore Malaysian water, such as Peninsular Malaysia Offshore, Sabah Offshore and/or Sarawak Offshore. The water depth of these offshore site locations was within the range from 60 m to 300 m in utilizing floating wind turbines from the research study by Li *et al.* (2024). In the same study, the wind speed was typically around 4 m/s until the maximum of 8 m/s. The wind catchments are all in the offshore region. Hence, the site location was generalized as a single location for Malaysia at far offshore and selected water depth was around 200 m.

Another important parameter for the analysis is to gather the information on significant wave height that will correspond to the global motion and response to the FOWTs coupling with mooring system. According to Yaakob *et al*. (2016), their study revealed that highest significant wave record was up to 3.0 m and wave period of 6s–7s in the 10-year data average probabilities of occurrence of all wave height-wave period combinations. In comparisons to the Robertson *et al.* (2017), the design environmental criteria is much higher than the data collected from studies on Malaysian waters. Hence, the numerical simulation models of design configurations on shared mooring and shared anchor utilized the design environmental criteria as shown in Table 1, with comparison of the data and benchmark from the experimental study done by Robertson *et al*. (2017) and metocean criteria data on offshore Malaysian waters by Shamsul and Ali (2021).

Environmental data, such as wind, wave, current and tide, have site-specific relationships governing their interactions with the floating facilities. Wind is considered and treated as constant in speed for all directions based on the 1-hour average velocity and the design wind is assumed to refer to an elevation of 10 m above still-water level.

Waves are modelled using the wave height and wave period of the design seastate in Malaysian offshore waters based on the JONSWAP spectrum. Peakedness (gamma value) of the JONSWAP spectrum is considered as per values in the environmental design criteria in Table 1. To assess the dynamic response of the mooring system, a time-domain analysis was conducted in OrcaFlex using a

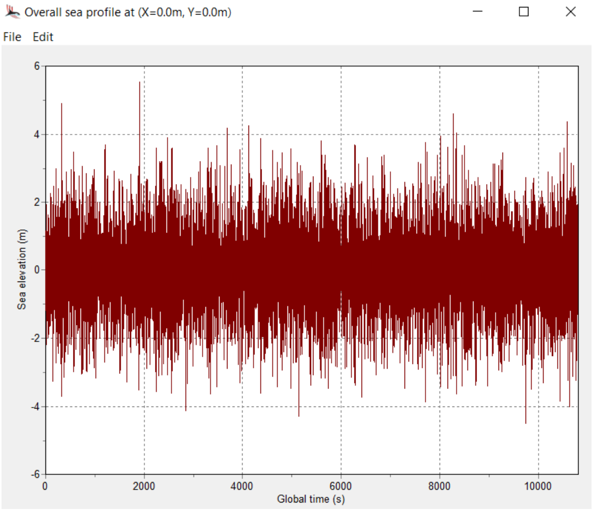


Fig. 2 Regenerated wave profile using JONSWAP spectrum in the 3hr duration

Table 1 OC5 FOWT Design Environmental Criteria

Experiment Environmental Criteria	*Robertson et al.* (2017)	Yaakob *et al.* (2016)	Shamsul and Ali (2021)	Current Study
Return Period	-	10 years	100 years	100 years
Location	Model Test at MARIN	Malaysia	Malaysia	Malaysia
Significant Wave Height, Hs	7 m	3.0 m	4.8 m	4.8 m
Wave period, Tp	8 sec	6-7 sec	10.3 sec	10.3 sec
Current speed, Cs	1 m/s	-	1.15 m/s	1.15 m/s
Wind speed, Ws	13.05 m/s	8 m/s	20.0 m/s	20.0 m/s

3-hour simulation duration. The JONSWAP spectrum was employed to generate irregular, long-crested seastates for input into the model. The resulting regenerated spectrum, as shown in Fig. 2, provides valuable insights into the frequency content of the simulated wave environment and its potential impact on the mooring system's behaviour.

3.3 Modelling approach

The modelling approach for numerical simulations of single baseline FOWT and multiples in array of FOWF with shared moorings and shared anchors configurations is benchmarked and simplified from the research studies by Subbulakshmi et al. (2022) to suit to the present research study. There are 3 main steps from setting up panel model to dynamic analysis until getting the post-processing results in OrcaFlex as presented in Fig. 3. These steps are typically used in the analysis of conventional and individualized mooring system of a FOWT.

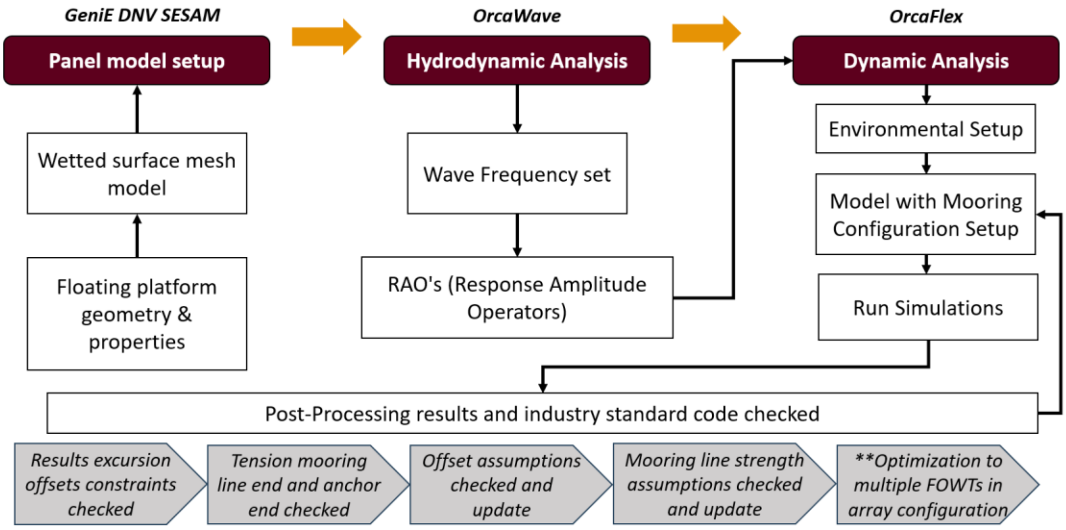


Fig. 3 Modelling Flowchart for numerical simulations of FOWT and FOWF

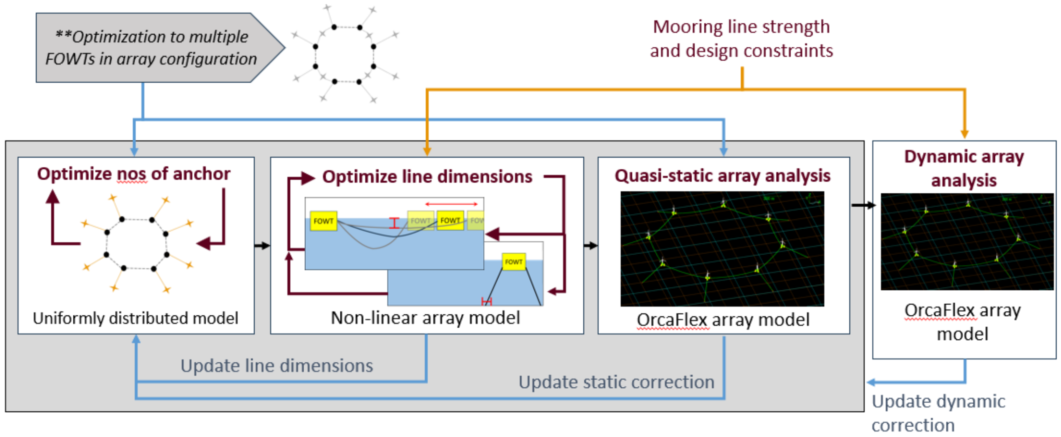


Fig. 4 Numerical simulation workflow for multiple array FOWF

As for analyses on the shared mooring design for multiples in array of FOWF, same steps from flow chart as presented in Fig. 3 can be applied. However, there was a study from Hall et al. (2022), designing an array of FOWF with shared mooring configuration involved more variables and considerations as compared to designing of a conventional and individualized mooring system of a FOWT. The considerations that are used for the shared mooring design of FOWF is to begin with simplification and optimizing the array configuration by reduction of number of anchors, quasi-static optimization of shared mooring line within the array and iterative design adjustment process that uses time-domain coupled dynamics modelling of the full system in OrcaFlex. The methodology of these additional considerations for dynamic analysis of shared mooring design in an array of FOWF is presented in Fig. 4.

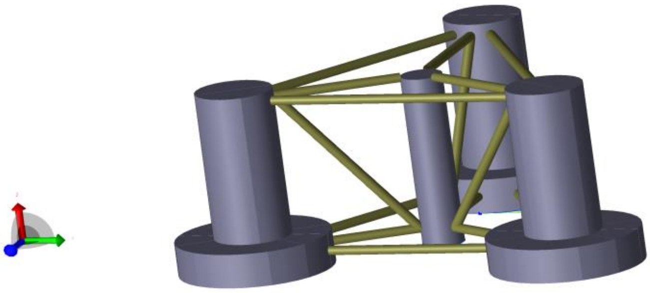


Fig. 5 Geometry model for OC5 DeepCWind using GeniE of DNV SESAM module

Table 2 OC5 FOWT – Weight properties

Model Component	Weight
Floating platform mass, including ballast	12,919 MT
Tower Mass including instrumentation	493.5 MT
Rotor Nacelle Assembly (RNA) mass	544.9 MT
Total	13,958 MT

The panel model of semisubmersible FOWT was performed in GeniE of DNV SESAM module. Panel modelling of OC5 DeepCWind was performed using the geometry from research experimental studies on OC5 and OC4 (Robertson *et al*. 2014, Robertson *et al*. 2017) (see Fig. 5). Then, the wet surface property was assigned for those elements that were submerged in water, in which this wetted surface received pressure loads in the hydrodynamic analysis during the exportation to OrcaWave.

