

Increase in annual energy production through passive self-adjusting layouts of floating wind farms

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by

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To my mother ...

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NOMENCLATURE

List of Acronyms

AEP	Annual energy production of a wind farm
AWP	Water plane area
BEM	Blade element momentum
BMS	Baseline mooring system
BWFL	Baseline wind farm layout
CG	Center of gravity
CFD	Computational fluid dynamics
DEA	Drag-embedment anchor
DEL	Damage equivalent loads
DoF	Degree of Freedom
DWM	Dynamic wake meandering
FEM	Finite element method
FloatingWAYS	Floating wind array layout design
FLORIS	Flow redirection and induction in steady-state
FOW	Floating offshore wind
FOWT	Floating offshore wind turbines
FWF	Floating wind farms
GWFL	Gridded wind farm layout

IEA	International energy agency
IPC	Individual pitch control
LCOE	Levelized cost of energy
LES	Large eddy simulation
MBS	Multibody system
MBL	Minimum breaking load
MC	Metacentric height
MDAO	Multidisciplinary design analysis and optimization
MS	Mooring system
MSL	Mean sea level
NREL	National Renewable Energy Laboratory
PI	Proportional-integral
QTF	Quadratic transfer function
RANS	Reynolds averaged Navier-Stoke
RAOs	Response amplitude operators
RNA	Rotor nacelle assembly
SCADA	Supervisory control and data acquisition
SEPLA	Suction piles and plate anchors
SNOPT	Sparse nonlinear optimizer
SQP	Sequential quadratic programming
TRL	Technology readiness level
VLA	Vertically loaded anchor
YITuR	Yaw and induction-based turbine repositioning

List of Symbols

η_{farm}	Wind farm efficiency
D	Wind turbine rotor diameter
AEP_{opt}	Optimum AEP of a wind farm in the absence of wake
$\mathbf{X}(\omega)$	Wave excitation coefficients
$\mathbf{A}(\omega)$	Added mass coefficients

$\mathbf{B}(\omega)$	Radiational damping coefficients
C_t	Thrust coefficient
C_p	Power coefficient
$CapEx$	Capital expenditure
$OpEx$	Operational expenditure
$DeCom$	Decommissioning cost
E_{loss}	Total electrical losses of a wind farm
L	Length of a mooring line
d	Diameter of a mooring line
O_g	Global coordinate system
O_w	Wind direction coordinate system
wd	Wind direction
$\mathbf{R}_w$	Rotational matrix from O_g to O_w
m	Wohler exponent
T_{sim}	Simulation time
S_c	Amplitude of cycle c
N_c	Number of cycles with amplitude S_c
$DEL_{lifetime}$	Lifetime damage equivalent load
ws	Wind speed
$f(ws, wd)$	Probability density function of wind speed and wind direction distribution
D_{ws_s, wd_j}	Fatigue damage at load case with wind speed ws_s and direction wd_j
$D_{25-year}$	25-year fatigue damage
$T_{25-year}$	Turbine lifetime of 25 years
k_{TN}	Intercept of the T-N curve
N	Number of cycles to failure
A	Nominal cross-section area
I_x	Moment of area around the x-axis
I_y	Moment of area around the y-axis
r	Tower's outer radius

F_z	Force in the z-axis direction
σ	Axial stress
θ_σ	Angular position at which axial stress is calculated
θ_b	Angular position at which blade root bending moment M_b is calculated
M_x	Bending moment around x-axis
M_y	Bending moment around y-axis
$M_{b,x}$	Blade root bending moment around x-axis
$M_{b,y}$	Blade root bending moment around y-axis
M_b	Blade root bending moment
n_{ws}	Number of wind speeds
n_{wd}	Number of wind directions
P_{farm}	Power produced by the wind farm
P_{opt}	Optimum power produced in the wind farm with zero wake losses
N_T	Number of wind turbines in a wind farm
W_{loss}	Wake losses of a wind farm
E_{wd_j}	Energy produced by the wind farm at wind direction j
AEP_{gain}	Gain in wind farm's AEP
$dist_{min}$	Minimum allowable distance between turbines in the wind farm
Cr_{max}	Maximum allowable crosswind displacement
Cr	Crosswind displacement matrix
$AncR$	Anchoring radius
FL_r	Fairlead radius
L_{min}	Minimum mooring line length
L_{max}	Maximum mooring line length
FL_{depth}	Fairlead depth
R_L	Radial distance between anchoring radius and fairlead radius
β	Ratio of mooring line length
R	Rotational matrix
θ	Rotation angle around z-axis

ψ	Rotation angle around y-axis
ϕ	Rotation angle around x-axis
$\mathbf{F}_{\text{hub}}$	Aerodynamic force vector at the hub
$\mathbf{F}_{\text{aero}}$	Aerodynamic force vector at the MSL
$\mathbf{M}_{\text{hub}}$	Aerodynamic moment vector at the hub
$\mathbf{M}_{\text{aero}}$	Aerodynamic moment vector at the MSL
$\mathbf{R}_{\text{azimuth}}$	Rotational matrix from rotor to hub reference frame
$\mathbf{R}_{\text{up tilt}}$	Rotational matrix from hub to tower top reference frame
$\mathbf{R}_{\text{twr}}$	Rotational matrix from tower top to tower base reference frame
$\mathbf{R}_{\text{ptfm}}$	Rotational matrix from tower base to global reference frame
$\mathbf{r}_{\text{arm}}$	Moment arm
$\mathbf{X}_0$	Unloaded equilibrium position of the MS database
$\mathbf{X}$	Loaded equilibrium position of the MS database in x-axis
$\mathbf{Y}$	Loaded equilibrium position of the MS database in y-axis
$\Delta \mathbf{X}$	Displacement from unloaded to loaded position of MS database in x-axis
$\Delta \mathbf{Y}$	Displacement from unloaded to loaded position of MS database in y-axis
F_1	Horizontal component of the tension of line one
F_2	Horizontal component of the tension of line two
F_3	Horizontal component of the tension of line three
a	Angle between F_1 and F_2
b	Angle between F_1 and F_{aero}
r_0	Radial displacement of the unloaded FOWT
diff	Difference between the targeted and MS crosswind displacements
$\mathbf{MS}_{\text{temp}}$	Temporary list of MS design
$\Delta y_{w, \text{rot}}$	Crosswind displacement of an MS after rotating its headings
k	Shape parameter of Weibull distribution
λ	Scale parameter of Weibull distribution
$\mathbf{K}$	Stiffness matrix
H_s	Significant wave height

T_p	Wave period
F_t	Rotor thrust
$F_{t,x}$	Rotor thrust component in the x direction
$F_{t,y}$	Rotor thrust component in the y direction
$C_{Meander}$	Wake meandering coefficient in FAST Farm
f_c	Cut off corner frequency in FAST Farm
$U_{amb,h}$	Ambient wind speed at hub height
ΔU	Difference between wind speed at hub height and $U_{amb,h}$

List of Subscripts

$(\cdot)_i$	referring to wind turbine i in the wind farm
$(\cdot)_j$	referring to wind direction j
$(\cdot)_s$	referring to wind speed s
$(\cdot)_0$	referring to baseline case
$(\cdot)_g$	referring to global coordinate system
$(\cdot)_w$	referring to wind coordinate system
$(\cdot)_{farm}$	referring to wind farm
$(\cdot)_{st}$	referring to the value at the start of the optimization process
$(\cdot)_c$	referring to the fatigue cycle c

ABSTRACT

Wind energy is essential for transitioning to sustainable energy sources. To harness its full potential, it is crucial to access locations with abundant wind resources. Interestingly, 60% to 80% of the most promising wind energy sites are located in deep waters offshore. These sites can only be utilized using offshore wind turbines.

Harnessing wind energy in deep waters not only taps into rich wind resources but also aims to boost the efficiency of wind farms by reducing energy losses. A significant source of these losses is known as wake losses.

The power generated by a wind turbine depends heavily on the wind speed hitting its rotor, specifically, it is proportional to the cube of this wind speed. As wind passes through a turbine, the blades extract energy, resulting in the wind flow, leaving the turbine with less energy, lower wind speed, and higher turbulence. When this lower-energy wind reaches another turbine downwind, the second turbine receives less wind speed and, therefore, produces less energy compared to the turbine upwind. This difference in energy production due to the shadowing effect of the first turbine is called wake losses.

This research introduces a new method to reduce wake losses in floating wind farms. The approach involves passively relocating the floating offshore wind turbines to optimize their positions relative to each other.

Unlike fixed turbines, floating offshore wind turbines are secured to the seabed with mooring lines, which allow them to move within a certain range. The extent of this movement depends on the design of the mooring system, as well as the wind speed and direction. For a given mooring system, the displacement of the turbine changes with varying wind conditions. Thus, by smartly designing the mooring system, we can control the movement of floating turbines to minimize wake losses.

This study explores the concept of designing customized mooring systems to create a floating wind farm layout that can adjust itself passively and reduce wake losses. These self-adjusting layouts should not only reduce wake losses but also be cost-effective. The design must ensure that the new mooring systems' costs are lower than current state-of-the-art mooring systems. Additionally, the fatigue and extreme loads on the turbine components mustn't increase due to the larger displacements of the turbines.

The research findings show that a passively self-adjusting wind farm layout increases a floating wind farm's annual energy production (AEP). Importantly, this improvement is accomplished without increasing the extreme and fatigue loads on the turbines, maintaining the safety and reliability of the FOWTs. For a layout of nine turbines, the AEP was increased by 1.5%, and the mooring system costs were decreased by 4%. For the Horns Rev 1 layout in the North Sea with 80 turbines, the AEP increased by 1%, and the costs decreased by 6%. These results indicate significant potential for scalable and cost-effective improvements in floating offshore wind energy production.

In summary, this work presents a promising approach to enhancing the efficiency of floating wind farms by smartly designing mooring systems that allow turbines to adjust their positions passively. This innovation not only taps into abundant offshore wind resources but also enhances energy production and reduces costs, paving the way for more sustainable and efficient wind energy solutions.

ZUSAMMENFASSUNG

Windenergie ist entscheidend für den Übergang zu nachhaltigen Energiequellen. Um ihr volles Potenzial auszuschöpfen, ist es wichtig, Standorte mit reichlich Windressourcen zu erschließen. Interessanterweise befinden sich 60% bis 80% der vielversprechendsten Windenergiestandorte in tiefen Gewässern offshore. Diese Standorte können nur mit Hilfe von Offshore-Windturbinen genutzt werden.

Die Nutzung von Windenergie in tiefen Gewässern erschließt nicht nur reiche Windressourcen, sondern zielt auch darauf ab, die Effizienz von Windparks durch die Verringerung von Energieverlusten zu steigern. Eine bedeutende Quelle dieser Verluste sind sogenannte Nachlaufverluste.

Die von einer Windturbine erzeugte Leistung hängt stark von der Windgeschwindigkeit ab, die auf ihren Rotor trifft, insbesondere ist sie proportional zur dritten Potenz dieser Windgeschwindigkeit. Wenn der Wind durch eine Turbine strömt, entziehen die Blätter Energie, wodurch der Windstrom, der die Turbine verlässt, weniger Energie, eine geringere Windgeschwindigkeit und eine höhere Turbulenz aufweist. Wenn dieser energieärmere Wind eine weitere Turbine im Nachlauf erreicht, empfängt die zweite Turbine eine geringere Windgeschwindigkeit und produziert daher weniger Energie im Vergleich zur vorlaufenden Turbine. Dieser Unterschied in der Energieerzeugung aufgrund des Schatteneffekts der ersten Turbine wird als Nachlaufverluste bezeichnet.

Diese Forschung stellt eine neue Methode vor, um Nachlaufverluste in schwimmenden Windparks zu reduzieren. Der Ansatz besteht darin, die Positionen der schwimmenden Offshore-Windturbinen passiv zu optimieren.

Im Gegensatz zu feststehenden Turbinen sind schwimmende Offshore-Windturbinen mit Verankerungslinien am Meeresboden gesichert, die ihnen erlauben, sich in einem bestimmten Bereich zu bewegen. Das Ausmaß dieser Bewegung hängt vom Design des Verankerungssystems sowie von der Windgeschwindigkeit und -richtung ab. Bei einem gegebenen Verankerungssystem ändert sich die Verschiebung der Turbine je nach Windbedingungen. Durch eine intelligente Gestaltung

des Verankerungssystems können wir somit die Bewegung der schwimmenden Turbinen steuern, um Nachlaufverluste zu minimieren.

Diese Studie untersucht das Konzept, maßgeschneiderte Verankerungssysteme zu entwerfen, um eine schwimmende Windparkanordnung zu schaffen, die sich passiv anpassen und Nachlaufverluste reduzieren kann. Diese selbstanpassenden Anordnungen sollten nicht nur Nachlaufverluste reduzieren, sondern auch kosteneffektiv sein. Das Design muss sicherstellen, dass die Kosten der neuen Verankerungssysteme niedriger sind als die der aktuellen fortschrittlichen Verankerungssysteme. Darüber hinaus dürfen die Ermüdungs- und Extrembelastungen auf die Turbinenkomponenten durch die größeren Verschiebungen der Turbinen nicht zunehmen.

Die Forschungsergebnisse zeigen, dass eine passiv selbstanpassende Windparkanordnung die jährliche Energieproduktion (AEP) eines schwimmenden Windparks steigert. Wichtig ist, dass diese Verbesserung ohne eine Erhöhung der Extrem- und Ermüdungsbelastungen der Turbinen erreicht wird, wodurch die Sicherheit und Zuverlässigkeit der FOWTs erhalten bleibt. Für eine Anordnung von neun Turbinen wurde die AEP um 1.5% erhöht und die Kosten für das Verankerungssystem um 4% gesenkt. Für die Horns Rev 1 Anordnung in der Nordsee mit 80 Turbinen stieg die AEP um 1% und die Kosten sanken um 6%. Diese Ergebnisse zeigen ein erhebliches Potenzial für skalierbare und kosteneffiziente Verbesserungen in der schwimmenden Offshore-Windenergieerzeugung.

Zusammenfassend stellt diese Arbeit einen vielversprechenden Ansatz zur Verbesserung der Effizienz von schwimmenden Windparks durch die intelligente Gestaltung von Verankerungssystemen vor, die es den Turbinen ermöglichen, ihre Positionen passiv anzupassen. Diese Innovation erschließt nicht nur reichlich Offshore-Windressourcen, sondern steigert auch die Energieproduktion und senkt die Kosten, wodurch der Weg für nachhaltigere und effizientere Windenergielösungen geebnet wird.

INTRODUCTION

“*Ideas are the seeds of creation. They germinate and grow,
even if the sower is long forgotten.*”

1.1 Floating offshore wind potential

As climate change increasingly impacts our daily lives, there is a pressing need for a transition toward cleaner energy sources. This transition has led to a notable growth in installed wind energy capacity, with wind farms established onshore and offshore. However, onshore wind energy is limited by the scarcity of attractive sites with high energy resources and is often criticized due to noise emission and visual pollution. Consequently, offshore wind energy has gained attractiveness due to its reliable wind resources and high wind speeds. Offshore wind is divided into two categories; the first is the bottom fixed offshore wind, where the turbine is placed on top of a monopile or jacket structure attached to the seabed. However, bottom-fixed offshore wind is only economical in shallow water with a depth below < 60 m (Wind Europe, 2017). In the second category are floating offshore wind turbines (FOWTs) constructed in the deep water sites. FOWTs are not fixed to the seabed but instead anchored to the seabed using mooring lines.

According to Wind Europe (2017) report, 80% of the offshore wind resources in Europe and Japan lie in deep waters, while the percentage of the deep water offshore wind resources in the USA is 60%. Therefore, floating wind farms (FWFs) are constructed in wind sites with deep waters to harness wind energy resources. By the end of 2022, the global floating offshore wind

(FOW) installed capacity reached 123.4 MW, with projects in the pipeline with total capacities of 102.5 GW (Musial et al., 2023). DNV GL (2022) predicts that the global FOW installed capacity will reach 264 GW by 2050. This is a 2000-fold increase in 28 years. Hence, there is an urgent need to find smarter designs for floating wind farms, decreasing FOW's losses and the levelized cost of energy (LCOE). Therefore, I will present in this work an innovative method for designing FWFs to increase the annual energy production (AEP) while decreasing the costs. First, I will start by showing the state of the art of FOWTs design in the following section.

1.2 FOWTs design

FOWT design can be divided into four main components:

- **Rotor nacelle assembly (RNA)** of a FOWT is identical to the RNA for onshore and fixed-bottom offshore turbines. It consists of the blades, the hub, and the nacelle containing the generator.
- **Tower** of a FOWT is redesigned to withstand the higher loads at the tower base due to the platform motion in pitch and roll degrees of freedom (DoFs). As the floating platform pitches forward or backward or rolls right or left, the bending moment at the tower base increases. Therefore, the tower of a FOWT needs to be redesigned to withstand higher loads than onshore and fixed-bottom offshore wind turbines.
- **Floating platform** is the foundation that carries the tower and the RNA. Floating platforms can be classified into four categories based on their method of achieving hydrostatic stability. Spar (Mahfouz et al., 2020) and tetra-spar (Thomsen et al., 2021) floaters are ballast stabilized, while semisubmersible floaters (Mahfouz et al., 2020; Allen et al., 2020) depend on their large water plane area to achieve hydrostatic stability. Additionally, tension leg platforms (Matha, 2010) (TLPs) rely on the mooring lines' tension to achieve hydrostatic stability. Barge floaters (Vijay et al., 2016) achieve hydrostatic stability primarily through their large water plane area and ballast systems. Regardless of the floater hull shape, it can be made of concrete or steel. Several floating platform designs are currently used within the existing FWFs and the upcoming ones.
- **Mooring system (MS)** is responsible for the station keeping of the FOWTs. The number of mooring lines in an MS can vary according to the MS design loads to withstand the required design lifetime. Each mooring line is attached to the seabed with an anchor. The most common materials for mooring lines are steel chains, polyester synthetic ropes, and nylon synthetic ropes. Clump weights and buoyancy elements can be attached to the mooring lines to enhance the MS performance or to decrease the loads on the lines. MSs can be catenary, taut, or semi-taut, depending on the water depth at which the FOWTs

will be installed. There are several types of anchors, such as drag-embedment anchors (DEAs), suction anchors, vertically loaded anchors (VLAs), and suction piles and plate anchors (SEPLAs). The type of anchor used depends on the seabed soil and the magnitude and direction of the tension force of the attached mooring lines.

Since the FOWT is not fixed to the seabed but instead attached to it by the MS, the FOWT can move horizontally within a specific area at the mean sea level (MSL) plane. This area within which the FOWT can move freely is known as the watch circle. The watch circle's size and shape depend on the MS design. The MS provides stiffness for the FOWT in the surge, sway, and yaw DoFs. Hence, the mean displacement in the surge and sway depends on the MS design. The smallest surge and sway displacements happen at the cut-in wind speed of the FOWT, while the largest displacements happen at rated wind speed where the thrust force is the highest. Additionally, at the same wind speed but in different wind directions, the FOWT displacements are different.

Figure 1.1 shows an example of an MS watch circle. In the absence of wind and wave forces, the FOWT is at $(0,0)$, and the white ellipse in the middle is when the wind speeds are below the cut-in value. The red-shaded area is the watch circle between the cut-in and cut-out wind speeds of the FOWT. Each dotted line represents the watch circle of the FOWT at each wind speed between cut-in and cut-out speeds. As the wind direction changes, the FOWT position changes. Therefore, we can know the position of the FOWT in the watch circle in Figure 1.1 if we know the mean wind speed and direction.

Presently, state-of-the-art MS designs are influenced by the oil and gas industry and focused on constraining the horizontal movements of FOWTs, aiming to minimize the size of the watch circle. Two factors drive these limitations on horizontal excursions. Firstly, the layout design of the FWF imposes a minimum distance requirement between individual FOWTs to prevent them from getting too close to each other and increasing the wake losses. Secondly, cable design considerations also dictate restrictions on horizontal offsets, as larger excursions can lead to longer dynamic cables and increased fatigue and extreme loads. To the best of my knowledge, no work has been done quantifying the maximum FOWT excursions that the dynamic cable can withstand or quantifying the increase in cable costs as the FOWT's excursion increases.

Throughout this work, I will not address the impact of horizontal excursions on cable design, as it falls outside the scope of this research. Instead, I will focus on MS designs that allow large horizontal excursions compared to current state-of-the-art designs. However, I will always ensure that the constraint with a predefined minimum distance between the FOWTs in the FWF is always satisfied.

1.3 Wake losses inside a wind farm

Wind turbines are clustered together to benefit the most from attractive wind energy sites, and wind farms are strategically established in areas with abundant wind resources to harness wind energy efficiently. However, the expansion of wind farms, while maximizing energy production, introduces a challenge in the wake losses within the farm. When the wind flows through a wind turbine, the turbine converts the wind's kinetic energy into electrical power. The power generation capacity of a turbine is directly related to the cube of the average wind speed within the wind field.

Conversely, as the wind flows through the turbine and leaves, it does so at a reduced speed and with increased turbulence. When this slower, more turbulent air reaches a downstream turbine within the same wind farm, it has less kinetic energy to be harnessed. Consequently, the downstream turbine generates less power compared to its upstream counterparts. In addition, as the downwind field is more turbulent, the downwind turbine suffers from higher loads (Thomsen and Sørensen, 1999). This highlights the importance of optimizing wind farm layouts and turbine spacing to minimize wake losses and maximize energy production.

The current state-of-the-art wind farm design techniques mitigate wake losses by optimizing the layout. The optimization process can have different objectives depending on the wind farm and site conditions. The most common optimization objective is to increase the wind farm's AEP

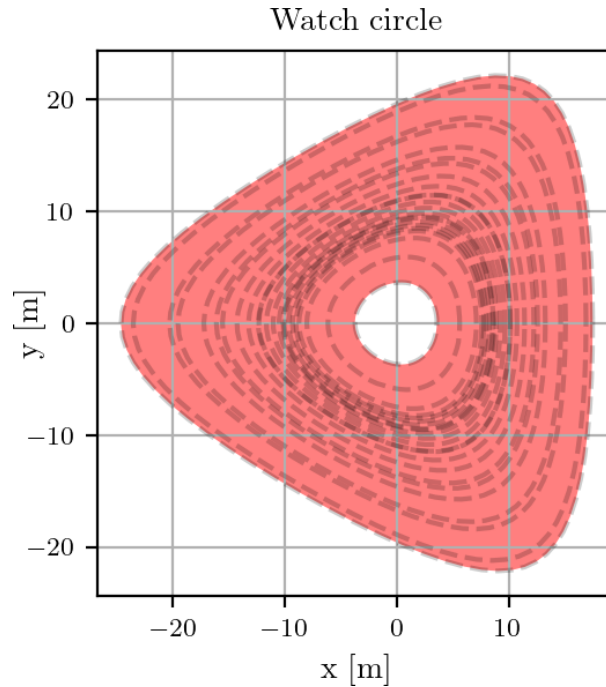


Figure 1.1: MS watch circle

(Thomas et al., 2023; Thomas and Ning, 2018). Another objective is to optimize the layout such that the power cable length is minimal or to optimize the wind farm to increase the energy density (Fleming et al., 2016). Finally, since the wind farm layout optimization is a complex problem with multidisciplinary components, multidisciplinary design analysis and optimization (MDAO) is used to decrease the overall LCOE of the wind farm (Perez-Moreno et al., 2018).