OrcaFlex is an industry software to perform coupled mooring analysis for floating bodies such as semisubmersibles, ship-shaped in offshore industry and renewable floating wind turbines as employed by various studies (Chemineau *et al.* 2023, Santarromana *et al.* 2024). OrcaFlex have included diffraction analysis within its own module namely OrcaWave, which uses potential flow theory to compute both first-order motion of RAOs and second order quadratic transfer functions (QTFs) (Orcina 2023). OrcaFlex relies on hydrodynamic tables for the floating structure inputs. OrcaFlex has the capability to model multi-body dynamics as implemented by Pillai *et al*. (2022).

3.4 Hydrodynamic analysis

After the panel modelling done in Genie of DNV SESAM module, the model was exported into OrcaWave for hydrodynamic analysis, which used potential flow theory to compute first-order response amplitude operators (RAOs). Design inputs used in OcraWave are listed in Table 3. The OC5 FOWT hydrodynamic analysis calculation was performed with OrcaWave software. Wave periods from 3s until 60s were studied for wave heading direction 0 deg to 180 deg. The first-order motion was computed in the frequency domain. This produced the RAOs in 6 DOFs (surge, sway, heave, roll, pitch and yaw).

Table 3 OC5 FOWT – Modeling Parameters

Parameter	Value
Water Density	1025 kg/m^3
Water Depth	200 m
Wave Period (Total 40 sets)	3s, 4s, 5s, 6, 7s, 8s, 9s, 10s, 11s, 12s, 13s, 14s, 15s, 16s, 17s, 18s, 19s, 20s, 22s, 24s, 26s, 28s, 30s, 35s, 40s, 45s, 50s, 55s, 60s.
Wave Heading	0 deg, 15 deg, 30 deg, 45 deg, 60 deg, 75 deg, 90 deg, 105 deg, 120 deg, 135 deg, 150 deg, 165 deg, 180 deg

In the field of naval architecture, a RAO is an engineering statistic that are used to determine the likely behaviour of a floating platform when operating at sea. RAOs are usually obtained from models or proposed floating platform designs tested in a model basin or from running a specialized numerical computer program, often both. RAOs are usually calculated for all ship motions and for all wave headings.

RAOs are effectively transfer functions used to determine the effect that a sea state will have upon the motion of a floating platform through the water. Generation of RAOs allows the simulation study to determine the modifications to a floating platform design and to provide certain assurances about the behaviour response of a proposed floating platform design. RAOs reported in translational and rotational amplitudes in the form of six degrees of freedom (DOF). Displacement in translational RAOs amplitudes are amplitudes due to wave of unit amplitude. Displacement in rotational RAOs are amplitudes in degrees due to wave of unit amplitude.

3.5 Mooring analysis

OrcaFlex is an industry software commonly used in conventional offshore floating platform simulations for mooring and stationkeeping. OrcaFlex is used to perform modelling, typical load cases considerations and stationkeeping results interpretation for the analysis of the mooring design of floating platform. Mooring system analysis has been performed to predict the extreme line tensions of the proposed mooring configuration under the extreme directional metocean data.

The responses are then checked against allowable values to ensure adequate strength of the current system. Time domain approach has been used to perform coupled simulations of mean, low, and wave frequency vessel and mooring system responses. Orcaflex solves the general equations of motion for the combined mean, low, and wave frequency responses of the vessel, mooring lines. The low frequency damping from the vessel and mooring lines are internally generated in the simulation. Also, the coupling between the vessel and the mooring system can be fully accounted. In other research studies of FOWT (Shamsul and Ali 2021, Wendt *et al*. 2013), the same simulation methodology is being applied to the mooring design on FOWT. Hence, OrcaFlex will be applied for the design configuration, static and dynamic analyses of various mooring system in this study.

3.6 Mooring system design

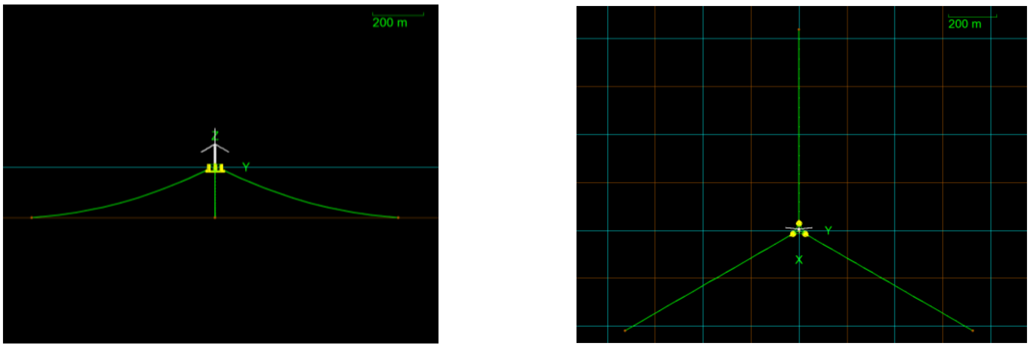
A considerable amount of research studies and experimental works on single FOWT of National Renewable Energy Laboratory (NREL) OC5/OC4 DeepCWind semisubmersible platform that is stabilized with catenary single line anchor mooring system. Many publications on the

Table 4 Numerical simulation test matrices for multiple arrays of FOWF with shared mooring design

Illustrate in Figures	Floating Platform & Mooring Configuration	Number of Wind Turbines (N)	Number of Shared Mooring Lines (SM)	Number of Anchors (SA)	Number of Mooring Lines (M)	Total Number of Mooring Lines and Anchors (T)	Angle between Adjacent Mooring Lines (A)
Fig. 6	Case #1a - Single FOWT, 5MW, Catenary Mooring	1	0	3	3	6	120°
Fig. 7	Case #1b - Single FOWT, 5 MW, Taut Mooring	1	0	3	3	6	120°
Fig. 8	Case #2a - 2 FOWTs, 10 MW, Taut Shared Anchor	2	0	5	6	11	120°
Fig. 9	Case #3a - 4 FOWTs, 20 MW, Taut Shared Anchor	4	0	8	12	20	90°
Fig. 10	Case #4a - 6 FOWTs, 30 MW, Taut Shared Anchor	6	0	12	18	30	120°
Fig. 11	Case #5a - 8 FOWTs, 40 MW, Taut Shared Anchor	8	0	16	24	40	135°
Fig. 12	Case #6a - Hybrid – 4 FOWTs, 20 MW, Taut Shared Alternate	4	2	6	8	16	90°
Fig. 13	Case #6b - Hybrid – 6 FOWTs, 30 MW, Taut Shared Alternate	6	3	9	12	24	120°
Fig. 14	Case #6c - Hybrid – 8 FOWTs, 40 MW, Taut Shared Alternate	8	4	12	16	32	135°
Fig. 15	Case #2b - 2 FOWTs, 10 MW, Taut Shared Mooring	2	1	4	4	9	120°
Fig. 16	Case #3b - 4 FOWTs, 20 MW, Taut Shared Mooring	4	4	4	4	12	90°
Fig. 17	Case #4b - 6 FOWTs, 30 MW, Taut Shared Mooring	6	6	6	6	18	120°
Fig. 18	Case #5b - 8 FOWTs, 40 MW, Taut Shared Mooring	8	8	8	8	24	135°
Fig. 19	Case #7 - Damage Condition – 8 FOWTs, 40 MW, Taut Shared Mooring, One Line Broken	8	8	7	7	22	135°

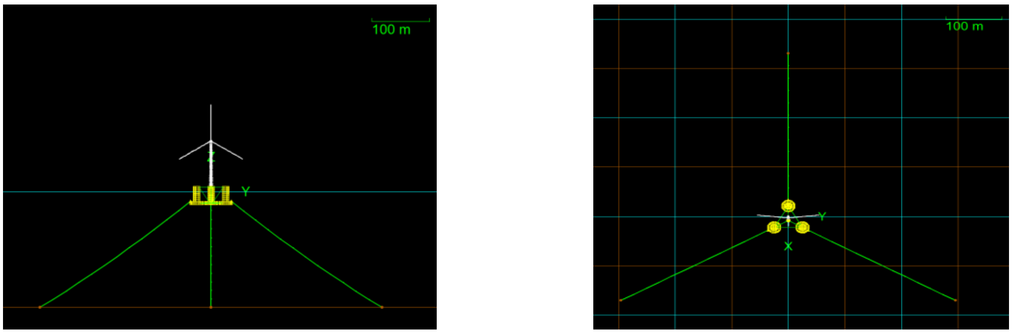
effectiveness of mooring system (Robertson *et al.* 2014, Robertson *et al.* 2017, Bayati *et al.* 2015, Li *et al.* 2021). In recent years, there are efforts in research studies to explore the possibilities of increasing the amount of generated renewable wind power from multiple offshore wind turbines in a fetch area. This allows the researchers and industry to explore further and deep-water wind potential (GWEC, 2023).

There is research being conducted to investigate the shared anchor configuration using three FOWTs. Pillai *et al.* (2022) investigated on the three FOWTs of 15 MW Volturn US-S semisubmersible platform with shared anchor configurations, while Balakrishnan *et al.* (2020) analyzed on the numerical simulation data of shared anchor configurations with three FOWTs using different floating platforms between spar and semisubmersible at 200 m water depth. Both the research works concluded that on the same outcome, whereby the configuration of three FOWTs sharing an anchor had reinforced past findings of having loads applied in opposing directions, which resulted in net force from the resultant vectors.



(a) Side Elevation View (b) Plan View

Fig. 6 Case #1a - Single FOWT, 5 MW, Catenary Mooring Model in OrcaFlex

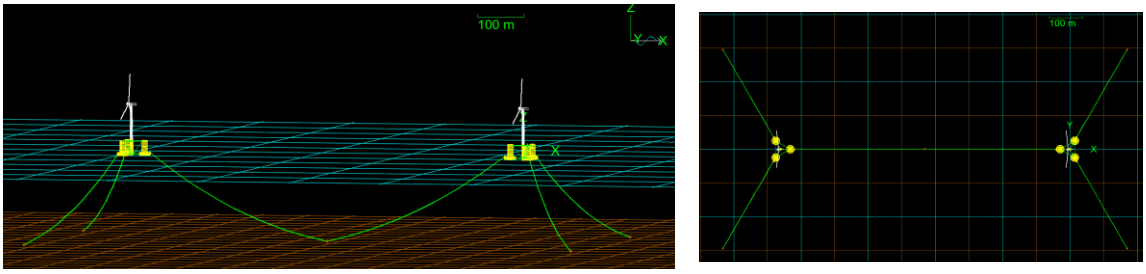


(a) Side Elevation View (b) Plan View

Fig. 7 Case #1b - Single FOWT, 5 MW, Taut Mooring Model in OrcaFlex

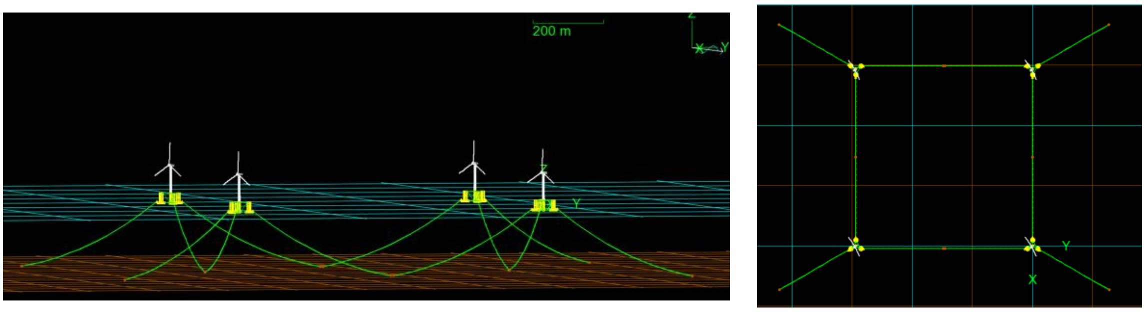
In this present study, a sensitivity test matrices of baseline FOWT and multiples array of FOWF with shared mooring design configuration were investigated. The model chosen in this present study 5 MW rating of OC5 DeepCWind Semisubmersible FOWT at 200 m water depth in offshore Malaysian water. The sensitivity test matrices are present in Table 4.

The array layout of the FOWF is being analysed with wind, wave and current in multiple headings collinearly. One design constraint that needs to be fulfilled is to consider for FOWT spacing between 2 or more, which the constraints was particularly mentioned in various research studies (Chen *et al.* 2022, Hall *et al.* 2022, Liang *et al.* 2023, Lozon and Hall 2023). The reason of such turbine spacing requirement is in consideration of the impacts of aerodynamic interactions and to avoid the wake effects that can influence negatively on the power output of wind turbines in a wind farm. Hence, the research studies suggested to observe the turbine spacing is 6 to 7 times of FOWT's rotor diameter in the initial configuration (Liang *et al.* 2023, Liang *et al.* 2024). Overall, the mooring system of a FOWT and multiples array in FOWF should be designed to satisfy several requirements, which can be summarized as studied by other researchers (Xu *et al.* 2019). Mooring systems must withstand wave, wind, and current loads in open sea environments. The offshore oil and gas industry, with its extensive experience in harsh conditions, serves as an excellent reference for designing mooring systems for FOWT and FOWF.



(a) Orthogonal 3D-View (b) Plan View

Fig. 8 Case #2a - 2 FOWTs, 10 MW, Taut Shared Anchor in OrcaFlex



(a) Orthogonal 3D-View (b) Plan View

Fig. 9 Case #3a - 4 FOWTs, 20 MW, Taut Shared Anchor in OrcaFlex

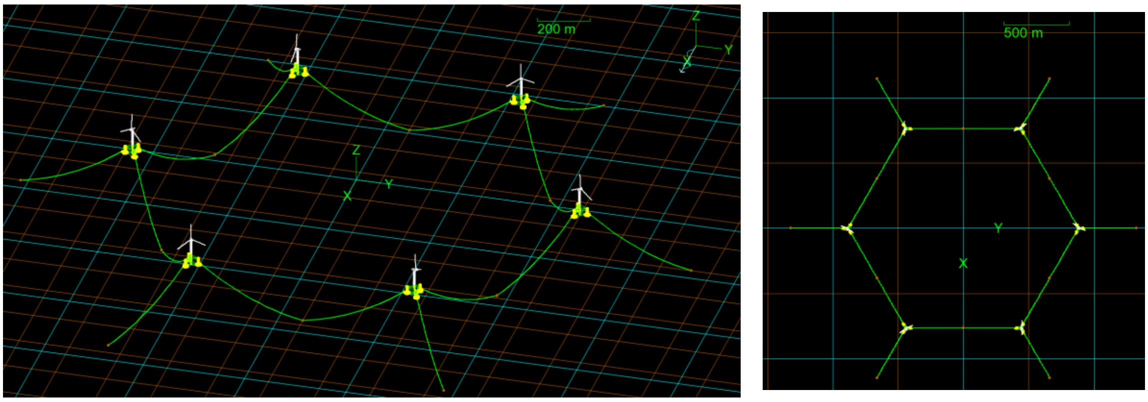
Mooring designs adhere to safety standards set by organizations like ISO, BV, API, ABS, and DNV. The design restricts the horizontal offset of FOWTs and arrays within allowable limits under extreme and survival conditions, even if one mooring line fails. Sensitivity case studies explore load reduction on multiple arrays using shared anchors and mooring lines. They are designed for practical inspection and maintenance, no service vessels are permitted inside FOWF spaces due to the dynamic movement of mooring lines. Mooring hardware is available off the shelf, and attention is given to the effective diameter and scope of mooring lines anchored at the seabed.

3.7 Wind loads

Wind forces that are acting on a moored FOWT can be calculated using simplified methodology from Det Norske Veritas (DNV), (2018). Wind loads can be calculated using the Eq. (1)

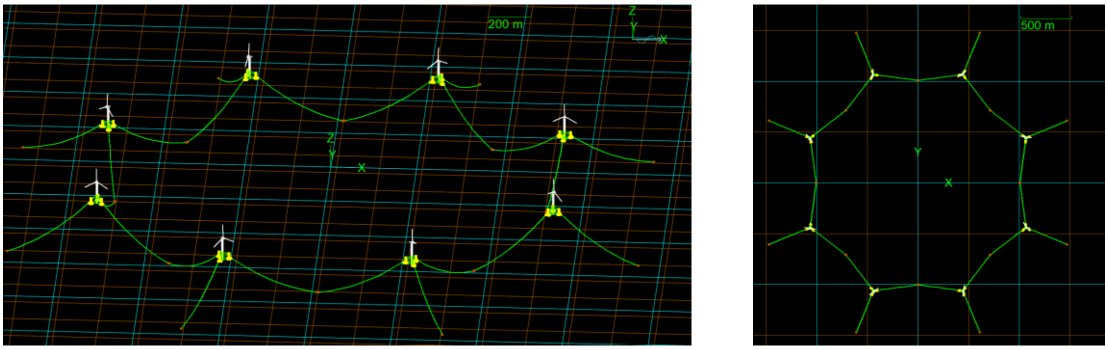
$$F = \frac{1}{2} \,.\, \rho \,.\, C \,.\, A \,.\, V^2 \qquad (1)$$

where, F represents the drag force; ρ is the air density (for wind drag), C is the drag coefficients for the wind direction depending on the shape and height coefficient of the exposed area of FOWT as given in Det Norske Veritas (DNV), (2017); A is the cross-sectional of exposed areas above the waterline and V is the magnitude of the wind velocity at 10m height above waterline.