Despite existing wind farm layout optimization techniques, wake losses still represent 10% – 25% in wind farms as shown in the works of Barthelmie et al. (2009, 2010). This is due to the complexity of the wind farm optimization problems and the existing constraints limiting the current wind farm optimization techniques. For example, the number of wind turbines to be placed inside the wind farm compared to the lease area or the shape of the lease area hinders the performance of the wind farm layout optimization algorithms.

Therefore, new methods emerged to decrease the wake losses inside the wind farm and mitigate the effect of the wakes independent from the wind farm layout optimization. The first approach is wake steering by optimizing the nacelle yaw angle of each turbine inside the farm according to the wind direction, as shown in the works of Stanley et al. (2022, 2023). Wake steering tries to overcome the inability to relocate the wind turbines by deflecting the wake so as not to hit the downwind wind turbine rotor. The goal is to yaw the upwind turbines to horizontally deflect the wakes away from downwind ones and increase the farm’s energy production.

1.4 Relocating FOWTs out of the wake

With the emergence of FOWTs and FWFs, another approach came up to relocate the FOWTs out of the wakes and benefit from the ability of FOWTs to move. The goal is to mitigate wake losses inside an FWF by relocating the FOWTs to steer the wake of the upwind turbines away from the downwind ones. The idea is explained in Figure 1.2, where the black dots are the static equilibrium positions of the wind turbines in the absence of wind. The left side is a fixed bottom wind farm, where the positions of the wind turbines are fixed, and the right side is a relocating FWF where the FOWTs move in the crosswind direction to mitigate wake effects.

The idea of relocating the downwind FOWTs out of the wakes of upwind ones was first discussed by Fleming et al. (2015). Two wind turbines were placed behind each other, and for one wind direction, the downwind turbine was displaced in the crosswind direction. The results showed that displacing the downwind turbine in the crosswind direction by a distance equivalent to one rotor diameter (D) increased the power of the downwind turbine by 41%. However, the downwind turbine was displaced manually, and how to achieve this displacement was not discussed. In Fleming et al. (2015), the authors assumed the FOWTs could relocate in the crosswind direction.

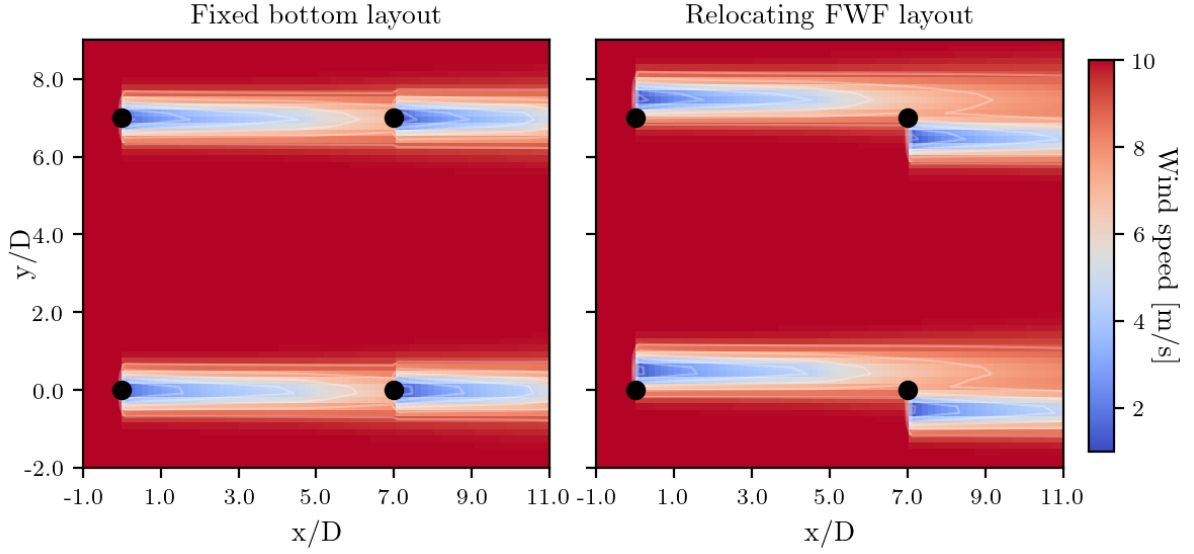


Figure 1.2: Relocating FOWTs in an FWF. The black dots are the static equilibrium position of the wind turbines in the absence of wind

$$\eta_{farm} = \frac{AEP_{farm}}{AEP_{opt}} \quad (1.1)$$

Rodrigues et al. (2015) added pulleys on the floating platform and developed a controller to change the mooring lines' tension according to the wind directions. The goal is to change the mooring lines' length and the MS stiffness and move the FOWT. The method was applied on a wind farm with a capacity of 180 MW and 36 identical FOWTs. The results showed that the wind farm efficiency η_{farm} increased by 4.4%. The wind farm efficiency is defined in equation 1.1. AEP_{farm} is the AEP of the wind farm calculated, including the wake effects, while AEP_{opt} is the optimum AEP calculated, assuming an ideal situation where the wake losses are zero.

Kheirabadi and Nagamune (2019a,b, 2020) presented a new yaw and induction-based turbine repositioning (YITuR) controller design to increase the energy production of an FWF. The goal was to yaw FOWTs to create a crosswind force to move them out of the wake because when the nacelle is yawed, a component of the thrust force acts in the crosswind direction. Additionally, due to yawing the nacelle, wake steering deflects the wake and decreases wake losses. The results showed that the farm efficiency using the YITuR controller increased by 22% compared to the farm efficiency without the YITuR controller for a single wind direction and a single wind speed. However, the results showed that the method's performance depends on the MS design governing the FOWTs displacements.

1.5 Motivation and objectives

The results from Rodrigues et al. (2015); Kheirabadi and Nagamune (2019b,a, 2020) show that relocating the FOWTs in an FWF to decrease wake losses has high potential. However, both methods depend on controllers to actively yaw the RNA or change the mooring line length according to the wind direction to increase the FWF's energy production. Moreover, both methods were verified only using static tools without dynamic verification. Additionally, the effect of relocating the FOWTs on their fatigue and ultimate loads was not quantified. These missing gaps motivated me to go deeper into this topic.

Therefore, the goal of this work is to answer three research questions:

1. **Can passive relocation of FOWTs inside an FWF reduce wake losses and the MS costs?**

The idea is to develop a methodology to integrate the MS design as part of the FWF layout design and use the MS to passively relocate the FOWTs out of the wake based on the wind direction. I will also analyze the effect of different MS design parameters on the FOWT's ability to relocate and the shape of the watch circle. Additionally, I will check if the new MS designs are cheaper than the current state-of-the-art MS designs.

2. **How do the MS design parameters affect the watch circle?**

The MS design parameters control the FOWT's relocation. The MS watch circle describes how much the FOWT is allowed to relocate for every wind direction. I will study how each of the MS design parameters affects the shape of the watch circle, focusing only on catenary MS designs.

3. **What are the consequences of relocating FOWTs on the fatigue and ultimate loads experienced by the FOWT?**

The current state-of-the-art MS design minimizes the relocation of the FOWTs. I will investigate the effect of the larger motion magnitudes on the FOWT's loads by checking the fatigue and ultimate loads of the different FOWT components (blades, tower, and mooring lines).

1.6 Research structure

The dissertation is structured in eight chapters; I aimed to make each chapter readable as standalone by stating each chapter's goals and conclusions. Since the research idea presented is novel, the dissertation is structured to show how the research idea develops, and the technology

readiness level (TRL) increases from one chapter to another. Chapter 2 briefly introduces the current state of the art of FOWT and FWF modeling techniques with a quick touchdown on the theory behind each method. Then, I will introduce the engineering models used in the work. Finally, I will introduce the reference FOWT and the reference MS design, along with the design loads for the different components of the FOWT. Chapter 3 introduces the method I developed to check if the FOWT displacement can decrease the wake losses in the FWF. The process is explained in detail, along with a simple example. Additionally, in Chapter 3, I show a detailed analysis of the different MS design parameters and how each parameter affects the shape and size of the watch circle to answer the second research question. In Chapter 4, I test the performance of the novel methodology against different user inputs and design choices to show the reliability of the tool developed. Chapter 5 focuses on answering the third and final research question on how the larger FOWT displacements affect its loads. A detailed analysis covering a wide range of fatigue and extreme load cases is carried out. To fully answer the first research question, the AEP gain newly designed FWF layout is verified using mid-fidelity models in Chapter 6. Chapter 7 adds more constraints on the developed method to test its capabilities in a realistic scenario on decreasing the wake losses inside the FWF. Finally, in Chapter 8, I summarize the findings and present the conclusion.

STATE OF THE ART

2.1 Overview

This chapter will present a literature review of the current techniques used while designing and modeling an FWF. Afterward, I will introduce the engineering tools and the coordinate reference system used throughout this work. Then, I will introduce the reference FOWT used throughout this research. Finally, I will introduce the methods used for load assessment, AEP, and wake loss calculations.

2.2 Modelling of the wind flow inside a wind farm

Figure 2.1 shows the three main aspects considered in the literature and the current state-of-the-art while modeling an FWF. The first aspect of modeling an FWF is to capture the wind flow inside the wind farm. Barthelmie et al. (2009, 2010) show that the wake losses inside a wind farm are between 10% – 25%, and (Thomsen and Sørensen, 1999) shows that the fatigue loads for a wind turbine in the wake are higher by 5% – 15% than a wind turbine in the free

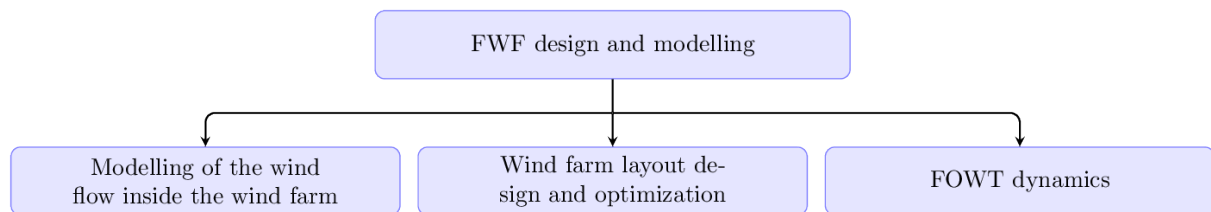


Figure 2.1: FWF design and modeling

flow. Therefore, capturing the wake evolution in a FWF with high accuracy is essential. The wake behind a wind turbine is divided into near and far wake regions (Porté-Agel et al., 2020). The near wake region extends for $2 - 4D$ behind the wind turbine, and the geometry of the RNA influences its complex flow and the pressure field behind the rotor. The far wake region starts afterward, and the wake evolution is no longer influenced by the RNA geometry but rather by the rotor thrust coefficient and the turbulent mixing due to the ambient turbulence and the turbulence at the shear layer of the wake (Ainslie, 1988). The wake profile is assumed to be Gaussian at the far wake region. Downwind turbines are placed at least $4D$ away from upwind ones; hence, the far wake region is more relevant for analyzing the loads and power production inside a wind farm. In general, the wind flow models inside a wind farm can be divided into three categories based on fidelity: high, mid, and low fidelity models.

2.2.1 Low fidelity wake models

The low-fidelity models are steady-state wake models, including velocity deficit, turbulence, and wake deflection models. The deficit model calculates the wind velocity deficit behind the turbine; examples of velocity deficit models are the Jensen wake model presented by Jiménez et al. (2009) and the Gaussian wake model presented by Bastankhah and Porté-Agel (2016); Niayifar and Porté-Agel (2016). The turbulence model accounts for the turbulence added to the wake as the wind passes through the turbine rotor. The implementation introduced in Crespo and Hernández (1996) is widely used as a steady-state turbulence model. Finally, the deflection model, such as the Gauss deflection model, accounts for the wake deflection caused by yaw misalignment.

The low-fidelity wake models are fast and are capable of capturing the power production of the wind farm with a good agreement to higher fidelity models. Therefore, these models are used in the design phase for wind farm layout optimization and for designing a wake steering control strategy for a wind farm. However, the low fidelity models cannot capture the loads on the turbine inside the wind farm and the meandering of the wake as it advects downstream.

2.2.2 Mid-fidelity wake models

Mid-fidelity wake models aim to fill in the gaps left by the low-fidelity models without becoming as computationally expensive as the high-fidelity models. Therefore, mid-fidelity models aim to capture the power production inside a wind farm and the loads acting on the turbines. The dynamic wake meandering (DWM) model is widely used as a mid-fidelity wake model. DWM consists of three main models to account for the wake's different aspects: velocity deficit, wake meandering, and wake-added turbulence (Larsen et al., 2008; Madsen et al., 2010; Hao,

2016). Velocity deficit is modeled based on a thin shear layer approximation of the Navier–Stokes equations in their rotational symmetric form, based on the work of Ainslie (1988), which assumed that the pressure gradients are negligible compared to the turbulent mixing of the velocity deficit in the far wake region. This assumption is valid as the pressure inside the wake recovers to atmospheric pressure after $2D$. Moreover, Ainslie (1988) assumed that the gradients of the velocity deficit in the axial direction are much smaller than those in the radial direction.

Wake meandering is the horizontal and vertical movements of the entire wake, as the wake does not move in a straight line behind a turbine. Wake meandering is necessary for load calculations at a downwind turbine as the turbine’s rotor can be partially in the wake or even out of the wake due to wake meandering, which will alter the fatigue loads on the rotor blades as well as the power produced by the turbine. Wake meandering is modeled based on the assumption that wakes act as passive tracers whose motion is governed by the large-scale turbulence structures in the wind field. Hao (2016) shows that turbulent eddies larger than $2D - 3D$ drive the meandering of the wake.

Finally, the wake’s turbulence intensity has three sources: the ambient turbulence intensity, the turbulence intensity from wake meandering and the wake-added turbulence. The wake-added turbulence accounts for small-scale turbulence in the wake resulting from the breakdown of the tip and root vortices of the upwind turbine, as well as wake shear. Madsen Aagaard et al. (2008) shows that including the wake-added turbulence in the DWM model increases the flap-wise fatigue loads on the blade by 6%, compared to when the wake-added turbulence is neglected. Madsen et al. (2010) shows that the value of the wake-added turbulence increases as the ambient turbulence decreases, which makes wake-added turbulence more critical for offshore wind farms where the ambient turbulence is usually below 10%. Similar conclusions were reached in the work of Kretschmer et al. (2021).

Free wake vortex methods represent an intermediate step between the mid-fidelity and high-fidelity wake models. The vortex-based methods track the vorticity shed behind the wind turbine rotor as it interacts with the wind field (Branlard, 2017; Dong, 2022). The fidelity of the free wake vortex method depends on the formulation used for the aerodynamic models of the blades and the flow models to capture the wake. The aerodynamic models used in vortex-free methods include the lifting line, potential panel, vortex lattice, and viscous-inviscid panel methods. The flow models include the filament wake methods, free wake filament methods, hybrid filament-particle-mesh methods, and particle-mesh methods (Ramos-García et al., 2022b). For more details on vortex-based methods, Branlard (2017) presents different free wake vortex methods and their pros and cons compared to each other and high-fidelity models.

2.2.3 High fidelity wake models

The high-fidelity models use computational fluid dynamics (CFD) to solve the Navier-Stokes equations. Tossas and Leonardi (2013) presents the Reynolds averaged Navier-Stoke (RANS) method and the large eddy simulation (LES) method as the two methods used to model the wind turbine flow. The accuracy of both methods is higher than that of low and mid-fidelity methods as fewer assumptions are made. Still, they are computationally expensive and cannot be used in the wind farm design process. The current practice only uses the LES and RANS simulations to verify the low and mid-fidelity model results, which are used to design and optimize the wind farm layout and controller. LES and RANS simulations are also used to study and understand the flow around a wind turbine.

2.2.4 Effect of FOWTs on wake evolution

Another aspect that affects the wind flow inside the farm and needs to be considered to capture the flow with higher accuracy is the movement of the FOWT. The movement of the FOWT in pitch, roll, surge, and sway DoFs leads to the oscillation of the rotor, which affects the wake produced by FOWT and alters its evolution compared to the wake of fixed bottom turbines. The first difference is due to the FOWT's pitch motion. Ramos-García et al. (2022b,a); Wise and Bachynski (2020) show that when the FOWT is pitched backward (rotor facing upwards) due to the thrust force, the wake is deflected upwards, which leads to a faster wake recovery. Ramos-García et al. (2022a) also shows that the power produced by a downwind turbine in an FWF is higher compared to a fixed bottom wind farm at ambient turbulence intensity lower than 10%.

Nanos et al. (2022) investigated the effect of using vertical wake steering to benefit from the wake deflection of a FOWT. The results showed that deflecting the wake downwards by pitching the FOWTs forward (rotor facing downwards) is more beneficial than pitching it backward. Forward pitching of the FOWT leads to a power gain of 8% for a downwind turbine with $6D - 8D$ spacing. The forward pitching was achieved using a ballast control that changes the floater's center of gravity (CG) and, hence, the mean pitch value. Moreover, the results showed that the wake deflection has a minor effect on the RNA fatigue loads, while the fatigue loads on the MS increased by 13%.

Finally, Ramos-García et al. (2022b) shows that the oscillation motions of the rotor of a FOWT increase the turbulence behind the turbine. This also leads to a faster wake recovery when compared to the wake of a fixed bottom turbine. The results show that the wake recovery at $6D$ behind a FOWT was 9% higher than a fixed bottom turbine.

2.3 FWF layout design

The second aspect of modeling an FWF in Figure 2.1 is wind farm layout design and optimization. A fixed-bottom wind farm layout design is a challenging problem with complex multidisciplinary design parameters. The layout optimization process optimizes the wind turbine positions to decrease the LCOE of the wind farm. Decreasing the LCOE is done by either reducing the costs of different components within the wind farm while increasing the AEP of the farm, reducing the wake losses, or increasing the AEP of the wind farm without increasing the cost of any of the components. The optimization process is constrained by the size and shape of the wind farm lease area and the number of wind turbines to be placed within this area.

The layout design and optimization process becomes more challenging for an FWF layout design. In an FWF layout design, more constraints and design parameters are added to the design optimization problem. An FWF layout design needs to account for the MSs coupled to the FOWTs to ensure they are not tangled and to keep a minimum distance between the mooring lines at all times. Moreover, the design needs to account for the bathymetry of the seabed, which might differ within the FWF lease area, leading to different mooring line designs. Additionally, the wind farm layout design needs to account for the various types of soil on the seabed, which affects the types of anchors used and their installation process. Finally, the inter-array cable connection inside an FWF has a necessary dynamic section since the FOWTs are not fixed in their position but move within their watch circles. To the best of my knowledge, only the recent works by Hietanen et al. (2024); Hall et al. (2024) shed light on some of these challenges for FWF layout design and presents a method to include these constraints and design parameters in the FWF layout design optimization problem.

Another main difference between FWFs and fixed-bottom wind farms is the ability of FOWTs to relocate their position inside their watch circles according to wind speed and direction. Currently, FOWTs are assumed to be fixed while the FWF layout is being designed. This assumption is inaccurate, and even if the motions of FOWTs are limited to 10% – 20% of the water depth, this is equivalent to 20 – 40 m for a water depth of 200 m. The work done by Fleming et al. (2015) shows how the energy produced by a downwind turbine increases by 4.1%, to up to 41% if it is displaced by $20\%D$ to up to $100\%D$. The results assumed that the downwind turbine was fully in the wake at the beginning of the study. Neglecting this effect during the layout optimization leads to a higher uncertainty in FWF's AEP calculations and, hence, a higher risk of investment (Bodini et al., 2020). The movement of the FOWTs can also lead to a decrease in AEP inside an FWF. If a downwind FOWT, which is assumed to be out of the wake or partially out during the design process, relocates its position to be in the wake, the AEP of the FWF will decrease.

The optimization algorithms used in wind farm layout optimization can be divided into two main groups: gradient-based and gradient-free methods. The gradient-based methods use the slope

and derivatives of the objective function to reach the optimum design. Gradient-based methods use the objective function's gradient and curvature to define the optimizer's step direction. Therefore, their performance is highly affected by the continuity and the smoothness of the objective function, as well as the initial conditions. Moreover, gradient-based methods can follow the slope of the curvature to the nearest local optimum and become unable to find the global optimum. However, due to their knowledge of the design space through the objective function derivatives, gradient-based methods scale better with larger problems with many design variables and constraints. Several methods exist to compute the derivatives for the gradient-based algorithms as introduced by Martins and Ning (2021), such as finite difference, complex step, and algorithmic difference. The choice of the method to calculate the derivatives depends on the knowledge and control over the optimization process. The finite difference method is used for a black box optimization, while an algorithmic differentiation is used for an optimization where the user can access the source code.

On the other hand, for gradient-free optimization, the optimization algorithm explores the design space by iteratively evaluating the objective function at various points without relying on gradient information. Therefore, computational costs become expensive as the size of the design variables and the design space increases. The step direction of a gradient-free method does not depend on the objective function and its derivative but rather on the optimization algorithm used.

The choice between gradient-based and gradient-free optimization methods in wind farm layout optimization depends on factors like the smoothness of the objective function, the level of control over the optimization process, and the scale of the problem. Gradient-based methods are advantageous for larger problems with derivable objective functions, while gradient-free methods are suitable for smaller-scale problems where derivatives are challenging to compute. Finally, it is common practice for wind farm layout optimization to repeat the optimization several times with randomized inputs to avoid local minimum. Gradient-based and gradient-free methods are widely used for wind farm layout optimization, as shown in the works of Fleming et al. (2016); Baker et al. (2019); Perez-Moreno et al. (2018).