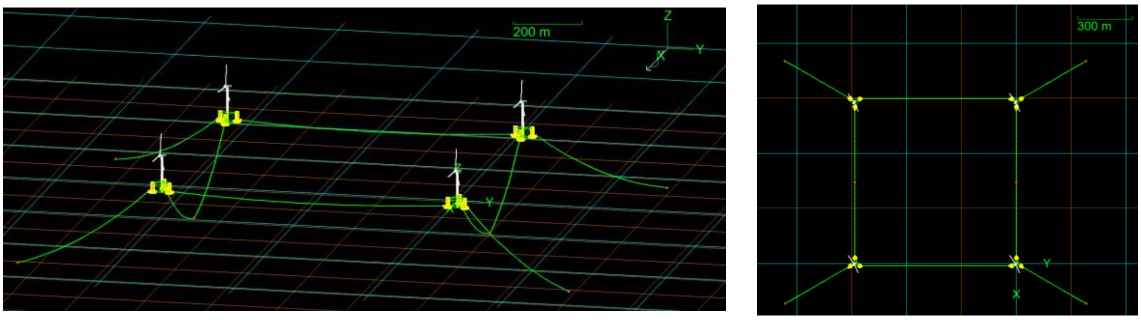
(a) Orthogonal 3D-View (b) Plan View

Fig. 10 Case #4a - 6 FOWTs, 30MW, Taut Shared Anchor in OrcaFlex



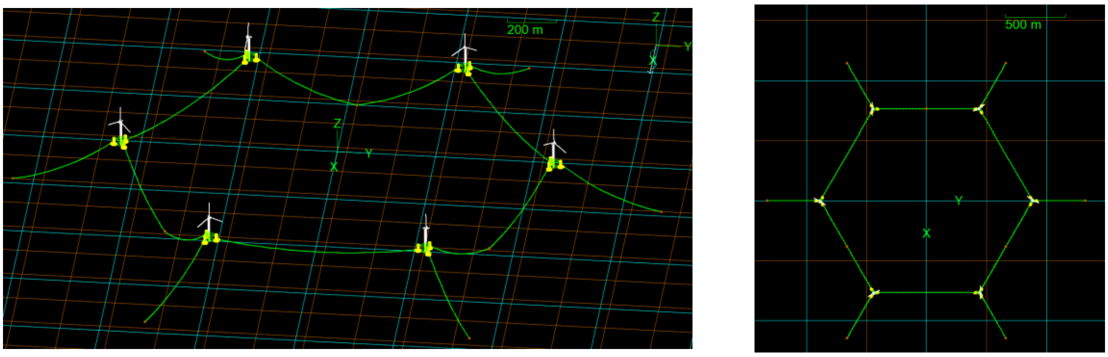
(a) Orthogonal 3D-View (b) Plan View

Fig. 11 Case #5a - 8 FOWTs, 40 MW, Taut Shared Anchor in OrcaFlex



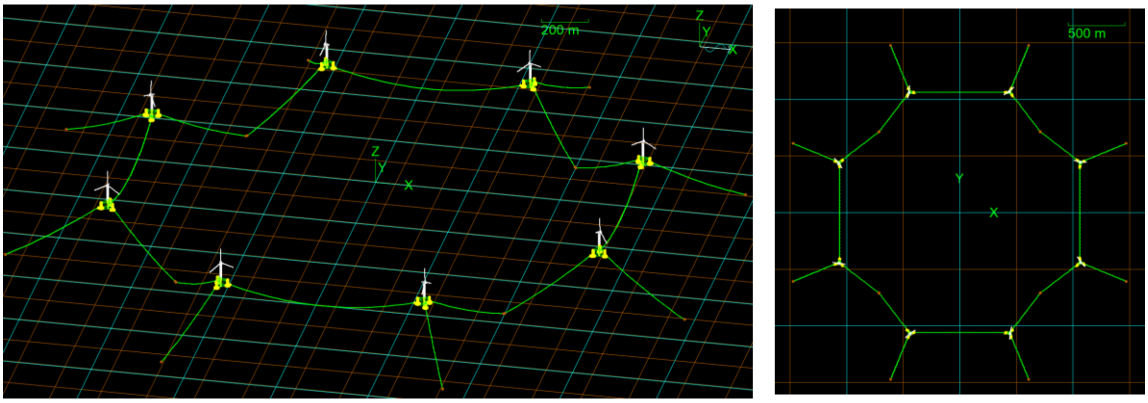
(a) Orthogonal 3D-View (b) Plan View

Fig. 12 Case #6a - Hybrid – 4 FOWTs, 20 MW, Taut Shared Alternate in OrcaFlex



(a) Orthogonal 3D-View (b) Plan View

Fig. 13 Case #6b - Hybrid – 6 FOWTs, 30 MW, Taut Shared Alternate in OrcaFlex



(a) Orthogonal 3D-View (b) Plan View

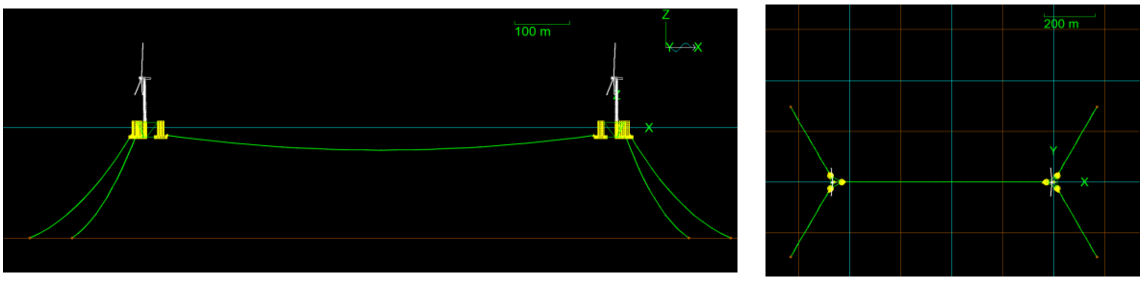
Fig. 14 Case #6c - Hybrid – 8 FOWTs, 40 MW, Taut Shared Alternate in OrcaFlex

3.8 Mooring design configuration for FOWF

The mooring configuration is designed for 200 m of water depth in offshore Malaysian waters. There are two types of mooring configuration, which are catenary and taut mooring system (Liang *et al.* 2023).

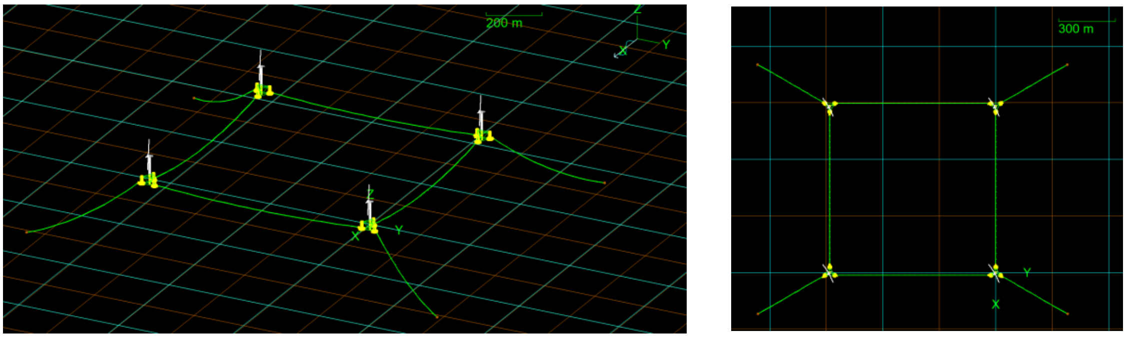
The mooring configuration designs are in Figs. 20(a) and 20(b) for single and baseline FOWT and are replicated for scalability in multiple arrays in FOWF. The post processing will be analyzed to satisfying industry code and standard to meet the safety factor of ULS and ALS.

The definition of ULS can be found in several standards, for example, ISO 19901-7 Part 7 (Standard 2013) and DNV-OS-E301 (DNV, 2007). Based on the industry standards from oil and gas platforms, they define ULS as "an ultimate limit state to ensure that the individual permanent mooring lines have adequate strength to withstand the load effects imposed by extreme environmental actions". As for the ALS, it is defined as "an accidental limit state to ensure that the permanent mooring system has adequate capacity to withstand the failure of one mooring line for reasons such as operational failure, adverse environmental events, for instance, hurricanes. The safety factors used for mooring design as shown in Table 5.



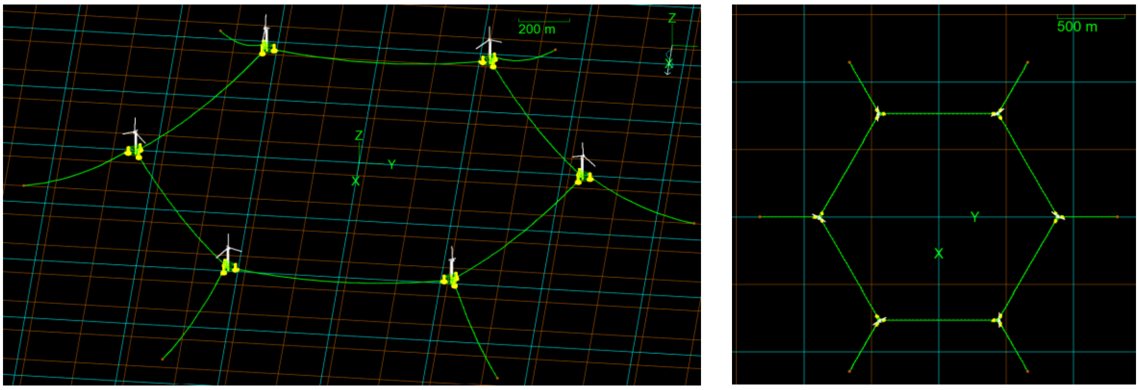
(a) Orthogonal 3D-View (b) Plan View

Fig. 15 Case #2b - 2 FOWTs, 10 MW, Taut Shared Mooring in OrcaFlex



(a) Orthogonal 3D-View (b) Plan View

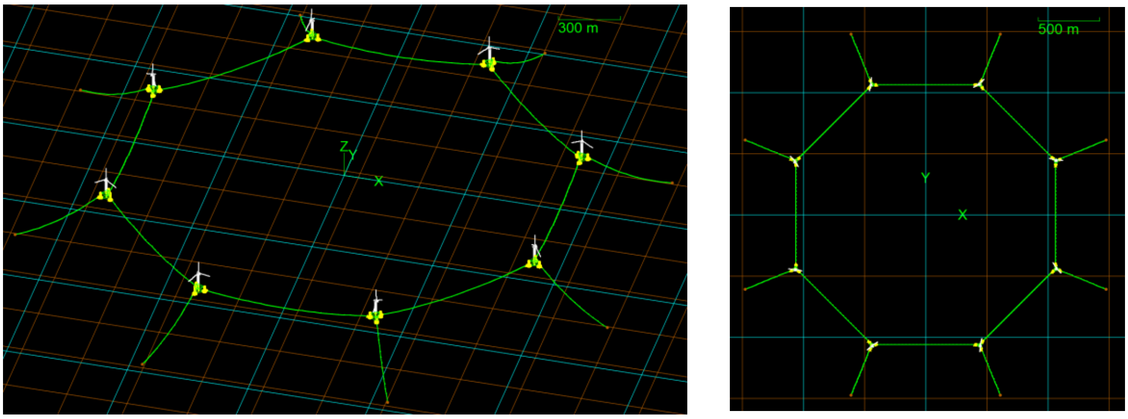
Fig. 16 Case #3b - 4 FOWTs, 20 MW, Taut Shared Mooring in OrcaFlex



(a) Orthogonal 3D-View (b) Plan View

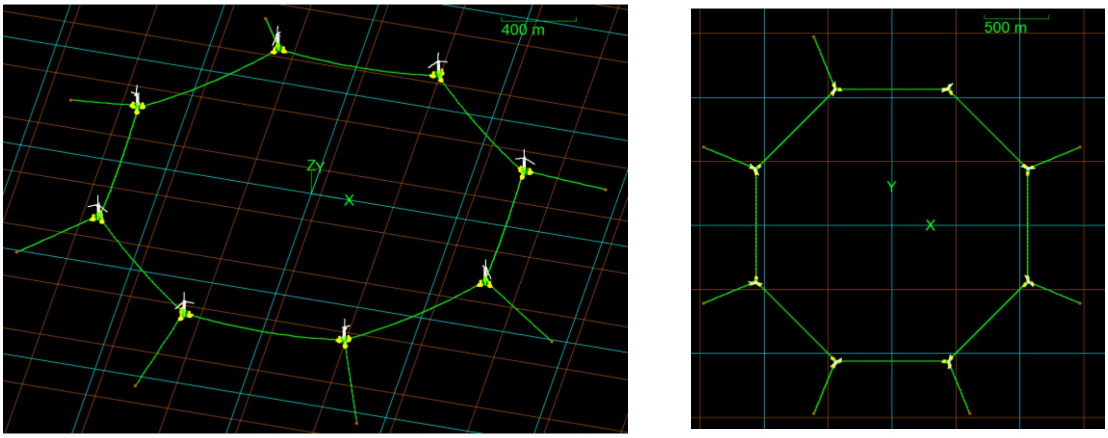
Fig. 17 Case #4b - 6 FOWTs, 30 MW, Taut Shared Mooring in OrcaFlex

In this study, the same chain mooring was used for both catenary and taut cases. It is important to note that typically, for taut mooring systems, polyester is used instead of chain. This distinction is crucial as the material properties and behaviour under load differ significantly between chain and polyester, potentially impacting the performance of the mooring system for stationkeeping.



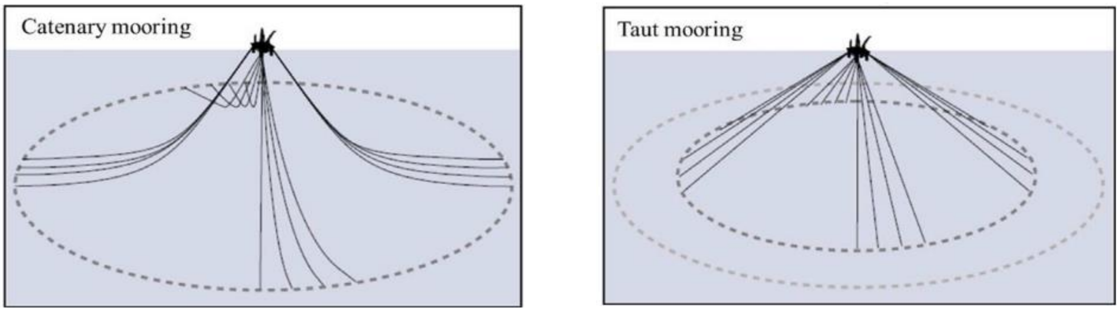
(a) Orthogonal 3D-View (b) Plan View

Fig. 18 Case #5b - 8 FOWTs, 40 MW, Taut Shared Mooring in OrcaFlex



(a) Orthogonal 3D-View (b) Plan View

Fig. 19 Case #7 - Damage Condition – 8 FOWTs, 40 MW, Taut Shared Mooring One Line Broken in OrcaFlex



(a) Catenary Mooring (b) Taut Mooring

Fig. 20 Mooring design configuration of a floater (Xu *et al.* 2024)

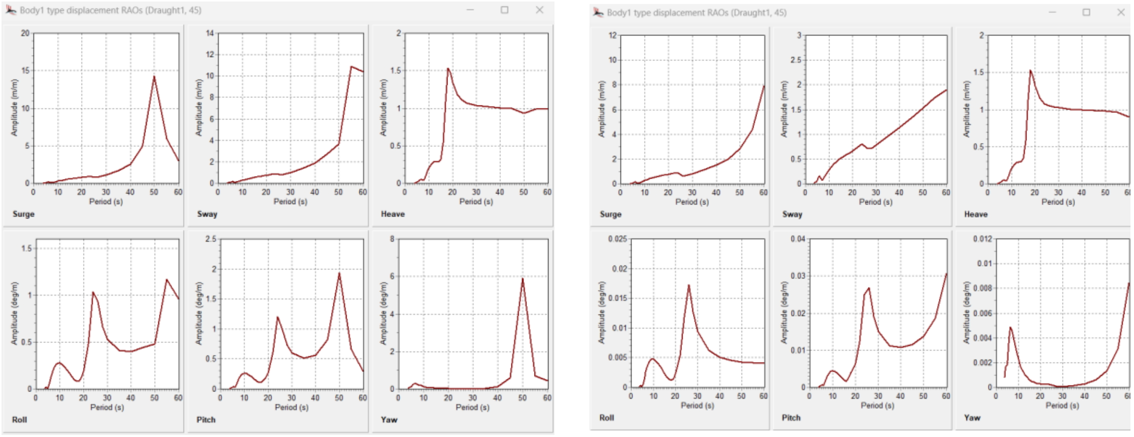
Table 5 Safety factors for mooring design from various industry standards

Industry Standards	Design Return Period	Permanent Mooring Chain Safety Factor		Permanent Anchor Safety Factor		Remarks
		ULS	ALS	ULS	ALS	
API RP 2SK (API (American Petroleum Institute), 2015)	100 years	1.67	1.25	2.0	1.0	•Application in offshore environment • Dynamic method using Time Domain
ABS Guide for Position Mooring Systems (ABS (American Bureau of Shipping), 2018)	100 years	1.67	1.25	2.0	1.5	• Application in offshore environment • Dynamic method using Time Domain
BV NR 493 (Bureau Veritas 2021)	100 years	1.67	1.25 1.00(1)	2.0	1.5	• Application in offshore environment • Dynamic method using Time Domain • (1) Two-line damaged condition
DNV-OS-E301 (Det Norske Veritas (DNV), 2007)	100 years	1.45	1.10	1.4	1.0	• Application in offshore environment • Dynamic method using Time Domain
ISO 19901-7 Part 7 (Standard, 2013)	100 years	1.67	1.25	2.0	1.5	• Application in offshore environment • Dynamic method using Time Domain
ABS Guide for building and classing FOWT (ABS, 2020)	50 years	1.67 2.0(2)	1.05	2.0	1.5	• Permanent sited FOWT • Dynamic method using Time Domain • (2) Non-redundant
BV NI 572 (Bureau Veritas 2019)	50 years	1.67 2.0(3)	1.25	2.0	1.5	• Permanent sited FOWT • Dynamic method using Time Domain • (3) Non-redundant
DNVGL-ST-0119 (Det Norske Veritas (DNV), 2018)	50 years	1.3(4) 1.5(5)	1.0	1.4	1.0	• Permanent sited FOWT • Dynamic method using Time Domain • (4) Consequence 1, (5) Consequence 2

The following design constraint and criteria that need to be observed and complied by every numerical simulation in the sensitivity test matrices as presented. The average maximum line tension should not surpass the factored minimum breaking strength of the line, as outlined in Table 5. Adopting a conservative approach, safety factors should adhere to the industry standard of BV NI 572 (Bureau Veritas 2019) to ensure the design of a durable FOWT and its application to multiple arrays in an FOWF, even though the design environmental criteria use a 100-year return period due to limited dataset references in published research papers. It is also assumed that the maximum platform offset will be restricted to no more than 20% of the water depth at the FOWT location. Additionally, there should be no vertical uplift force at the anchor.

Another design constraint that needs to be carefully evaluated, which is not observed in the industry code standard, is to allow for vessel navigation over the shared mooring lines, below the water surface or mean seal level (MSL) (Hall *et al.* 2022). The constraint is placed especially at the line midpoints. The outcome will be obtained from the post processing results of the numerical simulations of the sensitivity test matrices.

It is essential to acknowledge that the analysis was executed focusing solely on first-order motion. This method does not take into account second-order mean and slowly varying drift forces. Consequently, the maximum horizontal offset derived from this analysis may lack complete accuracy. Researchers need to recognize that the maximum horizontal offset, which encompasses both mean and slowly varying elements, is significantly affected by second order mean and slowly varying drift forces, as indicated in the study by Kim and Kim (2016). These forces can



(a) RAO of FOWT with Catenary Mooring at 45 degrees environmental direction

(b) RAO of FOWT with Taut Mooring at 45 degrees environment direction

Fig. 21 RAO plots of FOWT in OrcaFlex to validate resonance and natural frequency

considerably influence the overall motion and stability of FOWF structures. Future investigations should aim to include second-order mean and slowly varying drift forces in the dynamic analysis to achieve a more precise and holistic understanding of the maximum horizontal offset. This integration will enable a better evaluation of the performance and reliability of mooring systems under diverse environmental conditions.

The study assesses the failure scenario of the shared mooring system, such as one line breakage at anchor point. However, these scenarios may not cover all the possible failure modes and causes that may occur in the real operation of the FOWF. For example, the study does not consider the effects of fatigue, corrosion on the mooring components or failure at the shared mooring line, which may reduce their strength and durability over time. The study also does not account for the human and operational factors, such as maintenance, inspection, repair, and emergency response, which may affect the failure prevention and mitigation of the mooring system.