2.4 Modelling techniques of FOWTs

The last aspect of FWF modeling in Figure 2.1 is modeling each FOWT. A FOWT is a multidisciplinary system with different excitation forces summarized in Figure 2.2. The numerical tools that capture the FOWT and its components can be divided into three categories according to their fidelity level: low fidelity, mid-fidelity, and high fidelity. The FOWT models try to capture all the excitation forces and their effects on the FOWTs' loads and motions. The excitation forces on a FOWT include the inertia forces and structure dynamics of the blades

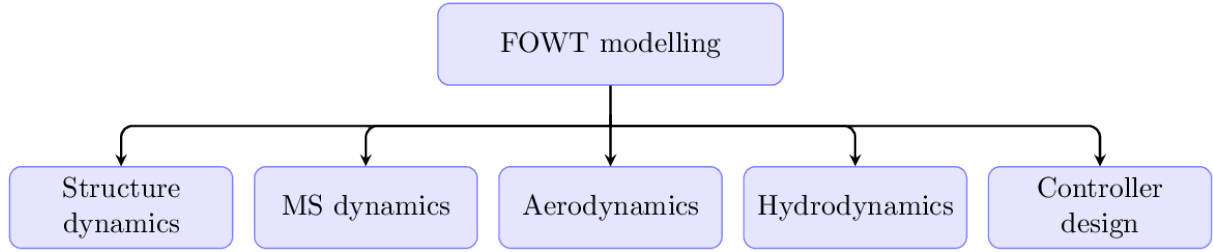


Figure 2.2: FOWT modelling

and the tower, the MS dynamics, the aerodynamic forces on the rotor, the hydrodynamic forces acting on the floating platform, and the servodynamic forces from the wind turbine controller. The fidelity with which the FOWT's components are modeled depends on the use case and the purpose of the research work. First, I start with the different fidelity used to capture the structure dynamics.

2.4.1 Structure dynamics

The current state-of-the-art of modeling FOWTs is to model them as multibody systems (MBS), which gives the numerical models flexibility. Different components of the FOWT are modeled with different methods and fidelity. Moreover, the details of the structure dynamics model of each component of the FOWT depend on the purpose of the numerical model and the research questions it tries to answer.

The floating platform is usually modeled as a rigid point mass with six degrees of freedom and a hydrostatic stiffness matrix. The hydrostatic stiffness of the floating platform can be calculated by knowing the CG of the floater, the water plane area (AWP), the water displaced volume of the floater, and the metacentric height (MC). An assessment of the effect of floater flexibility for a spar floater was presented in Borg et al. (2016). It was found that when a flexible mode was introduced, the overall response behavior of the rigid body modes was preserved. However, the response amplitude operators (RAOs) for linear wave forcing of surge and pitch increased. As the floating platform size increases and their designs become more flexible to decrease FOWT's cost, it can become more necessary to include the flexibility of the floater.

Due to the aerodynamic thrust force acting on the rotor, the tower bends and moves in the fore-aft and side-to-side DoFs, and hence, the tower is usually modeled as a flexible body. There are different methods for modeling the tower structure, such as finite element method (FEM), modal decomposition methods, or modeling the tower as a Timoshenko beam. FEM is the highest fidelity of these methods, and hence it is not commonly used for FOWTs dynamic simulations as it is computationally expensive; it is instead used to analyze the loads and stresses at different components of the system separately. The FEM is used to calculate the natural

frequencies and the mode shapes of the tower, which are later used in the modal decomposition method. Modeling the RNA is divided into two parts: the nacelle and hub are modeled as rigid point masses, while the blades are modeled using the same method used for modeling the tower structure.

The numerical models can further simplify the FOWT's structure according to their use case. For example, for wind turbine control design or tuning, the rotor is often modeled as a solid disk with the thrust and power coefficients at different tip speed ratios and pitch angles implemented as a look-up table. Moreover, the tower is flexible, and the DoFs of the floating platform are reduced to 3 DoFs (Lemmer et al., 2020). These simplifications are needed during the controller design and tuning as many simulations can be run quickly. Additionally, such simple models can be used for designing a tuned liquid damper for the FOWTs, as in the work by Yu et al. (2023).

2.4.2 MS dynamics

In dynamic models, mooring lines are modeled using lumped mass discretization, where the mooring lines are divided into sections with nodes at the start and end of each section where the segment's mass is lumped. The nodes are connected through cylindrical cables with the mooring lines' axial, torsional, and bending stiffness properties. The buoyancy and hydrodynamic forces are calculated directly at the nodes. The hydrodynamic forces account for the Morison drag and added mass, and wave kinematics can also be applied to several mooring line models. The friction of the mooring lines with the seabed is accounted for using horizontal friction coefficients and vertical spring-damper coefficients. (Hall and Goupee, 2015; Devries and Hall, 2018)

Several quasi-static numerical tools are available for modeling mooring lines. These tools also use lumped mass discretization, but the dynamic effects, including the drag and the hydrodynamic forces, are missing. These tools are used at an early stage for MS design and optimization.

2.4.3 Aerodynamics

Blade element momentum (BEM) theory is used to model the aerodynamic forces acting on FOWTs and calculate their power production and is considered an industry-standard method. BEM discretizes the blade into segments with a separate lift and drag coefficient for the local angle of attack at each element, with no interactions between the different blade segments. The lift, drag, and thrust forces are afterward integrated over the length of the rotor blades. BEM also applies tip loss correction factors to account for tip vortices that reduce the aerodynamic performance of the blades, such as the Prandtl tip loss correction. (Hansen, 2000; Manwell et al., 2009)

Despite being a reliable and computationally efficient method for calculating the rotor's aerodynamic forces, BEM cannot simulate unsteady aerodynamics. The oscillations of FOWT can cause the rotor to operate in unsteady aerodynamic states. Dong (2022) shows that due to the surge and pitch oscillations of the FOWT, the rotor can operate in its wake, known as the vortex ring state. Tran and Kim (2016) show that the amplitude of the aerodynamic power oscillation is four times higher when accounting for the unsteady aerodynamics. Additionally, the average mooring line tensions increase by 32%. Therefore, higher fidelity models, such as the free vortex and CFD models discussed in section 2.2, are needed to account for the FOWT's unsteady aerodynamics. The operation of FOWTs in an unsteady aerodynamic state differs from one FOWT design to another, as it is affected by the frequency of oscillations of the floating platform and their amplitudes (Tran and Kim, 2016; Ramos-García et al., 2022b).

In numerical models where the loads on the blades are not needed but instead the thrust force and the aerodynamic power, the rotor is modeled as a rigid disk. This approach is required when computational efficiency is necessary, especially for design and optimization, such as for the wind turbine controller design and optimization. Additionally, low-fidelity wake models consider the rotor as a rigid disk, and such numerical efficiency is needed for wind farm layout optimization.

2.4.4 Hydrodynamics

Hydrodynamic forces acting on a FOWT are divided into viscous and inertial forces. The inertial forces have two components: linear first-order forces and second-order forces. The potential flow theory calculates the inertial forces acting on the FOWT, using panel codes such as Ansys AQWA (ANSYS, 2015) and WAMIT (WAMIT, 2013). The first-order wave forces are due to the wave's Froude-Krylov force and the diffraction forces as the waves hit the floating platform. These are accounted for by the wave excitation coefficients $\mathbf{X}(\omega)$. The movement of the FOWT in water creates radiation forces that are accounted for with the added mass $\mathbf{A}(\omega)$ and the radiation damping $\mathbf{B}(\omega)$ coefficients (Faltinsen, 1990). These coefficients are calculated in the frequency domain and are functions of the wave frequency. Therefore, the Cummins equation (Cummins, 1962) is used to couple the frequency-dependent hydrodynamic properties to the time domain numerical tools.

The second-order wave loads are forces on a structure that are directly related to the square of the wave amplitude. These loads manifest at frequencies corresponding to the sum and difference frequencies of the linear wave spectrum. While these second-order forces typically have lower amplitudes than the first-order forces (which are linearly related to the wave amplitude), they can still significantly affect a FOWT system. One notable effect is the excitation of the natural frequencies of the floater, especially the lower-frequency modes like the surge and sway natural frequencies, which can lead to higher fatigue loads in the FOWT system Duarte et al. (2014).

The summation of the diagonal components of the quadratic transfer function (QTF) represents the mean drift force acting on the platform. This force contributes to the overall motion of the FOWT in response to wave-induced loads.

Viscous forces are captured using Morison equation (Morison et al., 1950). The Morison drag coefficients are empirical and depend on the hull shape of the floating platform. As the size of the platform becomes smaller compared to the incident wavelength, the effect of the viscous forces dominates, and inertia forces become smaller. As the size of the platform increases, the viscous effects are negligible, and inertia forces become dominant. For FOWT's modeling, a combination of potential flow theory and the Morison equation is widely used.

2.4.5 Controller design

The fixed-bottom wind turbine controller has two operation regions with different control strategies depending on the wind speed. The first region is below rated region; when the wind speed is below the rated wind speed, the controller incorporates a proportional-integral (PI) torque controller for regulating the generator torque. This PI controller adjusts the generator torque to align with the optimal blade tip-speed ratio, optimizing the turbine's performance for maximum power output. The second control region is active in the above-rated wind speed operation conditions. When the wind speed exceeds the rated wind speed, the controller employs a PI collective pitch controller. This controller's primary function is to adjust the blades' pitch angles to maintain the generator speed at its rated value while keeping the generator torque constant at the rated value (Mulders and Van Wingerden, 2018).

For a fixed bottom wind turbine controller to work for a FOWT, major tuning adjustments are required for the blade pitch controller in the above-rated wind speed region due to the couplings between the FOWT's pitch motion and the blade pitch controller. The coupling issue arises due to the lowest natural frequencies in FOWTs, which specifically relate to the surge and pitch motions of the platform. These natural frequencies are significantly smaller than those found in fixed-bottom platforms, which typically involve tower top fore-aft motions. The presence of these lower natural frequencies imposes limitations on the bandwidth of the pitch controller. A straightforward approach is de-tuning the controller to address this challenge and avoid instability. De-tuning prevents undesired coupling between tower top motions and the pitch controller, ensuring stable operation (Larsen and Hanson, 2007).

2.5 Engineering models

In this section, I will present only the numerical tools used in this work, with the capabilities of each tool. I divided the tools according to their fidelity level into low and mid-fidelity level numerical tools. All of the low and mid-fidelity engineering numerical models presented in sections 2.5.1 and 2.5.2 are open-access and developed by the National Renewable Energy Laboratory (NREL).

2.5.1 Low fidelity models

FLORIS

Flow redirection and induction in steady-state (FLORIS) is a tool developed for steady-state wake calculation in a wind farm; it can design and optimize a wake steering controller for the wind farm. In this work, I use FLORIS v3.1, with the wake model used was the Gaussian velocity model implemented within the tool based on the works of Bastankhah and Porté-Agel (2016); Niayifar and Porté-Agel (2016), and Gauss deflection model based on the works of Bastankhah and Porté-Agel (2016) and King et al. (2021). The turbulence model used was the Crespo-Hernandez model (Crespo and Hernández, 1996). The wake deflection in FLORIS only accounts for the horizontal wake deflection due to the yawing of the wind turbines. In this work, the yaw angle is always defined to be zero for all wind turbines within the wind farm; hence, no horizontal wake deflection occurs for all calculations done using FLORIS. The Gaussian wake model in FLORIS was verified, and its parameters were tuned in work done by Doekemeijer et al. (2022), where FLORIS results were compared to the supervisory control and data acquisition (SCADA) data from Anholt, Westernmost Rough, and Offshore Windpark Egmond aan Zee wind farms in the North sea.

The FLORIS input file contains a look-up table for the thrust C_t and power coefficients C_p of the wind turbine simulated at different wind speeds. The power and thrust coefficient is linearly interpolated if the wind speed is between any of the values in the look-up table. I used the aerodynamic values of the C_t and C_p , which do not include the effect of rotor tilt and the platform pitch angle. Hence, a FOWT's power is higher than predicted when using a mid-fidelity tool. A newly developed version of FLORIS can account for the FOWT pitch, but it was not used in the current research. Moreover, vertical wake deflection behind a FOWT is not captured in the current wake model in FLORIS.

MoorPy

MoorPy (Hall et al., 2021) is a quasi-static python-based MS analysis and design tool. In MoorPy, the FOWT is modeled as a point mass with 6 DoFs. MoorPy uses the CG, the AWP, the MC, and the displaced volume to calculate the hydrostatic stiffness of the FOWT. Additionally, MoorPy allows the user to apply a force vector on the FOWT at MSL to account for the aerodynamic forces and wave loads acting on the FOWT. MoorPy uses standard catenary equations to calculate the shape and tension of the mooring lines. Afterward, it computes the FOWT's static equilibrium position as it captures the nonlinear force-displacement relationships of the MS. Moreover, MoorPy calculates the linearized stiffness matrix of the MS at the FOWT's position. I did not apply additional loads to account for the wave loads in MoorPy and only accounted for aerodynamic forces.

2.5.2 Mid-fidelity models

OpenFAST

OpenFAST is an aero-elasto-hydro-servo state-of-the-art tool for FOWT modeling, as introduced in the work done by Jonkman (2007, 2009). OpenFAST consists of modules such as ElastoDyn, AeroDyn, ServoDyn, and Hydrodyn. OpenFAST models the FOWT as an MBS, where each module is responsible for modeling the multidisciplinary elements of an FOWT. ElastoDyn, SubDyn, and BeamDyn are three modules that are available in OpenFAST to model the FOWT structure dynamics with different fidelities; in my work, I use ElastoDyn for the blades, tower, and floating platform. ElastoDyn uses modal decomposition to model the blades and the tower. The first two bending modes are considered for the tower's side-side and fore-aft motions. The first two flap-wise modes and the first edge mode are considered for the blades. The floating platform is modeled as a point mass with six DoFs.

AeroDyn uses the BEM model to calculate the aerodynamic forces acting on the rotor. ServoDyn models the wind turbine controller and can model structural dampers such as tower dampers. However, no structural dampers are included in this work.

HydroDyn combines potential flow theory and the Morison equation to capture hydrodynamic viscous and inertial forces. I accounted for the viscous and inertial forces acting on the FOWT in this work. HydroDyn also models regular and irregular waves using JONSWAP or the Pierson-Moskowitz spectrum. I assumed fully developed waves in my work and used the Pierson-Moskowitz spectrum (Pierson and Moskowitz, 1964). MoorDyn is used to model the mooring lines using lumped mass discretization. Only the axial stiffness is included in MoorDyn at the moment, and no bending or tension stiffness is included while modeling the MS. I used

OpenFAST v3.4.1 to model the FOWT throughout this work. HydroDyn can model the water current, but no current was modeled in the current research, and the current is always assumed to be zero.

FAST Farm

FAST Farm is a numerical tool that can model an FWF in the time domain and analyze the loads acting on the FOWTs in the FWF and the power production of the FWF (Jonkman and Shaler, 2020). FAST Farm uses the DWM, introduced in section 2.2, to account for velocity deficits, advection, deflection, meandering, and merging inside the FWF. However, the wake-added turbulence is not included in FAST Farm v3.4.1 used in this work, so the fatigue loads are under-predicted. FAST Farm uses OpenFAST to solve the aero-elastic-hydro-servo dynamics of each FOWT in the FWF.

FAST Farm has two different formulations of the DWM: the polar model formulation and the curl model formulation. The polar model, introduced in Jonkman and Shaler (2020), models the wake as axis-symmetric on a polar grid and satisfies both momentum and mass conservation laws. The curl model introduced in Branlard et al. (2023), is implemented in a Cartesian grid and accounts for the effect of curled wake vortices by introducing cross-flow velocities. The momentum conservation law is satisfied, while the mass conservation law is not enforced. FAST Farm DWM model was verified, and its parameters were tuned for a 5 MW fixed bottom wind turbine against LES simulations in the works of Doubrawa et al. (2018); Jonkman et al. (2018). FAST Farm was tuned for the 5MW FOWT in the works of Carmo et al. (2024), showing that the curl model agreed better with the LES results than the polar model for FOWTs. Hence, I only used the curl model throughout this work. Due to the lack of work on tuning FAST Farm to a 15MW FOWT, I used the same tuning parameters as the 5MW FOWT.

2.5.3 Optimization algorithm

I used a sparse nonlinear optimizer (SNOPT), introduced in Gill et al. (2008, 2005), for state-of-the-art fixed bottom wind farm layout optimization. SNOPT is a gradient-based optimization algorithm employing a sequential quadratic programming (SQP) approach, refining the solution estimate and exploiting the problem's sparsity to reduce computational overhead. SNOPT excels in handling problems where the constraints and objective functions exhibit a sparse gradient structure, which makes it computationally efficient. SNOPT is widely used in wind energy for wind farm layout optimization as the work done by Thomas et al. (2023); Baker et al. (2019); Thomas and Ning (2018); Thomas et al. (2017), or for wake steering optimization Stanley et al. (2022, 2023).

SNOPT is not an open-source algorithm, but a free license can be obtained for academic purposes and renewed every three months. Throughout this work, I used SNOPT within the pyOptSparse (Wu et al., 2020) framework in python.

2.5.4 Cost model

LCOE is a metric for evaluating the economic performance of different energy resources, including wind farms. It describes the cost of one unit of electricity produced and is used to compare different energy resources. Additionally, it is used to compare different sites for wind farms and find economically attractive sites. The LCOE calculation as presented in Beiter et al. (2016); Benveniste et al. (2016) is shown in equation 2.1.

$$LCOE = \frac{CapEx + OpEx + DeCom}{AEP_{farm} - E_{loss}} \quad (2.1)$$

CapEx is the capital expenditure, which is the cost used to design and manufacture the different components of the wind farm and installation costs. *OpEx* is the annual operational expenditure, which includes maintenance, reparation, and inspection costs. *DeCom* is the decommissioning cost at the end of the wind farm's lifetime. While estimating the *OpEx* and *DeCom* costs, inflation is considered to predict the present value of these costs. *AEP_{farm}* is the farm's annual energy production. Finally, *E_{loss}* are the total electrical losses due to energy transmission from the wind farm to the grid.

In this work, I aim to design the MS to passively relocate the FOWTs in an FWF to increase the *AEP_{farm}*. In the FOWTs and FWF designs, I assume all other components and design parameters are fixed and will not be changed. However, larger relocation of the FOWT will lead to the redesign of the cable design to withstand larger excursions. Therefore, I cannot conclude the farm's overall LCOE without considering the new cable design. Since the cable design is not part of my current work or the research questions, I will only focus on decreasing the MS costs relative to a baseline MS design and increasing *AEP_{farm}* without a complete LCOE calculation. The decrease or increase in cost will only refer to the MS cost and not the complete LCOE calculation.

The MS costs are divided into mooring lines costs and anchors costs. In this work, all the MS designs will be made out of chains, and all mooring lines will have a catenary shape with a section of the mooring line lying on the sea bed. Therefore, all anchors will be DEA, with no vertical tension applied. The MS costs in United States dollars (\$) as defined by Beiter et al. (2016) as a function of the minimum breaking load (MBL) of the lines, in newtons, are shown

in equations 2.2, and 2.3, where L is the length of the mooring line in meters.

$$Chain_{cost} = (0.0591 \cdot MBL \cdot 10^{-3} - 87.6)L \quad (2.2)$$

$$DEA_{cost} = 10.198 \cdot MBL \cdot 10^{-3} \quad (2.3)$$

The chain MBL depends on the mooring line diameter d , in meters, as shown in equation 2.4. Therefore, a smaller diameter means a smaller MBL and hence less MS cost and vice versa. The MBL shown in equation 2.4 assumes the chains are made of steel grade R4s, which I used as a material for all MS designs.

$$MBL = 30.2 \cdot d^2(44 - 80 \cdot d) \cdot 10^6 \quad (2.4)$$

2.6 Reference coordinate system

I used two coordinate systems throughout this work, shown in Figure 2.3. The first coordinate system is the fixed global coordinate system (O_g), where the positive x-axis points towards the east and the positive y-axis points towards the north. The z-axis follows the definition of the right-hand rule and points upwards (pointing outside the paper). The second coordinate system used is a rotating coordinate system according to the wind direction, hence I will call it wind direction coordinate system (O_w). The x_w -axis of the wind direction coordinate system always points in the same direction of the wind, while the y_w -axis is always pointing in the crosswind direction as shown in Figure 2.3. The wind direction wd is measured from the positive x-axis and positive for counterclockwise rotation. The global and the wind direction coordinate systems originate on the Cartesian plane at (0,0,0). The two coordinate systems coincide when $wd = 0^\circ$. The wind coordinate system is achieved by rotating the global coordinate system around the z-axis. The transformation between the two coordinate systems is shown in equation 2.5. The transformation matrix (rotation matrix) around the z-axis is shown in equation 2.6.

$$O_w = R_w O_g \quad (2.5)$$

$$R_w = \begin{bmatrix} \cos(wd) & -\sin(wd) & 0 \\ \sin(wd) & \cos(wd) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2.6)$$

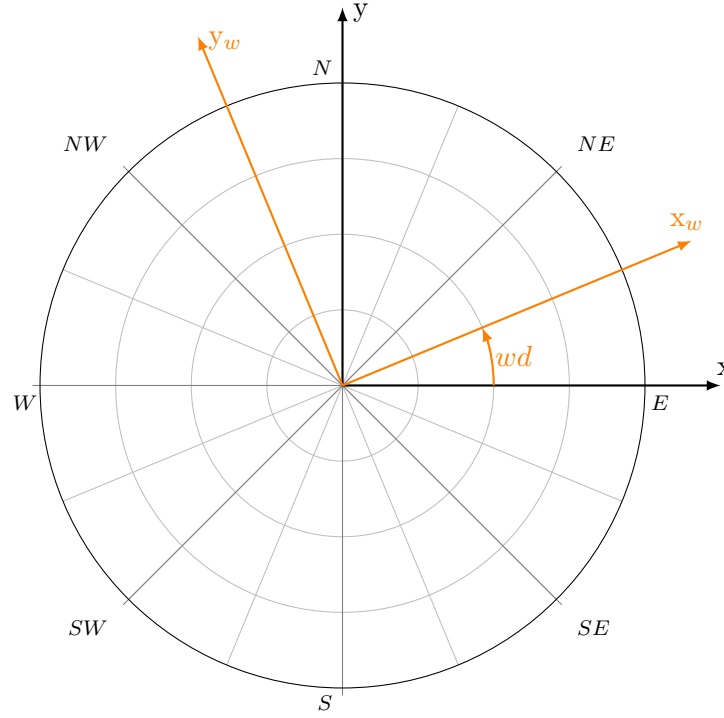


Figure 2.3: Reference coordinate systems

2.7 Reference FOWT model

The FOWT model utilized in this research originates from the Horizon 2020 project, COREWIND. The RNA is taken from the reference design of the 15 MW three-bladed upwind horizontal axis wind turbine developed within the International Energy Agency (IEA) task 37 Gaertner et al. (2020). The floating platform chosen for this model is the semi-submersible Activefloat platform, specifically designed for the Gran Canary site, as described in Mahfouz et al. (2020); Vigara et al. (2020).

A new coned-shaped steel tower was engineered to adapt this system to the mild sea conditions at the Gran Canary site and reduce the tower base loads. This tower is shorter than the original tower designed for the 15MW reference wind turbine with a fixed bottom configuration, as the wave heights in the Gran Canary site are low. Figure 2.4 visually represents the Activefloat platform. Activefloat is made of concrete and consists of three cylindrical external columns forming the three vertices of an equilateral triangle. Pontoons with a rectangular cross-section connect the three columns to the centroid of this triangle. At the point of intersection of the three pontoons stands a coned-shaped column to which the tower of the FOWT is coupled. The Activefloat platform has an active ballast option to keep the static mean pitch at zero. However, I am not activating this option in any of the steady-state or dynamic simulations done in this work. The details of the dimensions, hydrostatic, and hydrodynamic properties of Activefloat

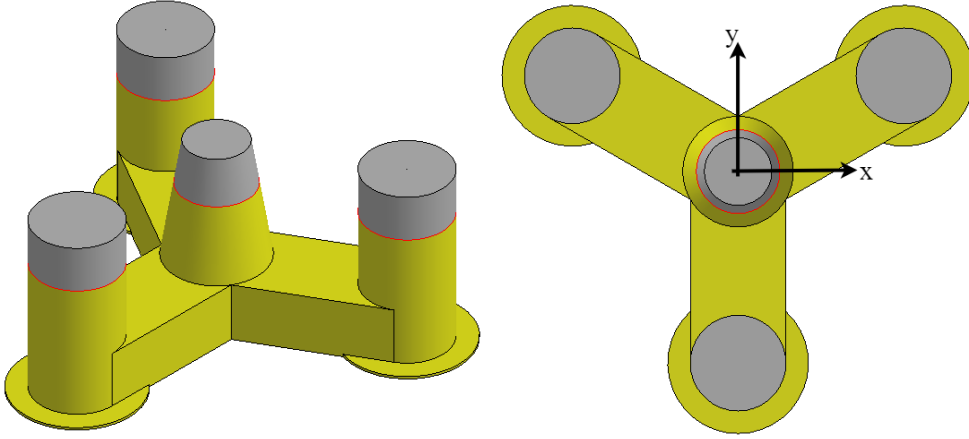


Figure 2.4: Activefloat platform design, the yellow section is below MSL while the gray is above. The top view on the right shows the orientation of the floater relative to the global reference frame

are presented here Mahfouz et al. (2021, 2020). The overall reference FOWT parameters I used in this work are summarized in Table 2.1. The orientation of the floating platform for all FOWTs throughout my work was fixed to the orientation shown in Figure 2.4. The OpenFAST model of the Activefloat coupled to the IEA 15 MW reference wind turbine can be downloaded here Duran et al. (2020). The method of deriving the drag coefficients used for the viscous drag forces in HydroDyn is explained thoroughly in Mahfouz et al. (2021, 2020).

The ROSCO controller v2.7 (NREL, 2021) controls the FOWT in my work. The parameters of the ROSCO controller of the fixed bottom 15MW reference wind turbine design were adapted and fine-tuned for use in the Activefloat FOWT design within the COREWIND project. Below the rated wind speed, the ROSCO controller incorporates a PI controller for regulating generator torque. This below-rated PI controller dynamically adjusts the generator speed to maintain the optimal tip-speed ratio for maximizing electrical power output. In my models, this controller was implemented with minor re-tuning.

The ROSCO controller switches to a PI collective pitch controller for above-rated wind speeds, maintaining the generator speed at its rated value while ensuring the generator torque remains constant. Extensive tuning is performed on the controller designed for wind speeds above the rated limit due to the challenging interactions between the tower's motion and the pitch controller. The PI collective pitch controller for above-rated wind speeds is designed using the Ziegler-Nichols method (Ziegler et al., 1942). The PI controller gains are calculated for a specific wind speed beyond the rated limit. The ratio between the original ROSCO PI controller parameters and the computed parameters using the Ziegler-Nichols method for that particular wind speed (13 m/s) is then used to scale the controller parameters for all wind speeds above the rated limit. The current work uses the controller without further tuning for all the MS designs evaluated.

Table 2.1: Reference FOWT parameters

Parameter	Value
Power rating	15 MW
Cut in wind speed	4 m/s
Cut-out wind speed	25 m/s
Rated wind speed	11 m/s
Rotor diameter D	240 m
Hub height	135 m
Total FOWT mass	37 kt
Vertical FOWT CG	-11 m
Activefloat's draft	26.5 m
Water displaced volume	36431 m ³
Tower natural frequency	0.4 Hz
Platform roll and pitch natural period	33 s
Water depth	200 m

Table 2.2: Parameters of baseline mooring design

Depth (m)	Anchoring radius (m)	Fairlead radius (m)	Fairlead depth (m)	Line length (m)	Line diameter (m)
200	600	42.5	15	623.3	0.1902

The parameters of the baseline MS (BMS) design used in this work are shown in Table 2.2. The BMS is a catenary MS made of three identical mooring lines. Figure 2.5 shows the mooring lines' profile and the BMS's top view. The BMS design used in my work was designed as part of the work done in Mahfouz et al. (2023). The design process goal was that the MS satisfies the fatigue of 25 years of damage and ultimate loads for the following load cases. Fatigue damage was calculated using three fatigue load cases at wind speeds of 10 m/s, 12 m/s, and 14 m/s with two wind directions, north to south and south to north, with waves and wind aligned. All six cases were assumed to have an equal probability of occurrence. The BMS was checked for ultimate loads against DLCs 1.6 and 6.1 from the IEC standard (IEC, 2019). The current work will perform more detailed fatigue and ultimate loads checks for the BMS in chapter 5. The maximum mean excursion of the BMS takes place at rated wind speed and is equal to 25 m, which is 12% of the water depth of 200 m. The water depth is fixed throughout the thesis to the same value of 200 m. The orientation of the BMS for all FOWTs throughout my work was fixed to the orientation shown on the right side of Figure 2.5. The headings of the BMS will not be rotated in the rest of this work. The reason for choosing this heading is clarified in Chapters

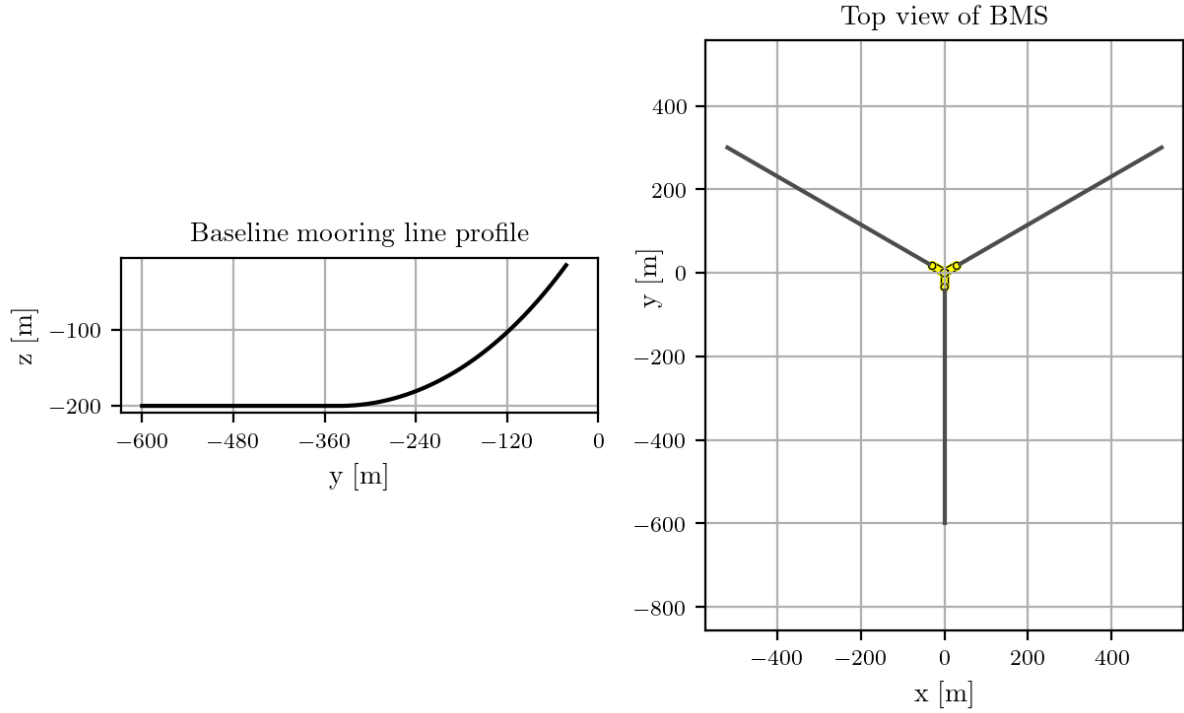


Figure 2.5: BMS mooring line profile on the left and top view on the right

5 and 7.

2.7.1 Loads assessment

The structural fatigue damage and the extreme loads were checked for the mooring lines, tower base, and blade root of the FOWT. The FOWT, coupled with the BMS, was used as a reference design to compare the loads on the FOWT coupled to the newly designed MSs throughout this work. The methods used to assess the fatigue damage and the extreme loads on each of the components are introduced throughout this section.

Fatigue loads

The fatigue loads will be assessed using three parameters: 1Hz damage equivalent loads (DELs), lifetime DELs, and 25-year fatigue damage. The 1Hz DEL is used to calculate the lifetime DEL, which will be used to assess the fatigue of the blade roots. The 25-year fatigue damage will determine the fatigue damage on the designed MS and the tower base. The 1Hz DELs are calculated using equation 2.7, where m is the Wohler exponent and T_{sim} is the simulation time. The rainflow-counting method was used to count the load cycles, where S_c is the cycle's

amplitude and N_c is the number of cycles with amplitude level S_c . Miner's rule was used to calculate the total damage. The 1Hz DEL is used afterward to estimate the lifetime DEL ($DEL_{lifetime}$) as shown in equation 2.8, where $f(ws_s, wd_j)$ is the probability density function of the occurrence of each 1Hz DEL at wind speed ws_s and wind direction wd_j . No mean load correction is applied in the fatigue calculation; hence, the mean load signals are not considered, which is a valid assumption as I compare the results to a baseline FOWT design.

$$DEL_{1Hz} = \left(\sum_{c=1}^n \frac{N_c}{T_{sim}} S_c^m \right)^{1/m} \quad (2.7)$$

$$DEL_{lifetime} = \left(\sum_{s=1}^{n_{ws}} \sum_{j=1}^{n_{wd}} f(ws_s, wd_j) DEL_{1Hz, ws_s, wd_j}^m \right)^{1/m} \quad (2.8)$$

The 25-year fatigue damage $D_{25-year}$ was calculated using equations 2.9, and 2.10. The D_{ws_s, wd_j} is the damage of each load case at each wind speed ws_s and direction wd_j , which is the sum of the contributions of each fatigue cycle to the damage of each load case. $T_{25-year}$ is the 25-year lifetime of the wind turbine. The probability of occurrence of the load cases in equations 2.8, and 2.10 is only a function of wind speeds and direction and not of the waves. This is because the wave loads will be constant for each wind speed and direction in this work.

$$D_{ws_s, wd_j} = \sum_{c=1}^n \frac{n_{c, ws_s, wd_j}}{N_{c, ws_s, wd_j}} \quad (2.9)$$

$$D_{25-year} = \frac{T_{25-year}}{T_{sim}} \sum_{s=1}^{n_{ws}} \sum_{j=1}^{n_{wd}} f(ws_s, wd_j) D_{ws_s, wd_j} \quad (2.10)$$

I calculated the 25-year fatigue damage for the MS designs using the T-N curve for studless chain mooring lines as defined within the API (2005) standard in equation 2.11, with Wohler exponent $m = 3$ and intercept $k_{TN} = 316$. *Tension* is the fairlead tension of the mooring lines, and N represents the cycles to failure. The MBL is a function of the mooring line diameter d as in equation 2.4.

$$N = k_{TN} \left(\frac{Tension}{MBL} \right)^{-m} \quad (2.11)$$

For the tower base, I calculated the 25-year fatigue damage using the S-N curve for steel as defined by the DNV GL (2014) standard using the endurance curve of type B1 (Ren and Xing, 2023) with a Wohler exponent of 4 for the number of cycles lower than 10^7 , and a Wohler exponent of 5 otherwise. Like the MS, rainflow-counting was used to calculate cycles from the

time series, and Miner's rule was used for total damage. The axial stress was calculated from the bending moments and axial force as shown in equation 2.12. A is the nominal cross-section area of the tower, I_x and I_y are moments of the area around the y-axis and x-axis and since the tower base is a cylinder, I_x and I_y are equal. r is the tower's outer radius, equal to 5 m for the Activefloat design. F_z is the axial force, M_x , and M_y are the bending moments around the x-axis and y-axis, respectively. Finally, θ_σ is the angle at which the stress is calculated on the tower circumference, and I calculated the stress at 12 points over the tower circumference.

$$\sigma = \frac{F_z}{A} + \frac{M_y}{I_y} r \cos(\theta_\sigma) - \frac{M_x}{I_x} r \sin(\theta_\sigma) \quad (2.12)$$

I used lifetime DEL to calculate the fatigue structural damage on the blades. I summed up the time series of the blade side and fore-aft moments ($M_{b,x}$, and $M_{b,y}$ respectively) to calculate the blade root moments at 12 spots around the blade root, θ_b is the angle at which the total bending moment is calculated. Then, I used the location at the blade root circumference, where the lifetime DEL is highest for the load assessment. The overall blade root moment M_b is calculated as shown in equation 2.13; for calculating the blade's DELs, a Wohler exponent of 10 was used.

$$M_b = M_{b,y} \cos(\theta_b) - M_{b,x} \sin(\theta_b) \quad (2.13)$$

Extreme loads

I used the 50-year extreme wind and waves to assess the performance of the FOWT under extreme loading conditions. The MS designs must pass extreme environmental conditions with a safety factor 2 as defined within the API (2005) standard. Therefore, the maximum mooring line tension should be less than 50% of the line's MBL. Additionally, the extreme loads of the tower base were also checked, ensuring the stress calculated in equation 2.12 was always below the yield strength of the tower with a safety factor of 2. As shown in Chapter 5, for a relocating FOWT, the design is driven by the fatigue loads. Hence, I focused more on the structure fatigue damage due to relocating the FOWT.

AEP calculations and wake losses

Since the first research question I will try to answer in this work is to increase the AEP of the FWF, I will take the time to present the AEP calculation equation and the wake losses calculation. The AEP is calculated using equation 2.14, where the n_{ws} and n_{wd} are the numbers of wind speed and wind directions, respectively. $f(ws_s, wd_j)$ is the probability of occurrence of

the wind speed ws_s and the wind direction wd_j . $P_{farm}(ws_s, wd_j)$ is the farm power at wind direction wd_j , and wind speed ws_s .

$$AEP_{farm} = \sum_{s=1}^{n_{ws}} \sum_{j=1}^{n_{wd}} f(ws_s, wd_j) P_{farm}(ws_s, wd_j) * 8760 \quad (2.14)$$

The optimum wind farm has zero wake losses, and the optimal AEP AEP_{opt} is calculated in equation 2.15. The optimum AEP is no longer a function of wind direction but only depends on the probability of occurrence of the wind speed. Additionally, the optimum AEP is not affected by the changes in the layout or the shape of the wind farm. N_T is the number of wind turbines in the farm, and $P_{opt}(ws_s)$ is the optimum power the wind turbine produces at wind speed ws_s .

$$AEP_{opt} = \sum_{s=1}^{n_{ws}} f(ws_s) P_{opt}(ws_s) * N_T * 8760 \quad (2.15)$$

The wake losses are shown in equation 2.16, as the difference between the farm's AEP and the farm's optimum AEP is divided by the optimum AEP.

$$W_{loss} = \frac{AEP_{farm} - AEP_{opt}}{AEP_{opt}} \quad (2.16)$$

Finally, the AEP gain of a wind farm layout is quantified relative to a baseline layout with baseline AEP (AEP_0) as shown in equation 2.17. E_{wd_j} is the energy produced by the newly developed wind farm design at wind direction wd_j , while E_{0,wd_j} is the energy produced of the baseline wind farm layout at wind direction wd_j .

$$AEP_{gain} = \sum_{j=1}^{n_{wd}} \frac{E_{wd_j} - E_{0,wd_j}}{AEP_0} \quad (2.17)$$

I will use all these definitions to quantify the wake losses and the AEP gain when analyzing the AEP performance for the rest of this work.

METHODOLOGY

3.1 Overview

In this chapter, I will present a novel method to design a passively relocating FWF layout to increase the FWF's AEP; the goal is to use this method to answer my first research question about the benefit of relocating the FOWTs inside the FWF. Therefore, the method does not try to achieve the absolute optimum layout by passively relocating the FWF layout; instead, it shows the potential of relocating the FOWTs. The method is summarized in Figure 3.2, consisting of four main steps. In this chapter, I will introduce each step and use a simple example to show the results of each step for clarification. The method was previously introduced in Mahfouz and Cheng (2023a), and this chapter is built on this work. The tool I developed to design the FWF and the MS designs is called FloatingWAYS (Floating wind array layout design); it is open-source and can be found here Mahfouz (2024).

Additionally, the effect of different catenary MS design parameters on the FOWTs' ability to relocate their position will be analyzed to answer the second research question of this work. The goal is to understand how each design parameter affects the shape of the watch circle and the magnitude of the FOWT displacement in the inwind and crosswind directions. The analysis was introduced before with fewer details in my paper Mahfouz et al. (2022).

The wind rose used in this chapter is the theoretical wind rose created with IEA Task 37 Baker et al. (2019) and introduced in Figure 3.1. During the design process in this chapter, I will assume that the wind speed is constant for all wind directions and is equal to 10 m/s. This value is chosen to be below the rated wind speed of the 15MW wind turbines as the above-rated wind speed wakes do not lead to wake losses. The wind rose consists of 16 bins for wind direction

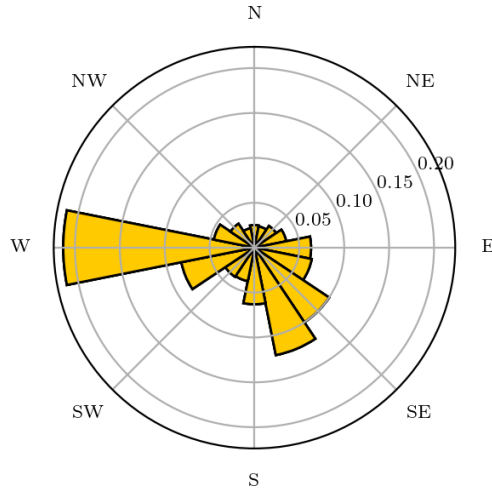


Figure 3.1: IEA Task 37 wind rose at a constant wind speed of 10 m/s

with a width of 22.5° . The AEP calculated in this chapter assumes that the wind speed is fixed at 10 m/s for all wind directions.

3.2 Fixed bottom layout optimization

The first step in the method (Figure 3.2) is to optimize the layout using the current state-of-the-art fixed-bottom wind farm optimization techniques. This step is not mandatory, and I could have used a gridded layout as a baseline, as this is common practice and many of the offshore wind farms in the North Sea have layouts where the turbines are placed in a grid pattern, such as Horns Rev1 and Horns Rev2 layouts. However, the wake losses are high since the gridded wind farm layouts are not optimized. Therefore, any slight FOWT relocation can lead to a higher energy gain than the baseline layout. Since I want to quantify the benefit of relocating FOWTs in an FWF, I wanted the baseline layout to be as close to the global optimum as possible. If relocating the FOWTs increases the AEP of an optimized FWF layout with low wake losses, it will surely increase the AEP of a non-optimized gridded FWF layout with higher wake losses, but not necessarily vice versa.

This optimization was done assuming a fixed-bottom wind farm following the current state-of-the-art layout optimization techniques. SNOPT optimizer is used with a major optimality tolerance set to $1e-5$ and a major feasibility tolerance set to $1e-6$. These values are based on the values used in the work done by Fleming et al. (2016), and I tested different values for the optimality tolerance, and decreasing the tolerance further does not lead to an increase in AEP of the optimized layout. The gradients were calculated using finite difference within pyOptSparse as in the work done by Fleming et al. (2016); Stanley et al. (2023). Calculating finite difference gradients is much simpler than exact gradients. However, using finite difference

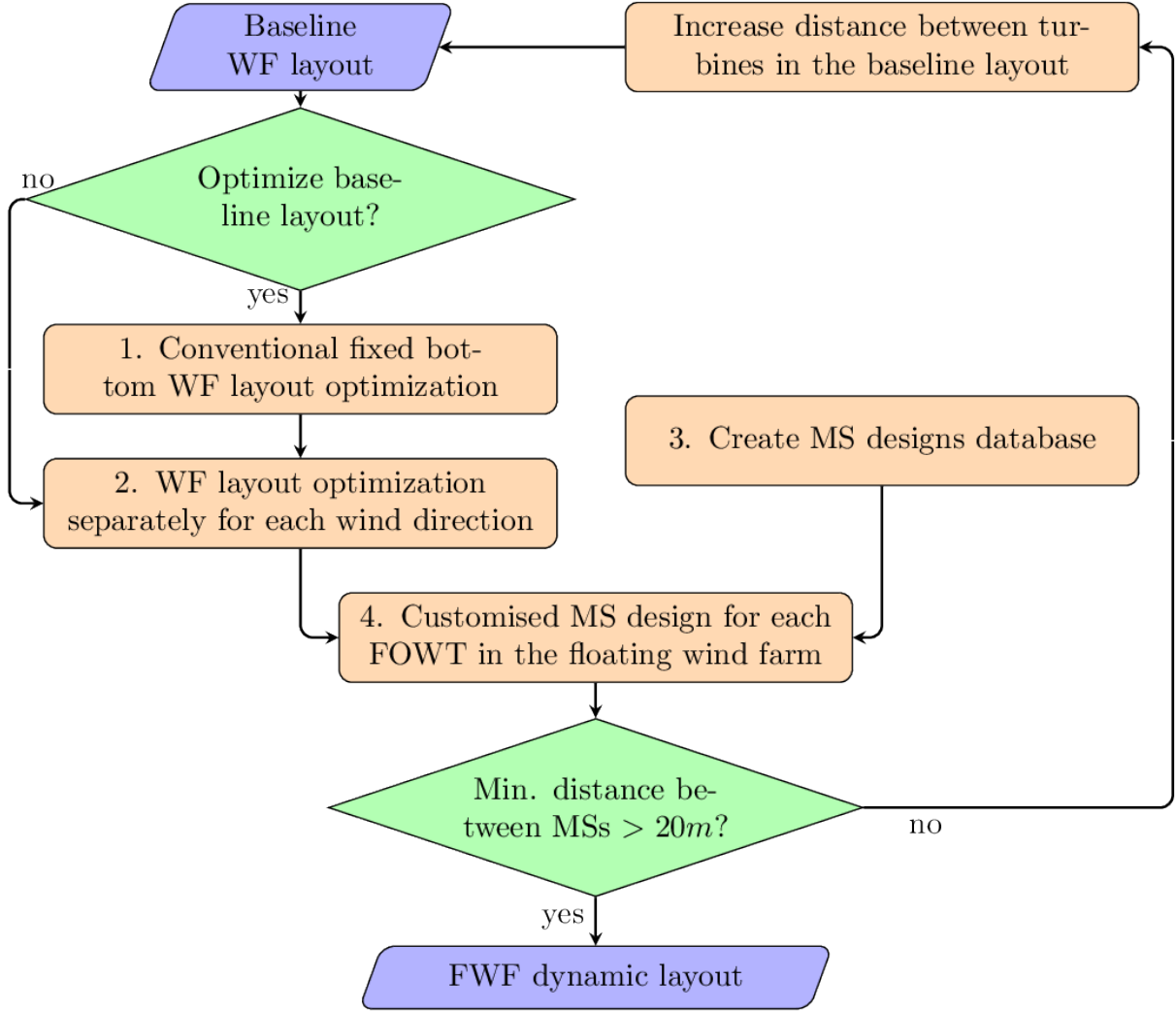


Figure 3.2: Overview of the methodology used to design passively relocating FWF layouts

gradients becomes computationally inefficient as the wind farm gets bigger, as shown in the work of Thomas et al. (2017). However, since the wind farm I used to demonstrate the method is small and this step is not the core of this work, I decided to use the finite difference gradients with the values mentioned above for the tolerances.

$$\begin{aligned}
 &\underset{x_i, y_i}{\text{minimize}} && - \frac{AEP(x_i, y_i) - AEP_{st}(x_{i,st}, y_{i,st})}{AEP_{st}(x_{i,st}, y_{i,st})} && i = 1..N_T \\
 &\text{subject to} && \frac{\sqrt{(x_i - x_q)^2 + (y_i - y_q)^2}}{dist_{min}} \geq 1 && i, q = 1..N_T \quad i \neq q \\
 &&& (x_i, y_i) \in Area && i = 1..N_T
 \end{aligned} \tag{3.1}$$

The objective function and the constraints are shown in equation 3.1. It is recommended in

Table 3.1: Wake losses of the wind farm before and after optimization at wind speed of 10 m/s

	Gridded layout	Optimized layout (BWFL)
W_{loss}	-21.31%	-5.92%

the PyOptSparse and SNOPT manuals to scale the objective function, the constraints, and the design variables to be closer to 1 or in the same order of magnitude (Gill et al., 2008; Wu et al., 2020). The objective is to maximize the AEP of the wind farm by changing the positions (x_i, y_i) of each turbine i inside the farm, where N_T is the total number of turbines. Since gradient-based optimization searches for local minimum, the goal is to minimize the negative value of the farm's AEP. AEP_{st} is the AEP of the wind farm at the beginning of the optimization process, while $(x_{i,st}, y_{i,st})$ are the starting positions of the turbines before the optimization starts. The AEP_{st} is constant and is not updated with each optimization step. The Gaussian model within FLORIS was used to calculate the farm's AEP.