4. Results and discussions

Following the methodology in the previous section, the performance of the shared mooring and shared anchor for various cases of multiple arrays in FOWF were analysed in OrcaFlex with the baseline design of single FOWT used as a measure for comparison. Many OrcaFlex simulations were run using the various configurations based on the test matrices in Table 4 to show the dynamic behaviour of the shared mooring and shared anchor with baseline design of single FOWT to withstand design environmental condition of 100-year return period. The following sections outline the results for the dynamic analyses of multiple arrays of FOWT with combinations of shared-mooring and shared-anchor array in FOWF.

4.1 FOWF platform resonance and natural frequency

The dynamic characteristics of FOWT within multiple arrays in FOWF are mainly depicted

Table 6 Horizontal offsets comparisons for Single FOWT catenary and taut mooring

Test Matrix	Mooring Configuration	Max (m)	Mean (m)	Inter Quartile Range (IQR) High (m)	Inter Quartile Range (IQR) Low (m)	Standard Deviation, Sd (0.75*IQR) (m)
Benchmark	5 MW DeepCWind Model (Chen *et al.* 2023) – Linear extrapolation	15.73	5.05	N/A	N/A	3.01
CASE#1a	Single FOWT Catenary Mooring	14.99	5.46	6.13	3.43	2.03
CASE#1b	Single FOWT Taut Mooring	14.08	8.04	11.76	4.28	5.61

through their platform motions, influenced by forces from the wave, wind, current, and mooring systems. These motions span six degrees of freedom in the form of *x*, *y* and *z*-direction in translational and rotational movements known as surge, sway, heave, roll, pitch, and yaw. FOWTs' behaviour is also shaped by resonance and the system's natural frequency, which are determined by the mooring lines' stiffness and dampening properties along with the FOWT's RAO hydrodynamic traits. The RAO hydrodynamic traits of FOWT, which was imported from OrcaWave, can be plotted by OcraFlex for catenary mooring and taut mooring as shown in Figs. 21(a) and 21(b) respectively. This section analyses on the comparison in the dynamic response of FOWTs between the 2 different configurations from a standard design with single turbine FOWT.

The FOWT semi-submersible platform exhibits an inherent oscillation period of below 30 seconds (Orcina Ltd., 2014). The results are taken from the OrcaFlex plots that show the peak response of heave motion at period of less than 20 seconds, whilst the peak response of roll motion at period of 28 seconds. This characteristic period is distinctively outside the conventional frequency and resonance spectrum observed in standard semi-submersible platforms, which typically have shorter oscillation periods. The oscillation period, or natural period, is the time it takes for the platform to complete one full cycle of motion when disturbed. For FOWTs, this period is influenced by the mass, buoyancy, and hydrodynamic properties of the structure. The semi-submersible platform's design, with its large displacement and substantial water-plane area, contributes to a lower natural frequency and longer oscillation period. This shows that the natural frequency of FOWTs is lower than that of typical sea wave frequencies, which is deemed as resonance avoidance. This is beneficial as it minimizes the risk of resonance, a condition where the frequency of wave forces matches the natural frequency of the platform, leading to large amplitude oscillations that can be detrimental to the structure's integrity.

4.2 Mooring comparison between catenary and taut configuration for FOWF

The performance and efficiency of a single FOWT depend on the choice of mooring design, which affects the motion and mooring line tension of the platform. To evaluate the effects of different mooring designs, numerical simulations were conducted to compare the horizontal offsets and mooring line tension of a FOWT with catenary and taut mooring configuration under various wind and wave conditions. The results are presented in Tables 6 and 7, which show the horizontal offsets, tension force at fairlead and tension force at anchor for each mooring design.

As shown in Table 6, the catenary mooring exhibited larger horizontal offsets than the taut mooring in all directions, especially in surge and sway. This implies that the catenary mooring was

Table 7 Comparisons of max tension load for Single FOWT catenary and taut mooring

Test Matrix	Mooring Configuration	Maximum Tension Force At Fairlead (kN)	Maximum Tension Force At Anchor (kN)
Benchmark	5 MW DeepCWind Model (Chen *et al.* 2023)	4,599.8	N/A
CASE#1a	Single FOWT Catenary Mooring	4,507	4,389
CASE#1b	Single FOWT Taut Mooring	4,597	4,469

Table 8 Benchmarking on the design mooring system properties using single FOWT as baseline

Key Parameters	Catenary	Catenary-Multiline	Single FOWT Catenary	Single FOWT Taut
Reference previous research paper	OC5 DeepCWind (Robertson *et al.* 2016, Chen *et al.* 2023)	OC3 Hywind and NREL OC4 DeepCWind (Balakrishnan *et al.* 2020)	Current Research simulation study	Current Research simulation study
Water Depth	200 m	200 m	200 m	200 m
Number of mooring lines	3	3	3	3
Angle between adjacent lines	120°	120°	120°	120°
Mooring length	835.5 m	902 m	820 m	348 m
Material	R3 studless chain	R3 studless chain	R4 studless chain	R4 studless chain
Chain Nominal Diameter	78 mm	124 mm	86 mm	87 mm

less effective in restraining the platform motion and maintaining its position. The taut mooring demonstrated smaller horizontal offsets due to its higher stiffness and lower slackness, which could reduce the dynamic effects of wind and wave loads.

As shown in Table 7, the catenary mooring exhibited lower tension force at both fairlead and anchor than the taut mooring under the 100-year return period in all cases of different headings, which the wave, wind and current are in co-linear directions. The catenary mooring had more mooring line length and weight, which increased the static tension and the drag force on the lines. The taut mooring demonstrated higher tension force at fairlead due to its shorter length and lighter weight, which reduced the static and drag components of the tension.

Furthermore, the design configuration of the single FOWT catenary mooring from the numerical simulations were further investigated with the other researchers' experimental model in their research works as presented in Table 8. The numerical simulation model in this study was validated with experimental data from the DeepCwind project in a wind-wave basin (Balakrishnan *et al.* 2020, Robertson *et al.* 2016, Robertson *et al.* 2014). Additionally, comparison between the present study and DeepCWind experiment conducted by Chen *et al.* (2023) for proof of validation as presented in Tables 6-8. The model showed good agreement with the experimental data in terms of the mean and standard deviation of the mooring line tension and the platform motion for different wind and wave scenarios. This indicates that the numerical simulation done for the single FOWT catenary was reliable and consistent with the existing literature. The observation also reveals that the mooring stiffness, line length and nominal chain diameter of the catenary mooring

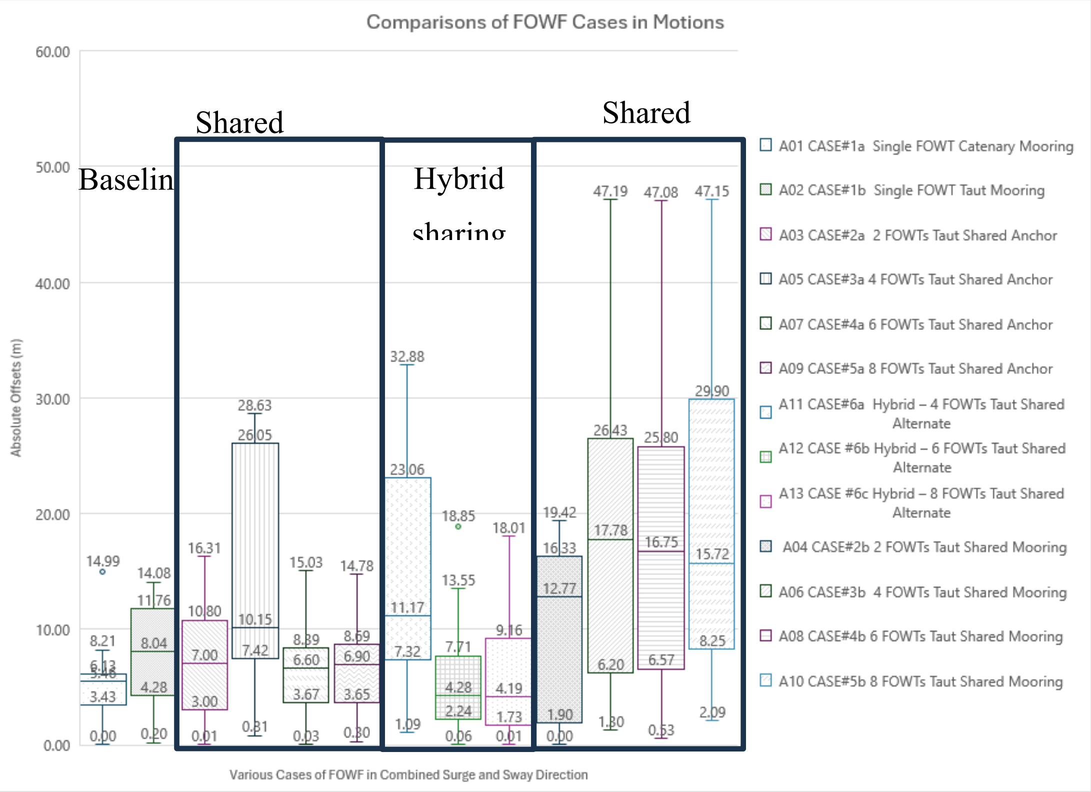


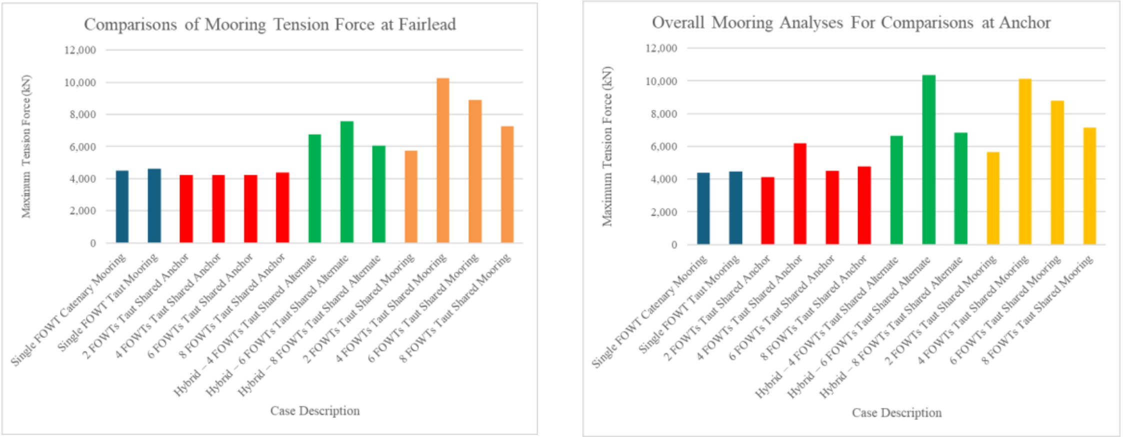
Fig. 22 Box and Whisker Plot Chart for Comparisons of FOWF in Horizontal Offsets

were within the range of the previous studies. This indicates that the numerical simulation done for the single FOWT catenary was reliable and consistent with the existing literature.