I applied two constraints shown in equation 3.1; the first constraint is to ensure the distance between any two turbines in the farm is larger than a defined minimum distance $dist_{min}$. The second constraint was ensuring all turbines were inside the defined farm boundary area. The wind farm I used as an input to the optimization algorithm is a square shape wind farm containing 9 turbines with a side length of $12D$, and the shortest distance between any two turbines was $6D$ as shown in Figure 3.3. The boundaries used to define the boundary area were extended by $1\%D$ in each direction so that the turbines were all within the wind farm at the beginning of the optimization process. This enhanced the performance of the optimizer to achieve a better-optimized layout. Therefore, the side length of the boundary square was $12.02D$. The positions of the turbines were normalized to be between 1 and -1 , as recommended in the SNOPT user manual (Gill et al., 2008). In this step, the farm is assumed to be a fixed bottom wind farm, so the MS anchors are not accounted for. When the MS is included later, the anchors will be outside the boundaries. The value of the constraint $dist_{min}$ was set to $4D$. This value is chosen to ensure the mooring lines inside the farm are not tangled, as I will show in section 3.6.

The optimization result is shown in Figure 3.3; the optimized layout will be used as a baseline wind farm layout (BWFL) for the rest of the methodology in this chapter. The BWFL will be used as a baseline to compare the effect of relocating the FOWT on AEP. The percentages of wake losses of the gridded layout and the optimized layout are shown in Table 3.1 and calculated as shown in equation 2.16.

3.3 Layout optimization for each wind direction

The method used for optimizing the BWFL separately for each wind direction is shown in Figure 3.4. I iterated over the wind directions of the wind rose, and the following steps were carried out for each wind direction wd_j . First, I start with rotating the wind farm layout to the wind direction coordinate system O_w such that the movement along the y_w -axis is only in the crosswind direction. Then, I optimized the BWFL layout for this wind direction. The optimization process's objective function and constraint are shown in equation 3.2. The optimization variables are the y components of the position of the turbines in the O_w reference frame. Therefore, the turbines are only allowed to move in the crosswind direction as the x components of the position of the turbines in the O_w reference frame remain constant. The objective is to maximize the energy produced by the farm at one wind direction E_{wd_j} , and the initial energy produced for this single wind direction at the beginning of the optimization process E_{st,wd_j} is used to normalize the optimization function. E_{st,wd_j} is a constant value equal to the energy produced by the BWFL at one wind direction.

$$\begin{aligned}
 &\underset{y_{i,wd_j}}{\text{minimize}} && - \frac{E_{wd_j}(y_{i,wd_j}) - E_{st,wd_j}(y_{i_{st},wd_j})}{E_{st,wd_j}(y_{i_{st},wd_j})} && i = 1..N_T \\
 &\text{subject to} && -1 \leq \frac{y_{i,wd_j} - y_{i_{st},wd_j}}{Cr_{max}} \leq 1 && i = 1..N_T
 \end{aligned} \tag{3.2}$$

Only one constraint is applied: the turbine displacement along the y_{wd} -axis is less than the

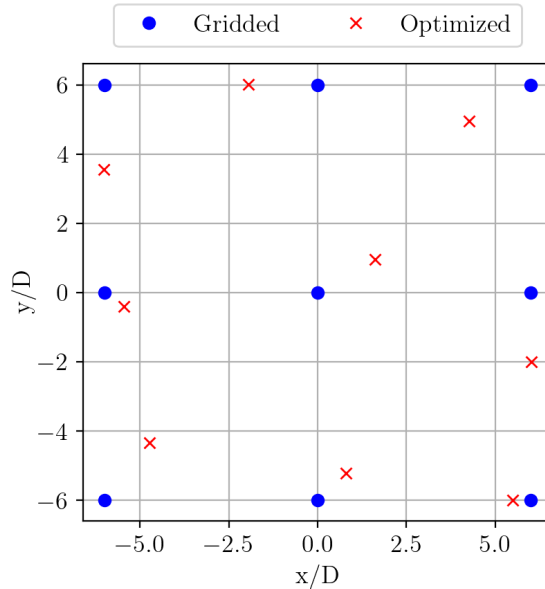


Figure 3.3: The wind farm layout before and after optimization

maximum allowable crosswind displacement Cr_{max} . I chose the value of Cr_{max} to be $0.5D$ (i.e., 120 m). I chose this value to have a total displacement of $1D$ in the case of two turbines aligned behind each other, and they displace $0.5D$ opposite each other in the crosswind direction. In the constraint function, y_{i,wd_j} is the new y_{wd} of the turbine positions in each step of the optimization process, and y_{i_{st},wd_j} is constant and equal to the y-position of the turbine at the beginning of the optimization process. The constraint function is normalized to be within -1 and 1 . FLORIS is used to calculate the energy of each wind direction E_{wd_j} , and SNOPT is used as a gradient-based optimization algorithm. Similar to section 3.2, the major optimality tolerance is set to $1e-5$, and the major feasibility tolerance is set to $1e-6$.

After iterating over all wind directions, I have a slightly different wind farm layout for each wind direction, forming the targeted layout of the wind farm. Figures 3.5 and 3.6 show the targeted layout of two wind directions compared to the BWFL. The targeted layout is on the right, while the BWFL is on the left. The black dots represent the BWFL and are used to

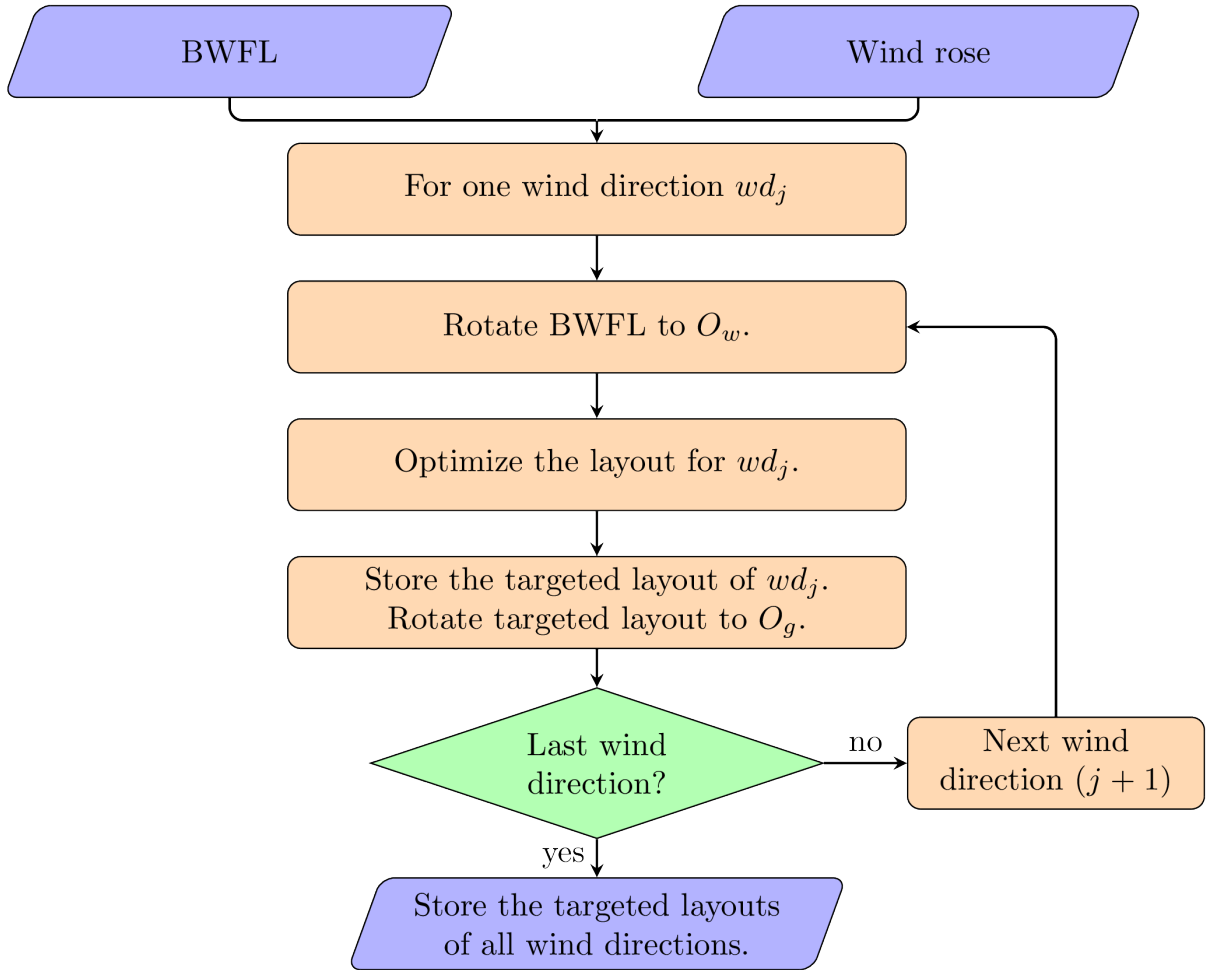


Figure 3.4: Method used for optimizing the BWFL separately for each wind direction

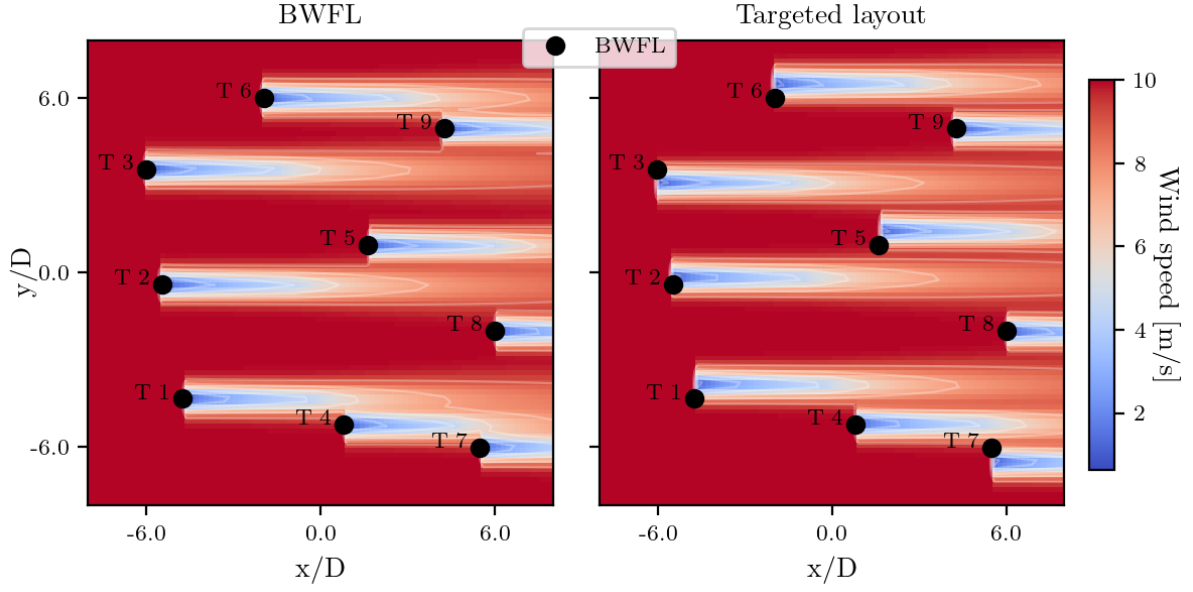


Figure 3.5: BWFL and targeted layout for wind direction of 0° . The black dots represent the BWFL

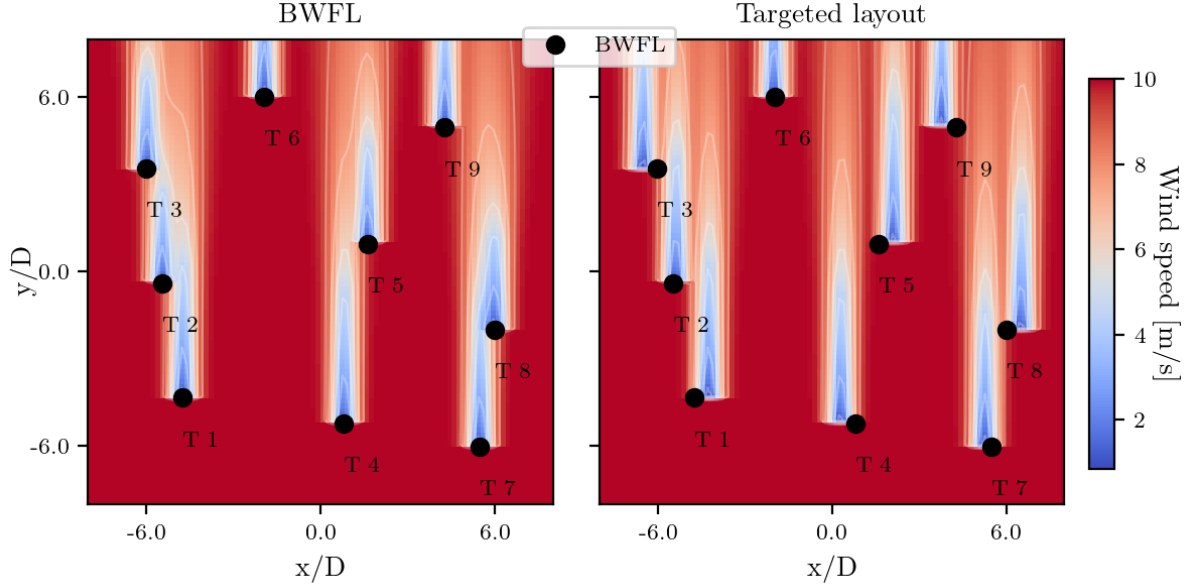


Figure 3.6: BWFL and targeted layout for wind direction of 90° . The black dots represent the BWFL

show the change in the positions of the wind turbines in the targeted layout to decrease wake losses. The targeted layout is unrealistic and impossible to achieve, as I cannot freely move the FOWTs to the required targeted displacements in all wind directions. In the optimization process, the crosswind movement for each wind direction is done independently, assuming there is nothing to constrain that movement and that the FOWTs can move freely for each wind direction separately with no coupling between the different wind directions. Realistically, I

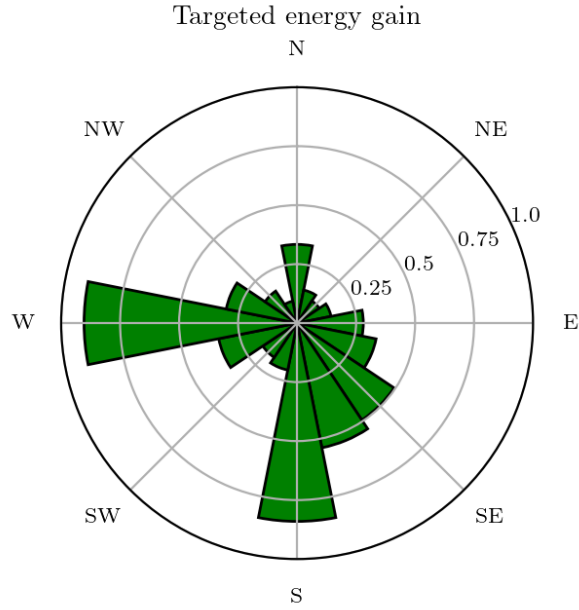


Figure 3.7: Overall targeted gain at wind speed of 10 m/s

aim to get the FOWTs to displace close to the targeted layout for as many wind directions as possible. However, the FOWT displacements are governed by the MS design, which cannot achieve the targeted displacement for all wind directions. The Figures of the targeted layout of all other wind directions are shown in Appendix A.

The matrix $\mathbf{Cr}$, in Table 3.2, shows the crosswind displacements each turbine needs to move for each wind direction to achieve the targeted layout. In the $\mathbf{Cr}$ matrix, each column is the crosswind displacements needed to be performed by the turbines for a single wind direction; hence, the number of columns is equal to 16 as the IEA Task 37 wind rose has 16 wind directions (n_{wd}). While each row in the $\mathbf{Cr}$ matrix represents the crosswind displacement of a single turbine for all wind directions, the number of rows is equal to the number of turbines in the BWFL (N_T) and equal to 9 turbines. Therefore, I end up with $\mathbf{Cr}$ being a 9 x 16 matrix, with each element representing the crosswind displacement of a wind turbine for a wind direction to achieve the targeted layout. For example, Cr_{34} is the crosswind displacement of turbine three at wind direction 4 (i.e., 67.5 degrees) and equals 120 m.

The energy gain achieved by the targeted layout for each wind direction compared to the BWFL is shown in Figure 3.7. The highest energy gain happens at wind direction 0° and wind direction 90°. The overall AEP gain compared to the BWFL is calculated using equation 2.17 and equals 5.41%. Table 3.3 shows the wake losses in the targeted layout. If the targeted layout is achieved, the wake losses are less than 1%.

Table 3.2: C_r the targeted crosswind displacement for each turbine i in each wind direction j

Wind dir.[°]	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
Turb 1	120	41	-49	-120	-120	120	51	120	-120	-43	58	120	120	-120	-120	-120
Turb 2	58	-64	-120	120	-21	-21	120	-120	-59	66	44	-120	21	21	-120	120
Turb 3	-108	-77	120	120	120	-120	-6	8	108	76	-120	-108	-120	120	4	-14
Turb 4	10	-120	120	-120	120	120	21	103	-10	120	-120	120	-120	-120	-27	-101
Turb 5	120	-120	-120	120	-120	59	120	-120	-120	120	120	-120	118	-56	-120	120
Turb 6	120	120	-78	-52	12	97	-120	120	-120	-120	43	53	-24	-98	120	-120
Turb 7	-120	-1	-21	-120	55	-120	-70	38	120	0	3	120	-55	120	69	-41
Turb 8	-3	39	-102	119	-120	17	117	120	4	-41	120	-120	120	-17	-118	-120
Turb 9	-6	106	120	47	120	-120	0	-119	7	-106	-120	-48	-120	120	-120	120

Table 3.3: Wake losses of the gridded wind farm layout, BWFL, and targeted layout

	Gridded layout	BWFL	Targeted layout BWFL
W_{loss}	-21.31%	-5.92%	-0.83%

3.4 Mooring system database

This section will introduce the database I created for the MS designs. The database contains different MS designs with various design parameters and the watch circle of each design. This section is split into four parts. First, I create a full factorial design matrix with all the MS designs to be included in the database. Second, I get the aerodynamic forces and moments acting on the wind turbine rotor and transfer them to MSL. After preparing these two inputs, I used MoorPy to create the database and store the watch circles. Finally, I present a sensitivity analysis of the effect of each design parameter on the shape of the watch circle and the ability of the FOWT to move in the crosswind direction.

3.4.1 MS full factorial design matrix

Before defining the design parameters that I will iterate over to create the full factorial design matrix, I introduce the design parameters that are kept constant in the list below:

1. **Number of mooring lines:** The number of mooring lines is kept constant and equal to three mooring lines, which is similar to the BMS.
2. **Material of mooring lines:** all three mooring lines are made of studless steel chains with R4S grade as the BMS.
3. **Water depth:** the water depth is kept constant and equal to 200 m throughout this work, similar to the water depth of the BMS.

I iterate over three design parameters to create the full factorial design matrix, and these parameters are introduced in the following list:

1. **Mooring line diameter (d)**

I chose three values for the mooring lines diameter d of 0.12 m, 0.15 m, and 0.18 m. I decided on those values based on my experience from previous work in Mahfouz et al. (2023), where I saw that a line with a diameter of 0.09 m had more considerable fatigue damage than the BMS. Therefore, with these three values of diameters and three mooring lines, I have 3^3 designs. All the mooring line diameter values are smaller than the mooring line diameter of the BMS, which equals 0.192 m.

2. Mooring lines headings

The line headings are the angle each line makes with the O_g coordinate system. Therefore, for the BMS in Figure 2.5, the line headings are 30° , 150° , and 270° . Since the BMS is symmetric, the difference between the headings of the three mooring lines is constant and equal to 120° .

The goal for the line headings was to include all possible combinations of the three line headings while ensuring none of the combinations is a rotated image of another one (Mahfouz et al., 2022). Since I have three mooring lines each line was allowed to be placed within a 120° range; line one can only be between 0° and 120° , line two between 120° and 240° and line three between 240° and 360° . The step used while changing the headings of each line was 10° , and any two lines were not allowed to lie on top of each other. Hence, the minimum accepted angle between two mooring lines was 10° . To ensure none of the MS designs were rotated images of another design, the difference between the mooring line headings was calculated, and the unique values of the MS designs were chosen. Applying this method, I had 72 possible combinations for the line headings.

The design of the Activefloat platform assumes that the MS design coupled to it is always an MS design with 120° difference between the lines headings and with the fairlead radius (FL_r) equals 42.5 m (i.e., the attachment points in the current Activefloat design is at the end of each of the three pontoons). However, I will neglect this assumption here and assume that the MS can be attached at any headings to the Activefloat platform with the same FL_r of 42.5 m. This is a valid assumption as, later on, the MS design can be modified to be attached to the Activefloat platform structure while maintaining the same watch circle.

3. Mooring lines anchoring radius and length

The anchor radius $AncR$ was chosen as a function of the rotor diameter. Two values of anchor radii were used for each line: $2.5D$ and $3.5D$. Following the approach presented in Kheirabadi and Nagamune (2020), the line length was defined as a function of the anchor radius and the sea water depth (equation 3.3). The minimum accepted value for the line length (L_{min}) is when the line is fully stretched, and the maximum (L_{max}) value is when there is no horizontal tension in the line. The $depth$ is the MSL depth of 200 m, and the FL_{depth} is the depth of the fairlead attachment point to the Activefloat platform at 15 m. Finally, R_L is the radial distance between the anchor and fairlead positions.

$$\begin{aligned}
R_L &= AncR - FL_r \\
L_{min} &= \sqrt{(depth - FL_{depth})^2 + R_L^2} \\
L_{max} &= depth - FL_{depth} + R_L \\
L &= L_{min} + \beta(L_{max} - L_{min})
\end{aligned} \tag{3.3}$$

Three values for β at 0.4, 0.6, and 0.8 were chosen for the length of each of the three lines. Therefore, I have six levels for each line for the anchor radius and the line length, and the total number of systems is 6^3 . The profiles of the mooring lines with different lengths and anchor radii are introduced in Figure 3.8.

After explaining the three parameters I iterated over, I created the full factorial design matrix. The matrix has three levels for the MS diameters d so 3^3 designs, 72 possibilities for the MS headings leading to 72 designs, and finally, six levels for the anchoring radius and the mooring line length L and hence 6^3 designs. Therefore, the full factorial design matrix has 419904 different MS designs.

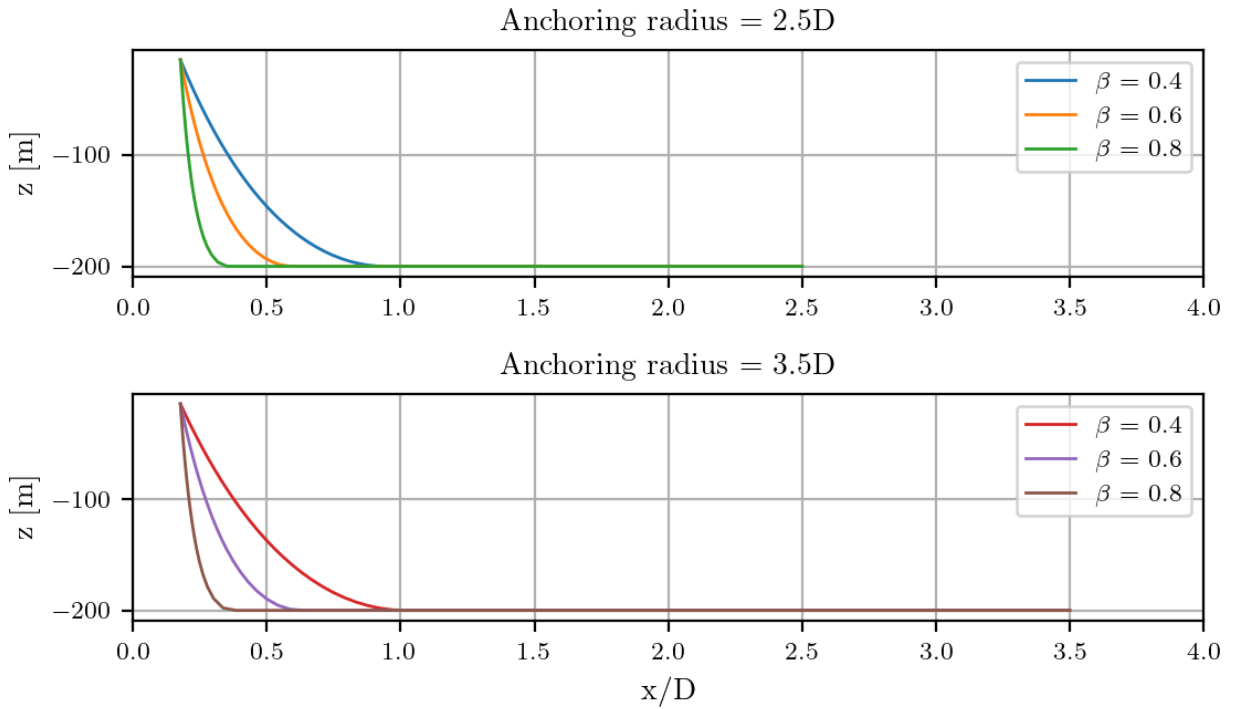


Figure 3.8: Mooring lines length and anchor radius

3.4.2 Aerodynamic forces at MSL

In MoorPy, the aerodynamic forces can only be applied at MSL, but I extract these values from OpenFAST at the rotor reference frame. Therefore, I needed to transfer the aerodynamic forces and moments from the rotor plane to the MSL. However, transferring the aerodynamic forces and moments to the global fixed reference frame at MSL is insufficient, as the aerodynamic forces and moments acting on the rotor change when the floating platform rolls, pitches, or yaws. Therefore, I needed to capture how the aerodynamic forces changed with the floater's motions. The translational motions of the FOWT do not affect the mean static wind forces and moments acting on the rotor, and hence, I will focus on the effect of the rotational motions of the platform. These two steps, first capturing the effect of the rotational motions and second transferring the aerodynamic force vector from the rotor frame to MSL, are explained in the following sections.

Effect of rotational motions on aerodynamic forces

The roll, pitch, and yaw rotational motions change the aerodynamic angle of attack and affect the rotor's aerodynamic loads. To calculate the effect of the rotational motions on the aerodynamic forces, I used OpenFAST simulations with a steady wind speed of 10 m/s while altering the roll, pitch, and yaw angles. In all of these steady wind simulations, the six DoFs of the floater were locked. I displaced the FOWT in roll, pitch, and yaw at the beginning of the simulation, and the FOWT remained fixed in the displaced position throughout the simulation. First, I ran the simulations with the FOWT with roll, pitch, and yaw set to 0° to get the aerodynamic force without the effect of the FOWT's motions. Afterward, I ran simulations with steps of 1° of the floater's pitch angle between 0° and 7° , while roll and yaw were kept fixed at 0° . I repeated the same procedure for the yaw DoF and changed the yaw angle of the floating platform between -10° and 10° , while roll and pitch were kept fixed at 0° . Finally, I repeated it for the roll DoF with values between -5° and 5° , while pitch and yaw were kept fixed at 0° .

The effects of roll, pitch, and yaw on the aerodynamic force vector at the rotor are shown in Figures A.10, A.11, and A.12, in Appendix A. For simplicity, I assumed the changes of the aerodynamic forces are linear and quantified the changes in the aerodynamic forces and moment per 1° change in roll, pitch, and yaw DoFs. Therefore, I did not create a look-up table; I directly used the slopes of the curves shown in Figures A.10, A.11, and A.12. Moreover, I assumed the effects of each DoF were independent, with no coupling effects between them. Section 5.3 will show that the impact of these assumptions on the watch circle is negligible.

Transferring the aerodynamic forces to MSL

After calculating the effect of the FOWT's movement on the aerodynamic forces, I transfer the aerodynamic forces and moments from the rotor plane to the MSL. To transfer from one reference frame to another, I used the rotation matrix implemented within MoorPy, which follows the following order of rotation: rotation around the z-axis, followed by rotation around the y-axis, and finally, rotation around the x-axis. The reason for using the same rotation matrix implemented within MoorPy is to assure the consistency of the results and to have a single rotation matrix while calculating the mooring database. The rotation matrix is introduced in equation 3.4, with θ being the rotation angle around the z-axis, ψ is around the y-axis, and ϕ is the rotation around the x-axis.

$$\mathbf{R} = \begin{bmatrix} \cos(\psi)\cos(\theta) & -\cos(\phi)\sin(\theta) + \sin(\phi)\sin(\psi)\cos(\theta) & \sin(\phi)\sin(\theta) + \cos(\phi)\sin(\psi)\cos(\theta) \\ \cos(\psi)\sin(\theta) & \cos(\phi)\cos(\theta) + \sin(\phi)\sin(\psi)\sin(\theta) & -\sin(\phi)\cos(\theta) + \cos(\phi)\sin(\psi)\sin(\theta) \\ -\sin(\psi) & \sin(\phi)\cos(\psi) & \cos(\phi)\cos(\psi) \end{bmatrix} \quad (3.4)$$

The aerodynamic forces and moments in OpenFAST are calculated at the rotor reference frame, which rotates with the blades. The first step was to transfer the aerodynamic loads from the hub rotating frame to the hub fixed reference frame by accounting for the blade's azimuth angle. Then, I accounted for the rotor uptilt angle and transferred the forces and moments from the hub reference frame to the tower top reference frame. The uptilt angle of the 15MW reference wind turbine is constant and equal to 6° . In OpenFAST, the tower top reference frame is not fixed but moves with the tower as it deflects. Afterward, I transfer the forces and moments from the deflected tower top to the tower base reference frame, which moves with the FOWT's platform. Finally, I accounted for the FOWT's rotational motions (roll, pitch, and yaw) and transferred the forces to the global fixed reference frame.

To transfer the aerodynamic forces from one reference frame to another, multiplying the aerodynamic forces by the rotational matrix is enough, as shown in equation 3.5, where $\mathbf{F}_{hub}$ is the aerodynamic force vector at the hub, $\mathbf{F}_{aero}$ is the aerodynamic force vector (in the x, y, and z-axis) at the fixed global reference frame at MSL (O_g), $\mathbf{R}_{azimuth}$ is the rotational matrix considering azimuth angle, $\mathbf{R}_{uptilt}$ considering uptilt angle, $\mathbf{R}_{twr}$ considering tower top deformations, $\mathbf{R}_{ptfm}$ considering platform rotational motions. On the other hand, to transfer the aerodynamic moments, the moment arm $\mathbf{r}_{arm}$ needs to be considered. The moment arm, in this case, includes the vertical and the horizontal distance between the MSL where the fixed global reference frame is located and the rotor hub as and cross multiplied by the aerodynamic force at O_g reference frame as shown in equation 3.6. $\mathbf{M}_{hub}$ is the aerodynamic moment vector (around

the x, y, and z-axis) at the hub rotational reference frame, and $\mathbf{M}_{aero}$ is the aerodynamic moment vector at O_g .

$$\mathbf{F}_{aero} = \mathbf{R}_{ptfm} \cdot \mathbf{R}_{twr} \cdot \mathbf{R}_{uptilt} \cdot \mathbf{R}_{azimuth} \cdot \mathbf{F}_{hub} \quad (3.5)$$

$$\mathbf{M}_{aero} = \mathbf{R}_{ptfm} \cdot \mathbf{R}_{twr} \cdot \mathbf{R}_{uptilt} \cdot \mathbf{R}_{azimuth} \cdot \mathbf{M}_{hub} + \mathbf{r}_{arm} \times \mathbf{F}_{aero} \quad (3.6)$$

3.4.3 Creating the mooring database

After preparing the inputs in the last two sections, I created the MS database. The method used to create the MS database is presented in Figure 3.9. The process starts with two inputs: the FOWT's parameters and the MS full factorial matrix. The full factorial design matrix was introduced in detail in section 3.4.1. The FOWT's parameters include the mass and water displaced volume of the FOWT and the CG, AWP, and MC. The CG is introduced as a function of the wind direction, as when the RNA rotates to face the wind, the CG rotates with it. Hence, the x and y components of the CG change as the wind direction change.

The first step was to build the MS design from the design matrix in MoorPy and then calculate the static equilibrium positions in the absence of any external forces. The static equilibrium position considers only inertial forces when the MS and the FOWT are coupled. This is important to consider, as the equilibrium position is not at the origin of the reference frame. The FOWT is displaced by the MS in the horizontal plane till the equilibrium between the three mooring line forces is achieved. I refer to the static equilibrium position vector as $\mathbf{X}_0$. I will refer to the equilibrium position when external forces are applied as $\mathbf{X}$. Finally, the difference between the two positions is $\Delta\mathbf{X} = \mathbf{X} - \mathbf{X}_0$.

The external forces applied were the aerodynamic forces at wind speed of 10 m/s. The hydrodynamic forces were neglected as the first-order hydrodynamic forces affect the amplitude of the dynamic motion around the steady-state mean but have no effect on the steady-state mean value calculated in MoorPy. Moreover, the mean drift force from second-order hydrodynamics is negligible compared to that of aerodynamic forces. Therefore, only the aerodynamic forces at 10 m/s are considered while creating the database. The aerodynamic forces were applied with an increment of 5° . Thus, 72 wind directions were considered while creating the MS database.

Afterward, I check if the MS fulfills the following constraints:

- A part of the line length should lie on the seabed for all wind directions. No vertical loads on the mooring line anchors.

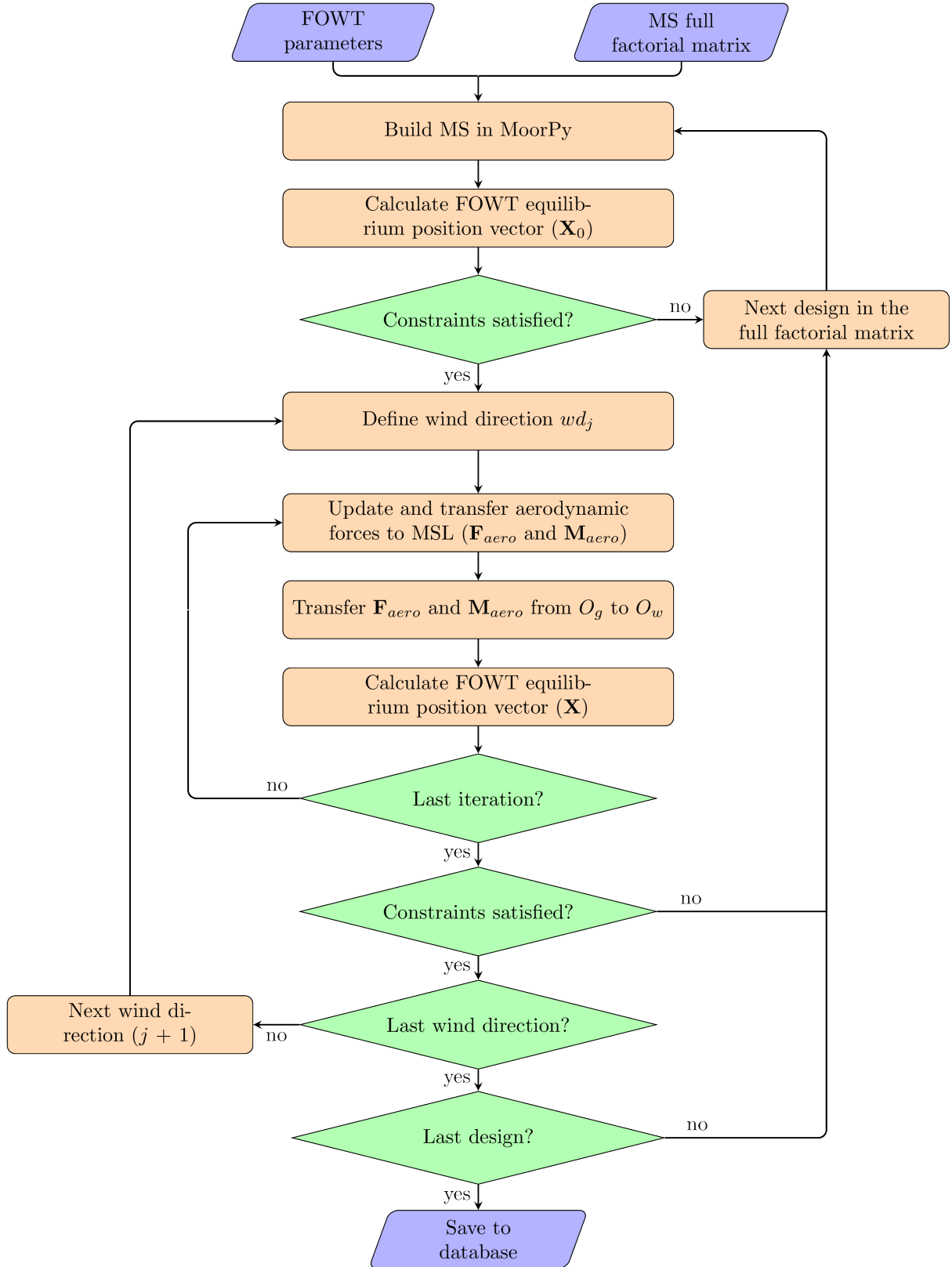


Figure 3.9: Method to create MS design matrix

- The yaw angle in $\mathbf{X}$ should be between -5° , and 5° . The MS design provides stiffness in the yaw direction for the FOWT. I did not allow higher yaw angles as I did not implement a yaw controller in my dynamic models. A higher FOWT's yaw angle will cause high power loss, which is counteractive to the goal of my method. Additionally, a higher yaw angle will lead to higher roll and pitch angles, which leads to higher tower base loads. This constraint and its effect on the FOWT loads will be discussed in detail in Chapter 5.
- The maximum allowable displacement $\Delta\mathbf{X}$ in the wind direction x_w , in the O_w reference frame is $1D$ (i.e. 240 m). I have no direct constraint on the crosswind motion, but since it is always smaller than the inwind motion, this guarantees that no crosswind motion of the MS design is higher than $1D$.

First, I calculate the static equilibrium position vector $\mathbf{X}_0$. Afterward, I start iterating over the wind directions to get the equilibrium position $\mathbf{X}$ of each MS and each wind direction. At the beginning of each iteration, I assume $\mathbf{X}$ to be a zero vector. First, I transfer the aerodynamic force from the hub reference frame to the O_g reference frame. Then, according to the wind direction, I rotate the aerodynamic forces from the O_g reference frame to the O_w reference frame. As introduced in section 3.4.2, the aerodynamic forces at MSL are a function of the FOWT's rotational displacements. Hence, I iterate 10 times over the aerodynamic forces till $\mathbf{X}$ converges. To check the number of iterations needed for convergence, I used a random sample with a size of 20995 MS designs; this sample represents 5% of the MS designs in the full factorial design matrix. I changed the number of iterations until the results converged after 10 iterations, so I decided to use 10 iterations for creating the database. The sensitivity analysis results performed for the different iterations are shown in Figure A.13 in appendix A.

Afterward, if the MS fulfilled the list of constraints, I saved it in the database. The database included $\mathbf{X}_0$, $\mathbf{X}_g$, $\mathbf{Y}_g$, $\Delta\mathbf{X}_g$, $\Delta\mathbf{Y}_g$, $\mathbf{X}_w$, $\mathbf{Y}_w$, $\Delta\mathbf{X}_w$, and $\Delta\mathbf{Y}_w$. $\mathbf{X}_0$ is a vector where each row is the position vector of the FOWT without aerodynamic force when coupled to an MS design in the database. While $\mathbf{X}_g$, $\mathbf{Y}_g$, $\Delta\mathbf{X}_g$, $\Delta\mathbf{Y}_g$, $\mathbf{X}_w$, $\mathbf{Y}_w$, $\Delta\mathbf{X}_w$, and $\Delta\mathbf{Y}_w$ are matrices similar to the $\mathbf{C}\mathbf{r}$ matrix, where each column represents the wind direction and each row represents an MS design in the database.

The $\mathbf{X}_g$, $\mathbf{Y}_g$ matrices are the x and y positions in the O_g reference frame for each wind direction. The $\Delta\mathbf{X}_g$, $\Delta\mathbf{Y}_g$ matrices are the difference between the final x and y positions of the FOWT and the static equilibrium positions in the absence of forces. Hence, $\mathbf{X}_g$ is the surge displacement of the FOWT, while $\mathbf{Y}_g$ is the sway displacement of the FOWT.

$\mathbf{X}_w$ and $\mathbf{Y}_w$ are the position matrices in the O_w reference frame in the wind and crosswind directions, respectively. Each row of the $\mathbf{X}_w$ matrix represents the movements of a single MS referred to by x_w , a vector with a length equal to the number of wind directions used to create the MS database. Similarly, each row of the $\mathbf{Y}_w$ matrix represents the crosswind movements of

a single MS and is referred to by y_w , which is a vector with the same length as the number of wind directions used to create the MS database. Therefore, x_w and y_w are not single values but vectors to describe the motions of a single MS in all wind directions.

Similarly, ΔX_w and ΔY_w are the position matrices in the O_w reference frame in the wind direction and crosswind direction, respectively. Each row of the ΔX_w matrix represents the displacements of a single MS is referred to by Δx_w which is a vector with the length equal to the number of wind directions used to create the MS database. Each row of the ΔX_w matrix represents the crosswind displacement of a single MS and is referred to by Δy_w which is a vector with the same length as the number of wind directions used to create the MS database. Therefore, Δx_w and Δy_w are not single values but vectors to describe the motions of a single MS at all wind directions.

The final number of MS designs that passed the constraints and saved in the database is 17862. Out of the 72 headings in the full factorial design matrix, only 31 designs passed the constraints and are included in the 17862 designs in the database.

3.4.4 The effect of MS design parameters on the watch circle

Understanding how each design parameter affects the watch circle of each MS design is crucial for this work. The goal is to analyze how each design parameter affects the FOWT's ability to relocate in the wind and crosswind directions. I will use this understanding later in the next steps while developing the method. Understating each design parameter's effect will help me find a way to simplify the optimization process in the following steps. Additionally, I will explain in this section how the MS can passively relocate the FOWTs in the crosswind directions. The effect of each of the iterating design parameters is analyzed one after another in the following sections.