After analysing the horizontal offsets and mooring line tensions, it can be concluded that the taut mooring system outperformed the catenary mooring for a single FOWT in terms of motion control and overall performance metrics. Specifically, the taut mooring system offered superior motion control with smaller horizontal offsets compared to the catenary mooring. Furthermore, the taut mooring showed higher fairlead tension, enhancing its ability to withstand dynamic loads from wind and waves. However, it is crucial to acknowledge that this increased tension may result in larger vertical forces at the anchor points, potentially affecting anchor stability. Hence, careful consideration of anchor design and material selection is essential when choosing a taut mooring system. Additionally, the taut mooring provided economic and operational benefits, such as reduced material costs due to shorter mooring lengths, as shown in Table 8, and greater scalability for a FOWF. Consequently, the taut mooring configuration was selected as the optimal mooring design for further simulations of an FOWF.

4.3 Efficiency performance of mooring sharing for multiple arrays FOWF

The performance and efficiency of the taut mooring system for FOWF in multiple arrays of wind turbines were evaluated based on the numerical simulations conducted for different test



(a) Mooring Maximum Tension Force at Fairlead for Comparisons

(b) Mooring Maximum Tension Force at Anchor for Comparisons

Fig. 23 Comparisons of Mooring Maximum Tension Force in Intact Condition

matrices, as shown in Table 4, which simulations were performed for different configurations of FOWF with shared mooring lines and anchors and compared with the baseline case of a single FOWT. The test matrices, where the number of wind turbines (N), the number of mooring lines (M), the angle between adjacent mooring lines (A), and the total number of mooring lines and anchors (T) are listed for each configuration. The horizontal offsets of the FOWF in surge and sway directions were evaluated and compared using box and whisker plot charts in Fig. 22 and offset data in Table 9. The box and whisker plots show the minimum, maximum, median, lower quartile, and upper quartile values of the motion offsets for each configuration. The horizontal offsets indicate the stability and operability of the FOWF under different environmental conditions. The maximum horizontal offsets of 47 m in surge and sway directions occurred for the simulation matrices of FOWF under the category of taut configuration with shared mooring among the other test matrices.

The results show that the horizontal offsets of the FOWF increase as the number of wind turbines increases, due to the increased hydrodynamic interactions and interference effects among the wind turbines. However, the increase is not significant, and the horizontal offsets are still within the acceptable range for FOWF operation of 20% of 200m water depth. The sharing of mooring lines and anchors does not have a negative impact on the horizontal offsets of the FOWF, as the taut mooring system provides sufficient stiffness and damping to the FOWF. Thus, sharing mooring lines and anchors is an efficient way to minimize their number in a complex FOWF array without losing stability and functionality.

The tension forces at the fairleads of the individual and shared mooring lines were also evaluated and compared using bar charts in Figs. 23(a) and 23(b). The tension forces indicate the strength and durability of the mooring lines and anchors under different environmental loads. The results show that the tension forces at the fairleads of the mooring lines increase as the number of wind turbines increases, due to the increased hydrodynamic loads and coupling effects among the wind turbines. However, the tension forces are still within the design limits for the mooring lines and anchors based on the safety factors from industry standard in Table 5. The sharing of mooring lines and anchors does not have a negative impact on the tension forces of the mooring lines, as the taut mooring system distributes the loads evenly among the mooring lines and anchors. Therefore, the sharing of mooring lines and anchors is an effective and optimized approach to reduce the number of mooring lines and anchors required for a complex array of FOWF, without compromising the strength and durability of the mooring lines and anchors.

The tension forces at the fairleads of the mooring lines are generally higher for the configurations with 4, 6 and 8 wind turbines than for the configurations with 2 wind turbines, except for the configuration with 8 wind turbines and shared mooring lines and anchors (N=8, A=135°, T=24), which has lower tension forces of 7,253 kN than the configuration with 4 wind turbines and individual mooring lines and anchors (N=4, A=90°, T=12) with the highest tension forces of 10,261 kN. This indicates that the tension forces of the mooring lines are more sensitive to the total number of mooring lines and anchor per FOWF (T). The FOWF array (N=8) with higher number of mooring lines and anchors are better at distribution of the forces within the system as compared to the configuration of FOWF array with (N=4) wind turbines. Another indication that can be observed is the angle between adjacent mooring lines (A), as the configuration with (N=8) wind turbines and shared mooring lines and anchors has a larger angle (A=135°) than the configuration with (N=4) wind turbines and individual mooring lines and anchors (A=90°). The configuration with 8 wind turbines and shared mooring lines and anchors (N=8, A=135°, T=24), which has lower tension forces of 7,253 kN than the configuration with 4 wind turbines and individual mooring lines and anchors (N=4, A=90°, T=12) with the highest tension forces of 10,261 kN

The numerical simulations of different configurations of FOWF with shared mooring lines and anchors demonstrate that the sharing of mooring lines and anchors is an effective and optimized approach to reduce the number of mooring lines and anchors required for a complex array of FOWF, without compromising the stability, operability, strength, and durability of the FOWF. The sharing of mooring lines and anchors can also reduce the installation and maintenance costs of the FOWF, as well as the environmental impact of the FOWF on the seabed. Therefore, the sharing of mooring lines and anchors can enhance the scalability and feasibility of the taut mooring system for FOWF in multiple arrays of 2, 4, 6 and 8 wind turbines.

The benefits of shared mooring and anchor systems can be considered to decrease both the overall weight and length needed, leading to lower material, manufacturing, transportation, and installation expenses. By reducing the number of connection points, the system minimizes potential failure points, thereby cutting down on inspection, maintenance costs, and the risk of mooring failure and damage to FOWF. The system's reduced footprint and disturbance to the seabed lower environmental impacts and reduce the need for seabed preparation and clearance. Finally, shared mooring lines and anchors ensure stability, operability, strength, and durability of the FOWF. The taut mooring system provides adequate stiffness and damping while evenly distributing loads among the mooring lines and anchors.

4.4 Damage condition – One Line Broken (OLB)

In this section, the study is carried out to investigate the overall performance of a FOWF with 8 wind turbines when one of the mooring lines within the system is broken as in Fig. 19. The OLB mooring line was removed by selecting the most loaded tension force based on the test matrix of Case #5b as presented in Fig. 18. The selected FOWT with OLB was OC5 Semisub#1 with the most loaded tension force of 7,253 kN at Mooring #1 based on Case #5b. The results of the simulations were compared with the intact condition to assess the impact of the damage on the

(a) Box and Whisker Plot Chart for Horizontal Offsets Comparisons of 8 Wind Turbines in FOWF with OLB

(b) Motion Chart for Horizontal Offsets Comparisons of 8 Wind Turbines in FOWF

Fig. 24 Horizontal Offsets in Damage Condition with One Line Broken

structural stability, efficiency, and reliability of the system.

The horizontal offsets of the eight wind turbines in the FOWF with the damaged OLB line are shown using box plots and motion from time domain series, respectively in Figs. 24(a), 24(b) and Table 10. The FOWT with OLB experienced the largest increase in horizontal offsets, especially in the surge and sway directions, due to the loss of horizontal restraint from the broken line. The horizontal offsets of the other seven turbines were also affected by the damage, but to a lesser extent. The turbines closest to the OLB's wind turbine, the FOWTs showed an increase in horizontal offsets in the same directions as the OLB turbine, namely OC5 Semisub#2 and OC5 Semisub#8, indicating a coupling effect between the adjacent platforms. The turbines furthest from the OLB turbine, such as OC5 Semisub#4 and OC5 Semisub#5, showed a slight decrease in horizontal offsets, suggesting a redistribution of load within the FOWF. The overall standard deviation of the horizontal offsets increased from 16.24 m to 41.37 m in the combined direction of surge and sway direction, indicating a higher variability and instability of the system under the damaged condition.

The mooring tension forces at the fairlead and the anchor for the FOWF with the damaged OLB line are shown in Figs. 25(a), 25(b), and Table 11. As expected, the tension force in the broken OLB line dropped to zero after the damage occurred, while the tension forces in the adjacent FOWTs are in comparisons between Case #5b and Case #7 simulation results, to each anchor lines of the floater platform increased significantly. The maximum tension force at the fairlead increased from 7,253 kN to 9,997 kN with the comparisons of two simulation results in Case #5b and Case #7 respectively, representing an increase of 38%. The maximum tension force at the anchor increased from 7,133 kN to 9,885 kN with the comparisons of two simulation results in Case #5b and Case #7 respectively, representing an increase of 39% respectively. These increases in tension forces may pose a risk of failure or fatigue damage to the remaining lines of the OLB floater platform, as well as to the fairlead connections and anchors. The tension forces in the other platforms were also affected by the damage, but with varying degrees and directions. The platforms adjacent to the OLB platform showed an increase in tension forces in most of their lines, especially in the lines facing the OLB floater platform. This indicates an increase in load transfer

Table 9 Horizontal offsets comparisons for Multiple FOWF taut mooring in Intact Condition

Test Matrix	Mooring Configuration	Max (m)	Mean (m)	Inter Quartile Range (IQR)		Standard Deviation, Sd (0.75*IQR) (m)
				High (m)	Low (m)	
CASE#1a	Single FOWT Catenary Mooring	14.99	5.46	6.13	3.43	2.03
CASE#1b	Single FOWT Taut Mooring	14.08	8.04	11.76	4.28	5.61
CASE#2a	2 FOWTs Taut Shared Anchor	16.31	7.00	10.80	3.00	5.85
CASE#3a	4 FOWTs Taut Shared Anchor	28.63	10.15	26.05	7.42	13.97
CASE#4a	6 FOWTs Taut Shared Anchor	15.03	6.60	8.39	3.67	3.54
CASE#5a	8 FOWTs Taut Shared Anchor	14.78	6.90	8.69	3.65	3.78
CASE#6a	Hybrid – 4 FOWTs Taut Shared Alternate	32.88	11.17	23.06	7.32	11.81
CASE #6b	Hybrid – 6 FOWTs Taut Shared Alternate	18.85	4.28	7.71	2.24	4.10
CASE #6c	Hybrid – 8 FOWTs Taut Shared Alternate	18.01	4.19	9.16	1.73	5.57
CASE#2b	2 FOWTs Taut Shared Mooring	19.42	12.77	16.33	1.90	10.82
CASE#3b	4 FOWTs Taut Shared Mooring	47.19	17.78	26.43	6.20	15.17
CASE#4b	6 FOWTs Taut Shared Mooring	47.08	16.75	25.80	6.57	14.42
CASE#5b	8 FOWTs Taut Shared Mooring	47.15	15.72	29.90	8.25	16.24

Table 10 Horizontal offsets comparisons for Multiple FOWF taut mooring in Intact and Damage Condition

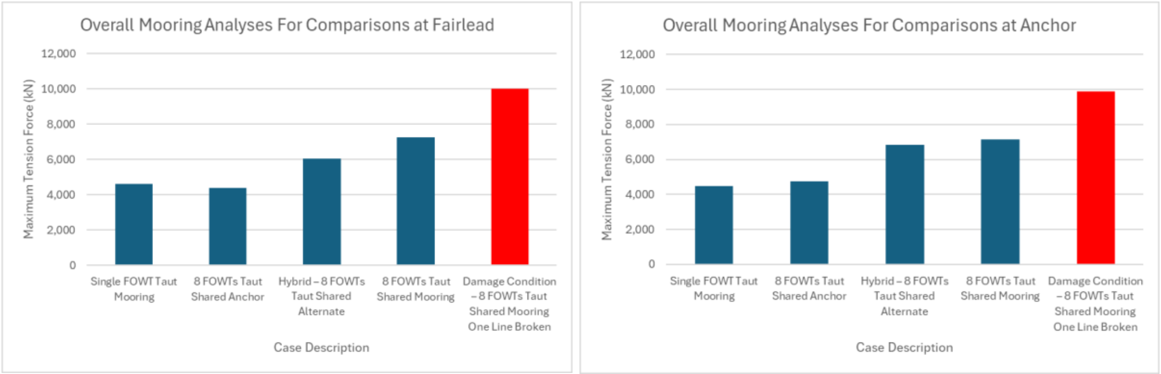
Test Matrix	Mooring Configuration	Max (m)	Mean (m)	Inter Quartile Range (IQR)		Standard Deviation, Sd (0.75*IQR) (m)
				High (m)	Low (m)	
Case #1b	Single FOWT Taut Mooring	14.08	8.04	11.76	4.28	5.61
Case #5a	8 FOWTs Taut Shared Anchor	14.78	6.90	8.69	3.65	3.78
Case #6c	Hybrid – 8 FOWTs Taut Shared Alternate	18.01	4.19	9.16	1.73	5.57
Case #5b	8 FOWTs Taut Shared Mooring	47.15	15.72	29.90	8.25	16.24
Case #7	Damage Condition – 8 FOWTs Taut Shared Mooring One Line Broken	24.62	435.88	63.21	8.05	41.37

and interaction between the neighbouring platforms due to the damage. The platforms furthest from the OLB platform, showed a decrease in tension forces in some of their lines, suggesting a decrease in load demand and participation in the system. From the percentage of incremental of tension forces between the intact condition in Test Case #5b and Test Case #7, indicating a higher variability and imbalance of the system under the damaged condition.

The power outputs of the eight wind turbines in the FOWF with the damaged OLB line were not being investigated. With the increase in horizontal offsets and such dynamic movements of the turbines under damaged condition, this will affect the power generation, which will lead to reducing outputs. This is mainly due to the increase in horizontal offsets, which reduced the alignment of the rotor plane with the wind direction, change in wake interference caused by the damage and thus the aerodynamic efficiency of the turbine. Therefore, a future research direction could be to quantify the impact of mooring line damage on the power production and efficiency of

Table 11 Mooring Maximum Tension Forces for FOWF comparisons between Intact and Damage Condition

Case No.	Description	Condition	Maximum Tension Force At Fairlead (kN)	Maximum Tension Force at Anchor (kN)
CASE#1b	Single FOWT Taut Mooring	Intact	4,597	4,469
CASE#5a	8 FOWTs Taut Shared Anchor	Intact	4,385	4,755
CASE #6c	Hybrid – 8 FOWTs Taut Shared Alternate	Intact	6,064	7,133
CASE#5b	8 FOWTs Taut Shared Mooring	Intact	7,253	6,822
CASE #7	8 FOWTs Taut Shared Mooring with One Line Broken	Damage	9,996	9,885



(a) Mooring Maximum Tension Force at Fairlead (b) Mooring Maximum Tension Force at Anchor

Fig. 25 Comparisons of Mooring Maximum Tension Force in Damage Condition with One Line Broken

the FOWF, and to explore the potential of using active control strategies to mitigate the loss of power output under such condition.

In summary, the damage of one mooring line in the FOWF had a significant impact on the overall performance of the system, affecting the structural stability, efficiency, and reliability of the wind turbines. The horizontal offsets and mooring tensions of the FOWF showed an increase in variability and imbalance, as well as an increase in average values, under the damaged condition. The adjacent floater turbines to the floater turbine with the damaged line experienced the most severe degradation in performance, while the other floater turbines were also affected by the damage through coupling and load redistribution effects. The results indicate that the FOWF is vulnerable to mooring line failures and that mitigation strategies are needed to maintain optimal performance under such conditions.

5. Conclusions

This research develops a numerical model for a floating offshore wind farm (FOWF) with a catenary mooring system, validated through experimental data. Using OrcaFlex, the model simulates various FOWFs under different wind, wave, and current conditions. Experimental data from the DeepCWind project demonstrated that the model accurately matched mooring tension and platform movements. Simulations involving 2, 4, 6, and 8 turbines using a taut mooring setup and shared mooring lines and anchors indicated material efficiency while ensuring stability. This was further quantified through efficiency and performance metrics. The reduction in the number of anchors and mooring lines needed for shared mooring systems compared to traditional ones was represented by the percentage decrease in material costs and installation time. For instance, shared mooring systems with taut lines have shown to reduce the number of anchors by approximately 30% and the length of mooring lines by 25%. The mooring systems' performance was assessed by motion offsets, tension force at the fairlead, and tension force at the anchor for each mooring design. Numerical simulation results indicated that the maximum displacement of the floating platforms remains within acceptable limits, with horizontal offsets were still within the acceptable range for FOWF operation of 20% of 200 m water depth under extreme environmental conditions.

The tension force at the fairlead and anchor for the shared mooring systems with taut lines was about 15% higher than conventional taut shared anchor mooring systems. However, implementing a shared mooring system introduces complexity to the dynamics of FOWTs, requiring the development of advanced simulation tools to meet modelling requirement. Finally, the impact of mooring line failure was examined, showing increased mooring line tension and platform movement after a line break, especially near the failure point, leading to reduced stability and control.

This study broadens our comprehension by investigating the effects of various arrays of FOWFs on both performance and safety. A numerical model was utilized to simulate four distinct configurations of FOWFs, arranged in groups of 2, 4, 6, and 8 units, either in parallel or ring formations. The impact of these arrays was assessed by comparing platform movements, mooring line tensions at the fairlead, and anchor mooring tensions under different wind, wave, and current conditions. The results revealed that multiple arrays introduced complexity and unpredictability into FOWF dynamics due to the hydrodynamic and aerodynamic interactions among the FOWFs.

The numerical model proved useful for the preliminary design and optimization of FOWFs. Furthermore, the report examined the influence of damage scenarios on FOWFs, such as mooring line or turbine failures. Damaged conditions were simulated and compared with intact scenarios in terms of platform motion, mooring line tension, and wake interference. The findings indicated an increased risk of instability and failure under damaged conditions, characterized by larger motions and loads due to imbalances in the mooring system or diminished power generation.

The current study acknowledges some limitations. Further research could explore experimental wave basin tests to validate numerical simulations involving multiple arrays of FOWF. More studies are needed to better understand power generation from FOWF under offshore conditions, including validating numerical models with wave basin data for various wind, wave, and current scenarios. Investigations should look into power output using configurations of 2, 4, 6, and 8 wind turbines arranged in different formations like staggered or hexagonal to optimize efficiency. Additionally, examining wake interference due to dynamic motions, both in intact and damaged conditions, can provide insights into power production and loads on downstream turbines.

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