Effect of MS headings

The first design parameter I analyze is the mooring line headings. Figures 3.10, 3.11, and 3.12 show the watch circle and the displacements in the wind directions and crosswind directions for three different line headings configurations of $(0^\circ, 120^\circ, 250^\circ)$, $(0^\circ, 140^\circ, 290^\circ)$ and $(0^\circ, 160^\circ, 260^\circ)$. In each of the Figures 3.10, 3.11, and 3.12, the colors represent four randomly chosen MS designs from the database sharing the same headings, but no constraints were set on the other design parameters. I will explain each subplot in the three Figures in the following paragraphs.

On the left side of Figures 3.10, 3.11, and 3.12, the watch circles of the MS in the x-y plane are shown. I show Δx and Δy , which are the displacements from static equilibrium in the

absence of wind forces ($\mathbf{X}_0$) to static equilibrium when F_{aero} is applied ($\mathbf{X}$). Therefore, in Figures 3.10, 3.11, and 3.12, the watch circles are centered around the origin of the O_g reference frame, this makes it easier to compare the watch circles of the different designs sharing the same mooring lines headings. Each dot in the left subplot of Figures 3.10, 3.11, and 3.12 represents the displacement of the FOWT for a single wind direction. The figures show that the shape of the watch circle does not change as long as the line headings do not change. Changing the other design parameters, like mooring line diameter or mooring line length, can be used to tune the value of the displacement and increase or decrease it without changing the shape of the watch circle.

In the middle subplot of Figures 3.10, 3.11, and 3.12, the displacement in the wind direction Δx_w is shown. The solid black lines show the mooring lines' headings. The radial distance represents the displacement value, and the angle represents the wind direction. The maximum displacement in the wind direction happens when the wind blows in the middle of two mooring line headings. As the angle between the mooring lines headings increases, the displacement in the wind direction increases. For example, in Figure 3.10, the biggest displacement happens at wind direction of 5° when the wind is blowing precisely at the middle of the two lines with headings 120° , and 250° . The smallest angle between two lines' headings is between the lines with headings 250° and 0° , and therefore, even when the wind is blowing exactly in the middle between the two lines (i.e., the wind direction of 125°), the displacement in the wind direction is smaller than that when the wind direction is 5° . This is also true for Figures 3.11 and 3.12.

In the subplots on the right side of Figures 3.10, 3.11, and 3.12, the absolute of the crosswind displacement $|\Delta y_w|$ is shown for MS designs with three headings for each wind direction. The first observation is that the crosswind displacement increases as the angle between two line headings increases. This is clear if Figure 3.10 is compared to Figures 3.11 and 3.12. The crosswind displacements in Figures 3.11 and 3.12 are higher as the angle between the mooring line headings is higher. The second observation is that if the angle between two line headings is small, there is no crosswind displacement, illustrated in Figure 3.11. For the wind directions between the two mooring lines with headings 290° and 0° , there is no crosswind displacement. In this case, the angle between the two mooring lines is 70° . The final observation is that the crosswind displacement has two peaks as the wind blows between two mooring lines. For example, in Figure 3.12 for the mooring line headings at 0° and 160° , the wind directions when the wind is blowing between these two lines are from 180° to 340° . Between these two wind directions, the crosswind displacement increases to reach a maximum value, drops to zero, and then increases again to reach a maximum value. In the following paragraphs, I will explain the relationship between the line headings, the wind direction, and the ability of a FOWT to relocate its position in the crosswind direction.

In Figure 3.13, F_1 is the horizontal resultant force of mooring line 1, and F_2 is the horizontal

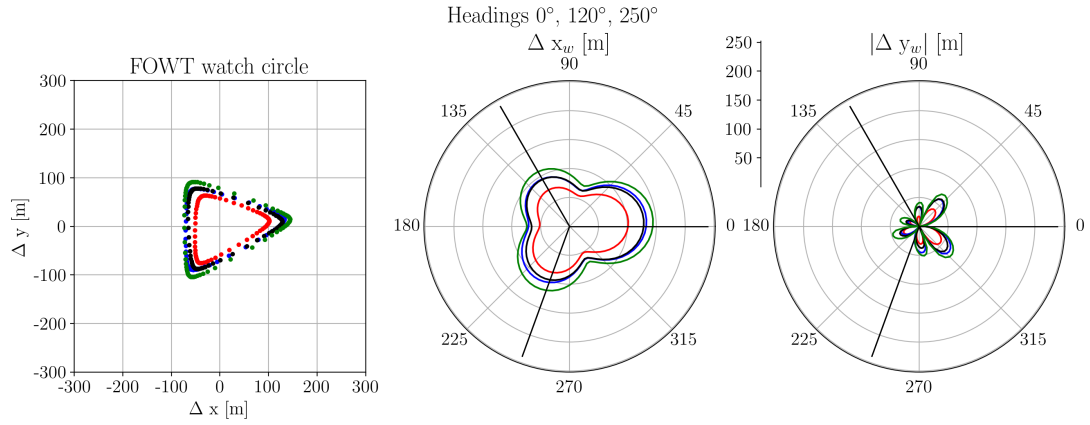


Figure 3.10: The watch circle, displacement in the wind direction, and the crosswind direction for four MS designs with line headings (0°, 120°, 250°)

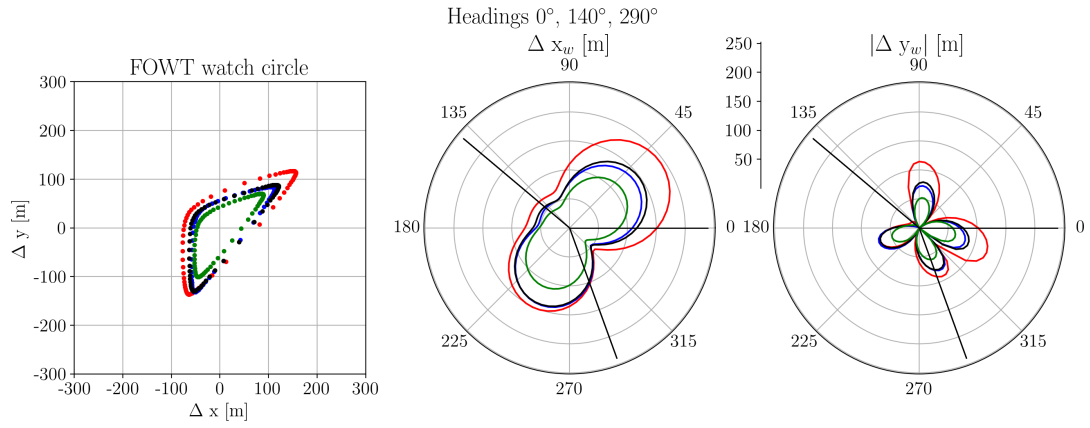


Figure 3.11: The watch circle, displacement in the wind direction, and the crosswind direction for four MS designs with line headings (0°, 140°, 290°)

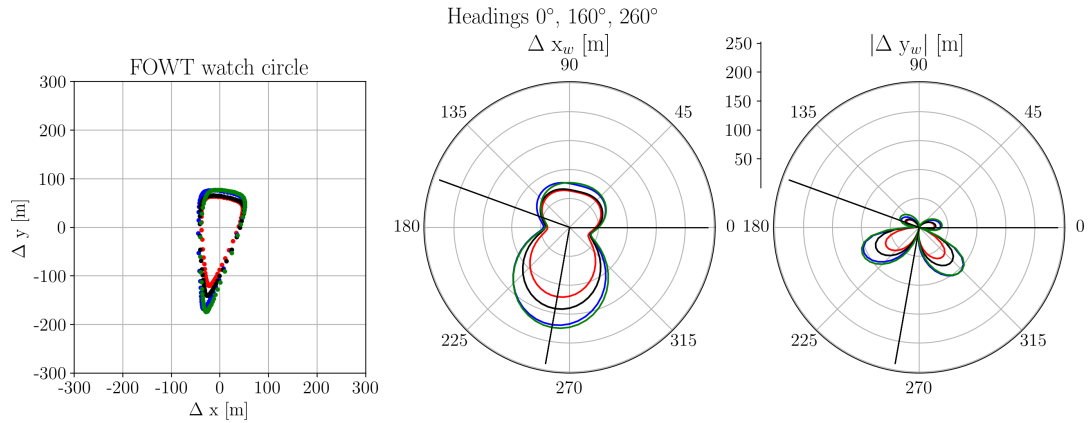


Figure 3.12: The watch circle, displacement in the wind direction, and the crosswind direction for four MS designs with line headings (0°, 160°, 260°)

resultant force of mooring line 2. F_{aero} is the horizontal resultant force of the aerodynamic forces acting on the FOWT after transferring it to the O_g at MSL. Angle a is the angle between

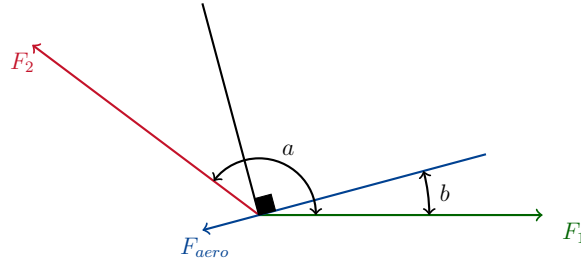


Figure 3.13: Aerodynamic force (F_{aero}), the tension force of mooring line one (F_1), and the tension force of mooring line two (F_2). a is the angle between the mooring lines tension forces, and b is the angle between the aerodynamic force and the tension force of mooring line one.

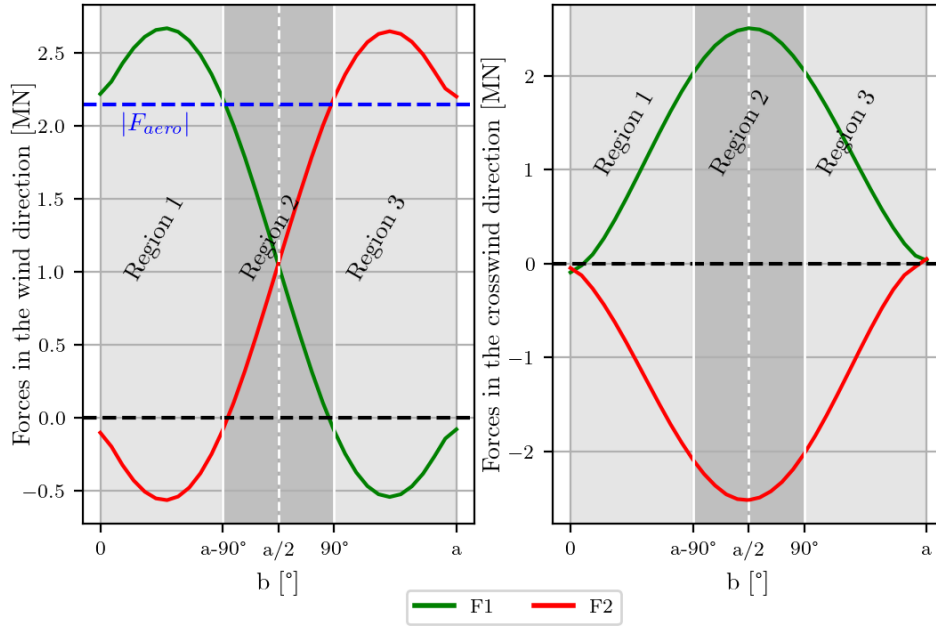


Figure 3.14: Horizontal forces of two mooring lines in the wind direction and the crosswind direction

mooring lines 1 and 2 headings. While angle b is the angle between F_{aero} , and F_1 . Therefore, when F_{aero} is opposite to F_1 , b equals zero. While when F_{aero} is opposite to F_2 , b is equal to a . The magnitude of the vectors in Figure 3.13 does not represent the magnitudes of the forces F_1 , F_2 , and F_{aero} . The Figure's goal is to define angles a and b as well as F_1 and F_2 .

Figure 3.14 shows how the magnitude of F_1 and F_2 change to achieve equilibrium as the wind direction changes from $b = 0$ to $b = a$. The tension force of the third mooring line is not plotted as when the wind is blowing between two mooring lines; they carry most of the tension force, while the force in the third mooring line in the MS becomes negligible compared to the forces F_1 and F_2 . In the Figure, F_1 and F_2 are decomposed into two components: the inwind component acting in the same direction as the wind and the crosswind component acting perpendicular to the wind direction. The left side of the Figure shows the components of the F_1 and F_2 forces in the wind direction, and the right side of the Figure shows the components of the F_1 and F_2

forces in the crosswind direction. For the right side of the Figure, the crosswind components of F_1 and F_2 must be equal and opposite for equilibrium to be achieved as the FOWT is not excited in the crosswind direction. Whenever F_1 is not exactly equal and opposite to F_2 , the small difference is compensated by F_3 .

In the left side of Figure 3.14, the components of the forces F_1 and F_2 aligned with F_{aero} are shown. For equilibrium to be achieved, the sum of the three forces should equal zero. F_{aero} is assumed to be negative, the absolute value of F_{aero} is plotted in the left side of Figure 3.14 for simplicity. I divided the Figure into three regions. Region 1 is for b between 0 and $a - 90^\circ$. Throughout Region 1, the component of F_2 in the wind direction is negative, meaning it acts in the same direction as F_{aero} . In contrast, the component of F_1 in the wind direction opposes both forces to achieve equilibrium. Therefore, the magnitude of the F_1 inwind component is higher than the F_{aero} through this region. At $b = a - 90^\circ$, the aerodynamic force F_{aero} is perpendicular to F_2 , so there is no inwind component for F_2 . In Region 2, F_1 and F_2 inwind components act in the same direction opposite to F_{aero} , and at $b = a/2$, both F_1 and F_2 components are equal. In region 3, the F_1 component in the wind direction is now acting in the same direction as F_{aero} and F_2 is opposing both of them; hence, the magnitude of F_2 is larger than F_{aero} .

The crosswind displacement is maximum in Regions 1 and 3. It decreases in Region 2 till it reaches zero at $b = a/2$, where the FOWT's displacement is only in the wind direction, then it increases again. If the angle a between two line headings is 90° or less, regions 1 and 3 do not exist, and hence, the crosswind displacement does not occur for these wind directions. Although

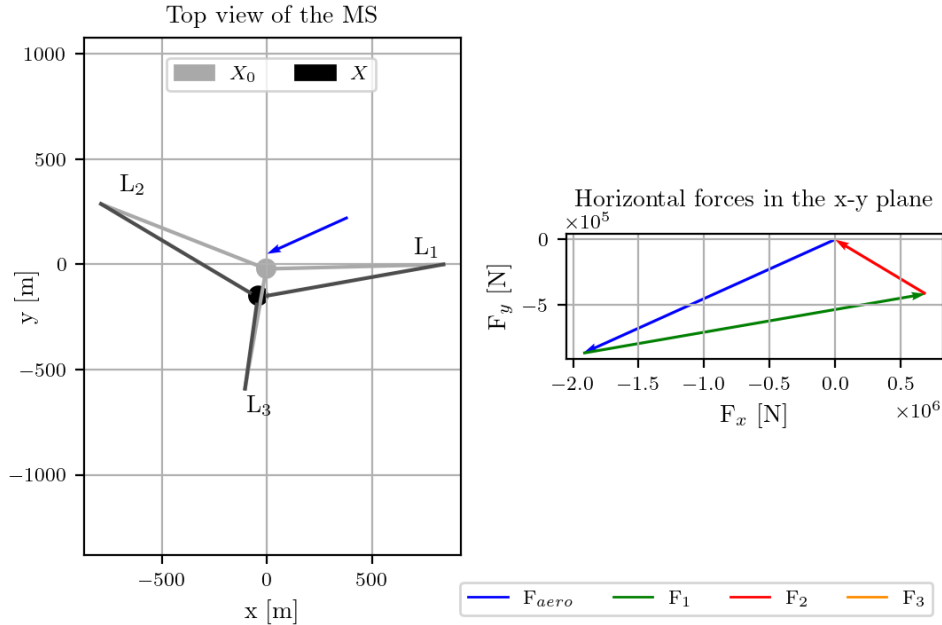


Figure 3.15: The equilibrium position of the FOWT and the forces acting on the FOWT in Region 1

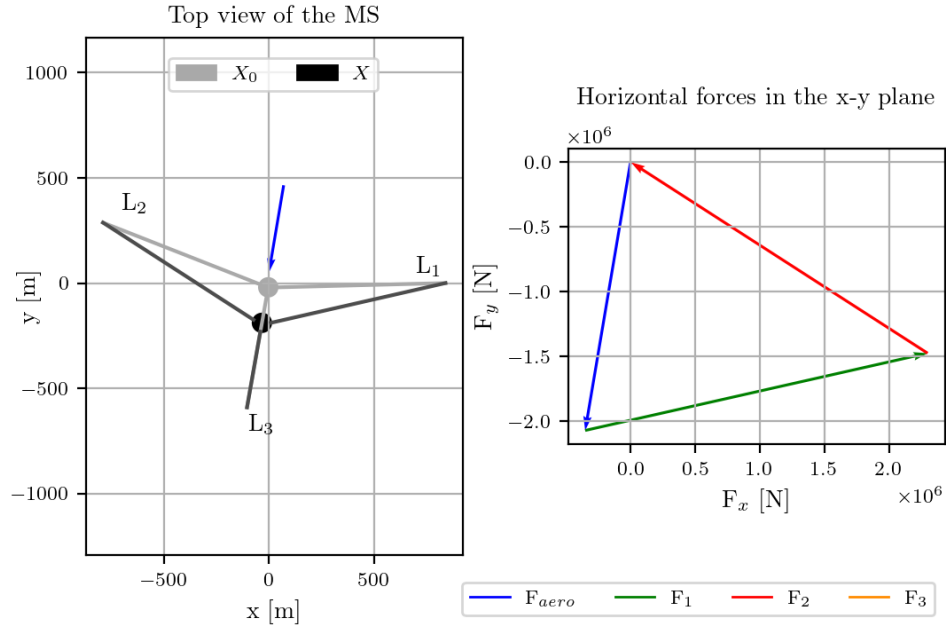


Figure 3.16: The equilibrium position of the FOWT and the forces acting on the FOWT in Region 2

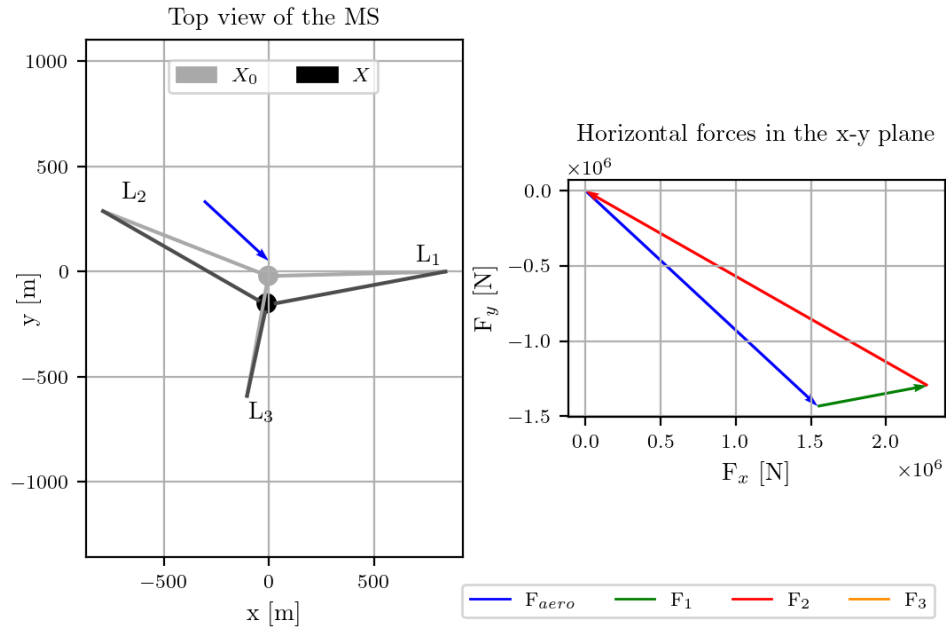


Figure 3.17: The equilibrium position of the FOWT and the forces acting on the FOWT in Region 3

Figure 3.14 shows a single case, the pattern explained is repeated for all MS designs in the database. Another explanation and visualization for why the crosswind displacement occurs in regions 1 and 3 but not in region two is provided using Figures 3.15, 3.16, and 3.17.

In Figure 3.15, the wind direction is in region 1. F_1 opposes F_{aero} and F_2 to achieve equilibrium

position. The left side of the Figure represents a top view of the FOWT and the mooring lines. Grey is the equilibrium position before F_{aero} is applied, and black is when the aerodynamic forces are considered. On the right side of Figure 3.15, the forces are drawn as vectors with their real magnitudes and directions, showing that equilibrium is achieved. It also shows that F_3 is very small compared to F_1 , F_2 , and F_{aero} , which is not visible as a vector but instead as a point. The Figure shows that for equilibrium to be achieved, the crosswind movement is necessary to make F_1 in the mooring line one more parallel and opposite to F_{aero} . Figure 3.17 shows the same effect when the wind direction is in region 3.

Figure 3.16 shows the wind direction in region 2, exactly with $b = a/2$. Therefore, the motion is only in the wind direction, and no crosswind motion is needed to achieve equilibrium. Moreover, the right side of Figure 3.16 shows that F_1 and F_2 are equal and act opposite to the aerodynamic force.

To summarise, the line headings have two main effects on the movement of the FOWT. First, they define the shape of the watch circle. The size of the watch circles can be changed by tuning the rest of the parameters. However, none of the other parameters can change the shape of the watch circle. The second effect is that if the difference between two mooring line headings is 90° or less, there will be no crosswind displacement for the wind directions between these two lines.

Effect of mooring line diameter

To check the effect of the mooring line diameters on the watch circle, I changed the mooring line diameters of the line with heading 0° to the three values of the mooring line diameters in the MS design database (0.12 m, 0.15 m, 0.18 m). All other design parameters were kept fixed and equal for the three lines. The line diameters of the other two lines were kept fixed at 0.15 m. The anchoring radius of all three mooring lines was equal to $3.5D$, and the line length ratio was kept equal for all three lines at $\beta = 0.4$.

Figure 3.18 shows the radial displacement of the FOWT (r_0) in the absence of aerodynamic forces on the left, the displacement in the wind direction in the center, and the absolute displacement in the crosswind direction on the right. The black solid lines represent the mooring lines headings at $(0^\circ, 140^\circ, 290^\circ)$. I will refer to them as lines 1, 2, and 3 respectively. The Figure shows that the MS with one line having a smaller diameter makes larger displacements in the wind direction and the crosswind direction. In unloaded conditions (left subplot of Figure 3.18), when line 1 has the smallest diameter of 0.12 m, the FOWT is pulled towards the other two lines. When the three lines have the same diameter of 0.15 m, the FOWT stays at an equal distance from the three lines. When line 1 has the largest diameter of 0.18 m, it pulls the FOWT towards its anchor. This difference in equilibrium position in the absence of aerodynamic forces causes the difference in the displacement both in the wind direction and in the crosswind direction

when aerodynamic forces are applied. Figure 3.18 shows that the movements are larger when the wind direction is between line 2 and line 3, but as discussed earlier, the tension force of line 1 is negligible for these wind directions. Therefore, the higher displacements in these wind directions are due to the difference in the r_0 . The effect of the line diameter is only visible on displacements that take place when the mooring line is oriented downwind.

Figure 3.19 shows the force-displacement curve on the left side and the profile of line 1 on the right side at a wind direction of 180° with the mooring line upwind. The slope of the force-displacement curve is the MS stiffness; the Figure shows the nonlinear stiffness of the catenary

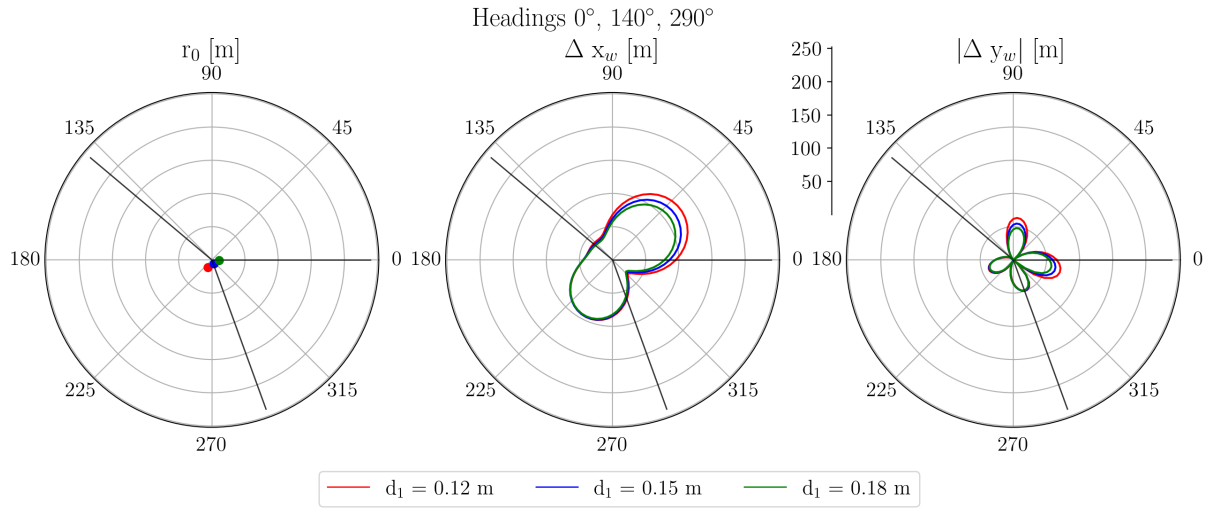


Figure 3.18: Effect of the mooring line diameters on the FOWT in the wind and crosswind directions. On the left side is the radial displacement of the unloaded FOWT r_0 . The center is the absolute displacement in the wind direction Δx_w , and on the right side is the absolute displacement in the crosswind direction Δy_w .

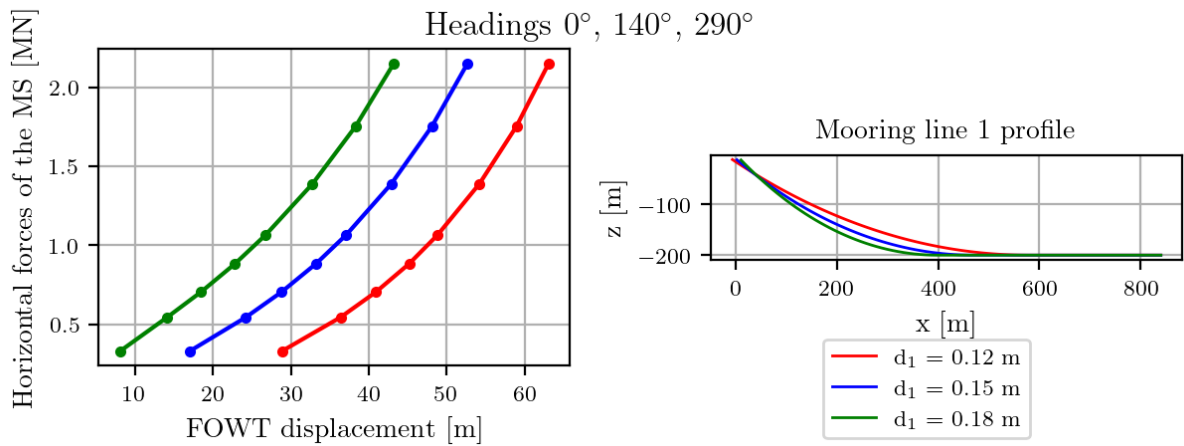


Figure 3.19: The force-displacement curve of the MS on the left. The profile of the mooring line at wind direction of 180° on the right

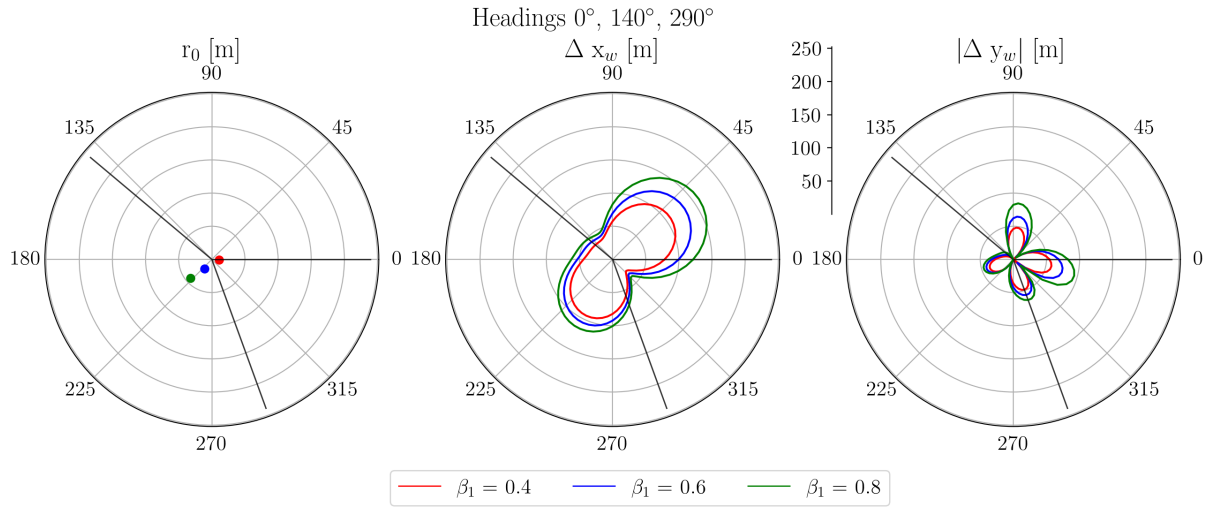


Figure 3.20: Effect of the mooring lines length on the FOWT in the wind and crosswind directions. On the left side is the radial displacement of the unloaded FOWT r_0 . The center is the absolute displacement in the wind direction Δx_w , and on the right side is the absolute displacement in the crosswind direction Δy_w .

MS designs. The stiffness of MS with the smallest diameter is more nonlinear than that of the MS with the highest diameters. On the right side, the profile of mooring line 1 is shown. As the diameter increases, a smaller hanging length is needed to achieve the equilibrium position. In contrast, the hanging length is larger for a small diameter to produce enough force to reach equilibrium.

Effect of mooring line length

To check the effect of the mooring lines' length, I used the same approach I used for the mooring lines' diameters. I fixed all the parameters of the three mooring lines and changed the mooring line length of line 1 at 0° heading. The diameters of the three lines were fixed to 0.18 m, and the anchoring radii were fixed to $3.5D$. The length of lines 2 and 3 were fixed at $\beta = 0.4$.

Figure 3.20 shows that the lines with longer lengths have higher displacements for all wind directions, both in the wind direction and in the crosswind direction. On the left of Figure 3.20, the radial displacement in the absence of aerodynamic forces r_0 of the FOWT is shown. When line 1 is longer than lines 2 and 3, the FOWT is pulled towards line 2 and line 3. This is because a longer mooring line needs to be pulled further to achieve the hanging length required to fulfill equilibrium. This is also true for the inwind and crosswind directions, where the displacement increases for all wind directions when line 1 is longer. Comparing Figure 3.20 to Figure 3.18 shows that for a catenary MS, the effect of the mooring line length on the ability of the MS to relocate is more significant than the effect of the mooring line's diameter.

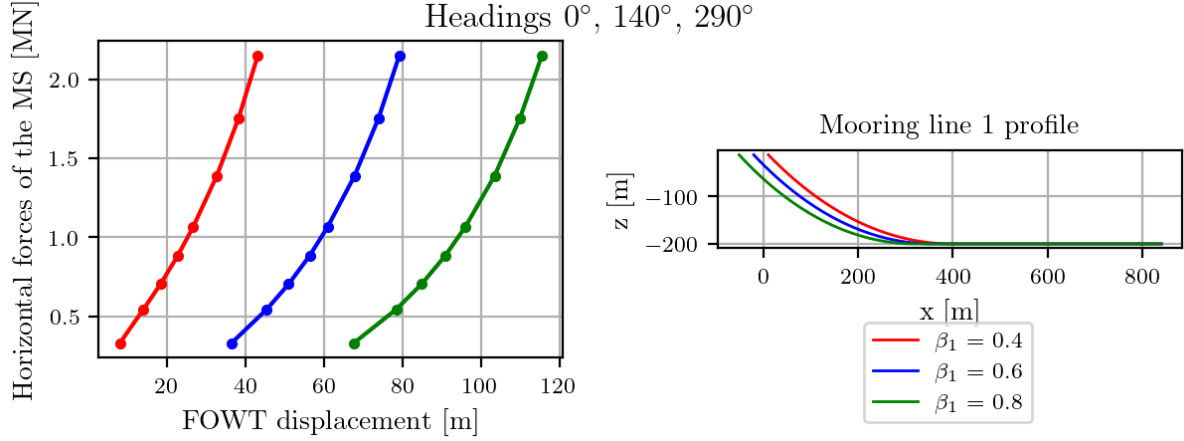


Figure 3.21: The force-displacement curve of the MS on the left. The profile of the mooring line at wind direction of 180° on the right

Figure 3.21 shows the force-displacement graph and the profile of the mooring lines at equilibrium for wind direction of 180° . The force-displacement graphs show the stiffness of the MS becomes more nonlinear as the length of mooring line 1 increases. The mooring line profiles show that as the line length increases, the displacement done by the line to reach equilibrium increases. The mooring line profiles of line 1 must have equal hanging mooring line lengths to achieve equilibrium. Therefore, for this to happen, a larger displacement is required for the line with a longer total length. The figure also shows that as the mooring line length increases, the MS design becomes more nonlinear.

Effect of mooring line anchoring radius

Finally, to check the effect of the anchoring radius on the ability of the FOWT to relocate, I kept all parameters of the three mooring lines constant. I changed the value of the anchoring radius of line 1 at heading 0° . The diameters of all three lines were fixed to 0.18 m; the mooring lines lengths were fixed to $\beta = 0.4$. The anchoring radii of mooring lines 2 and 3 were fixed to $3.5D$ while iterating over the two radii values of $2.5D$ and $3.5D$ for mooring line 1.

Figure 3.22 shows on the left subplot the displacements of the FOWT in the absence of wind to achieve static equilibrium; in the center subplot, the FOWT displacements in the wind direction and the crosswind direction on the right subplot. The Figure shows that the effect of the anchoring radius on the FOWT is minimal, and there is only a 2-5 meter difference between the two anchoring radii values. This difference is too small compared to the FOWT's rotor diameter. Since this work aims to relocate the FOWT to increase the FWF energy production, this is considered insignificant.

Finally, Figure 3.23 shows the force-displacement curve and the profile of mooring line 1 at equilibrium at a wind speed of 10 m/s and a wind direction of 180° . The Figure also shows that the anchoring radius has a minimum effect on the mooring line profile. However, the stiffness is slightly affected by the change of the anchoring radius, as shown on the left side of Figure 3.23. The system with an anchoring radius of 600 m ($2.5D$) is more nonlinear when compared to the anchoring radius of 840 m ($3.5D$).

3.5 Customized MS design

After having the targeted layout matrix $\mathbf{Cr}$, creating the MS database, and having the watch circles and the perpendicular motions of the FOWTs when attached to each MS design ($\Delta \mathbf{Y}_w$), the goal now is to create an optimization process to find a customized MS design for each FOWT in the FWF. Indeed, the most optimum way would be to use brute force optimization, try each MS design, and attach it to each FOWT in the FWF. The MS database of 17862 designs and an FWF of 9 FOWTs leads to 17862^9 possibilities, which is computationally inefficient. This is even without considering that each MS design can have a different orientation, which is crucial for the current work. Therefore, brute force optimization is inefficient, especially as this is a preliminary design phase.

Based on the knowledge from section 3.4.4 about how each design parameter affects the FOWT's relocation, I created a simple method to select a customized MS design for each FOWT in the FWF to decrease the computational costs. The method comprises two steps: First, I decrease the possible MS designs from the database that can be attached to each FOWT. In this step, the MS orientation is also considered. Second, I iterate over these possible MS designs till the

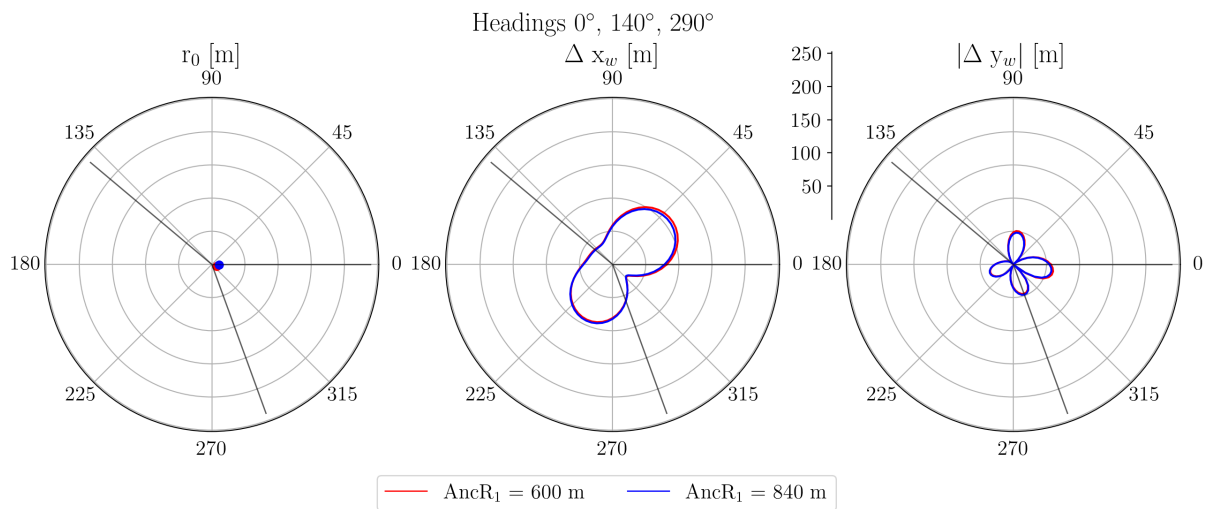


Figure 3.22: Effect of the anchoring radius on the FOWT in the wind direction and the crosswind direction

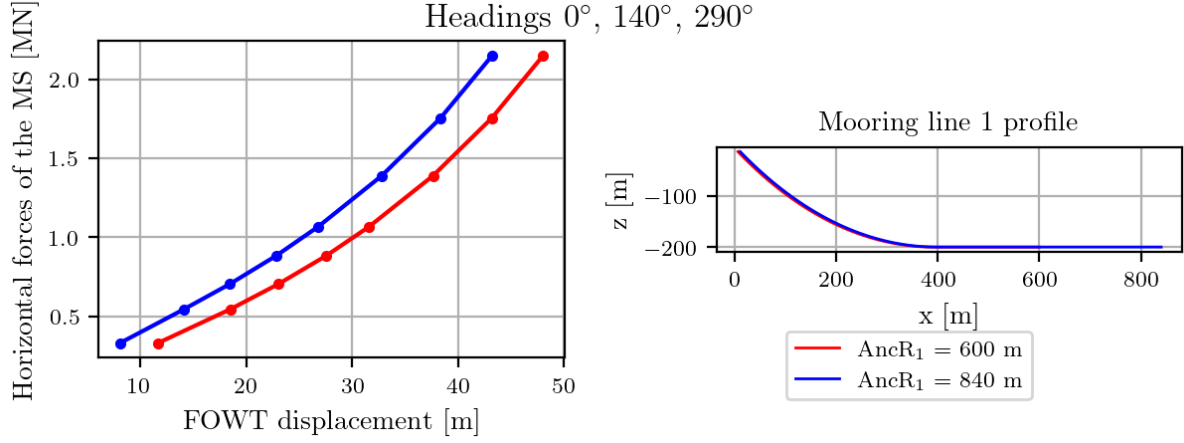


Figure 3.23: The force-displacement curve of the MS on the left. The profile of the mooring line at wind direction of 180° on the right

energy production of the FWF converges. These two steps are explained in detail in the two following subsections.

3.5.1 Possible MS designs for each FOWT

The method used to create a subset of the MS designs while considering different MS orientations is presented in Figure 3.24. The process iterates over each FOWT in the FWF, and the wind directions in the wind rose. I first find the targeted crosswind displacement Cr_{ij} from the Cr matrix, which represents FOWT i and wind direction wd_j . Then I make a list (MS_{temp}) of all MS designs where Cr_{ij} is achieved within a certain tolerance, and also save the MS orientation at which Cr_{ij} is achieved. The tolerance value is set to 5 m.

This is explained using the example in Figure 3.25. The targeted crosswind displacement of turbine 1 (Cr_1) is introduced in subplot (a). At wind direction of 0° degrees, the Cr_{11} value is 120 m. Subplot (b) shows the absolute crosswind displacement of an MS, where two orientations have crosswind displacement values within the range of 120 ± 5 m at 355° and 330° . Hence, this single MS will be stored twice in the MS list, once for each orientation. This is repeated for all MS in the database; all possibilities are stored in this MS list. I refer to this temporary list by MS_{temp} .

After creating MS_{temp} , I iterate over each MS design possibility in this list and rotate it for its orientation to match the wind direction j . Afterward, I drop the wind directions in the MS crosswind displacements but not in the Cr_i , as the resolution of the MS database is 72 points, but the resolution of Cr_i is 16, because I used a step of 5° to create the MS database, while the step of the wind directions in the wind rose in Figure 3.1 is 22.5° . Finally, I calculate the

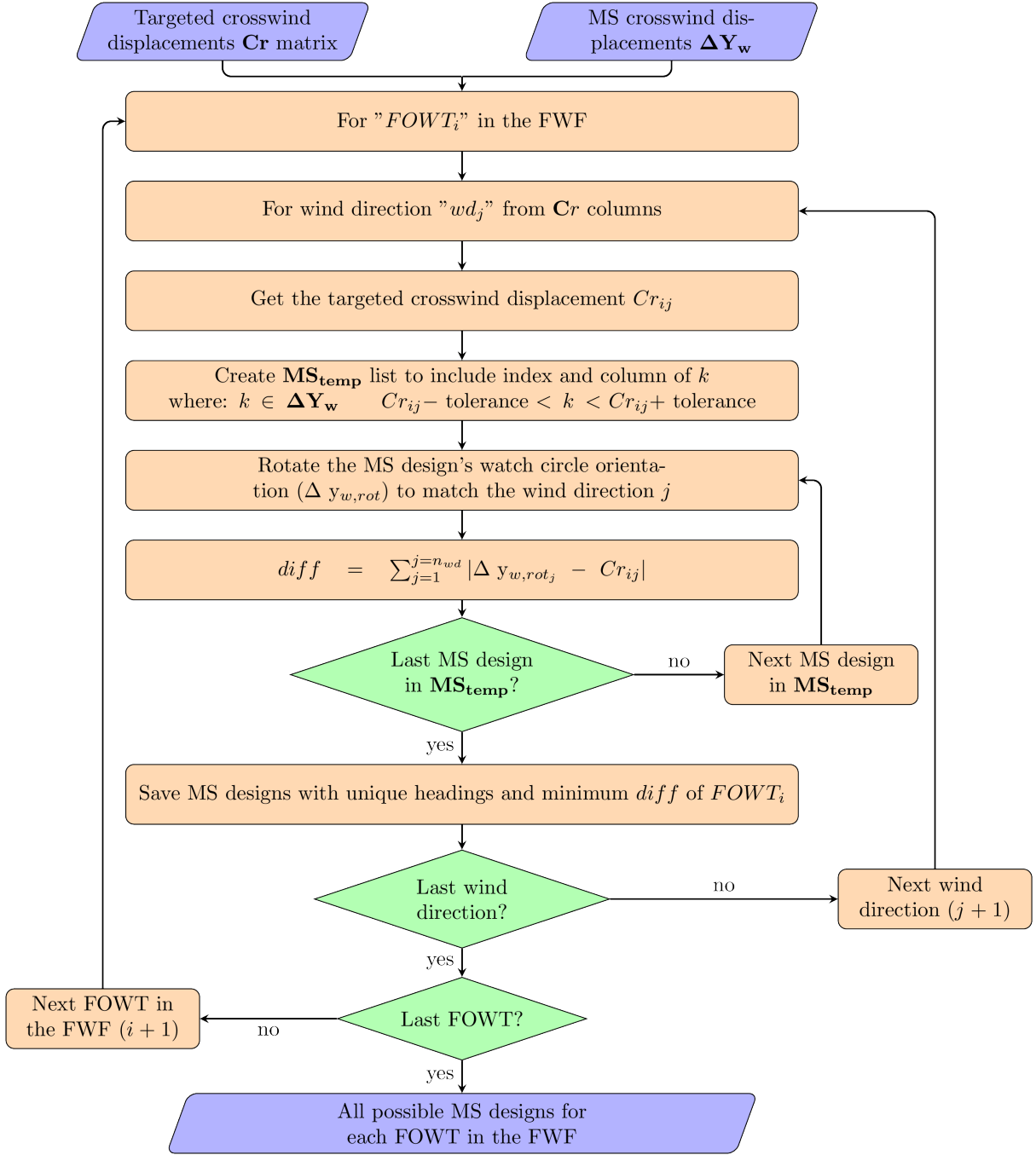


Figure 3.24: Method used to find a list of possible MS designs for each FOWT

absolute difference (*diff*) between the rotated crosswind displacement of the MS design after rotation $\Delta y_{w,rot}$. The *diff* value is stored for every MS design in MS_{temp} .

These steps are explained in Figure 3.25 in subplots (c) and (d). I rotated the MS design in subplot (b) by 30° to coincide the orientation with the wind direction of 0° . The rotation is visible when comparing the black lines in subplots (b) and (c) representing the mooring lines'

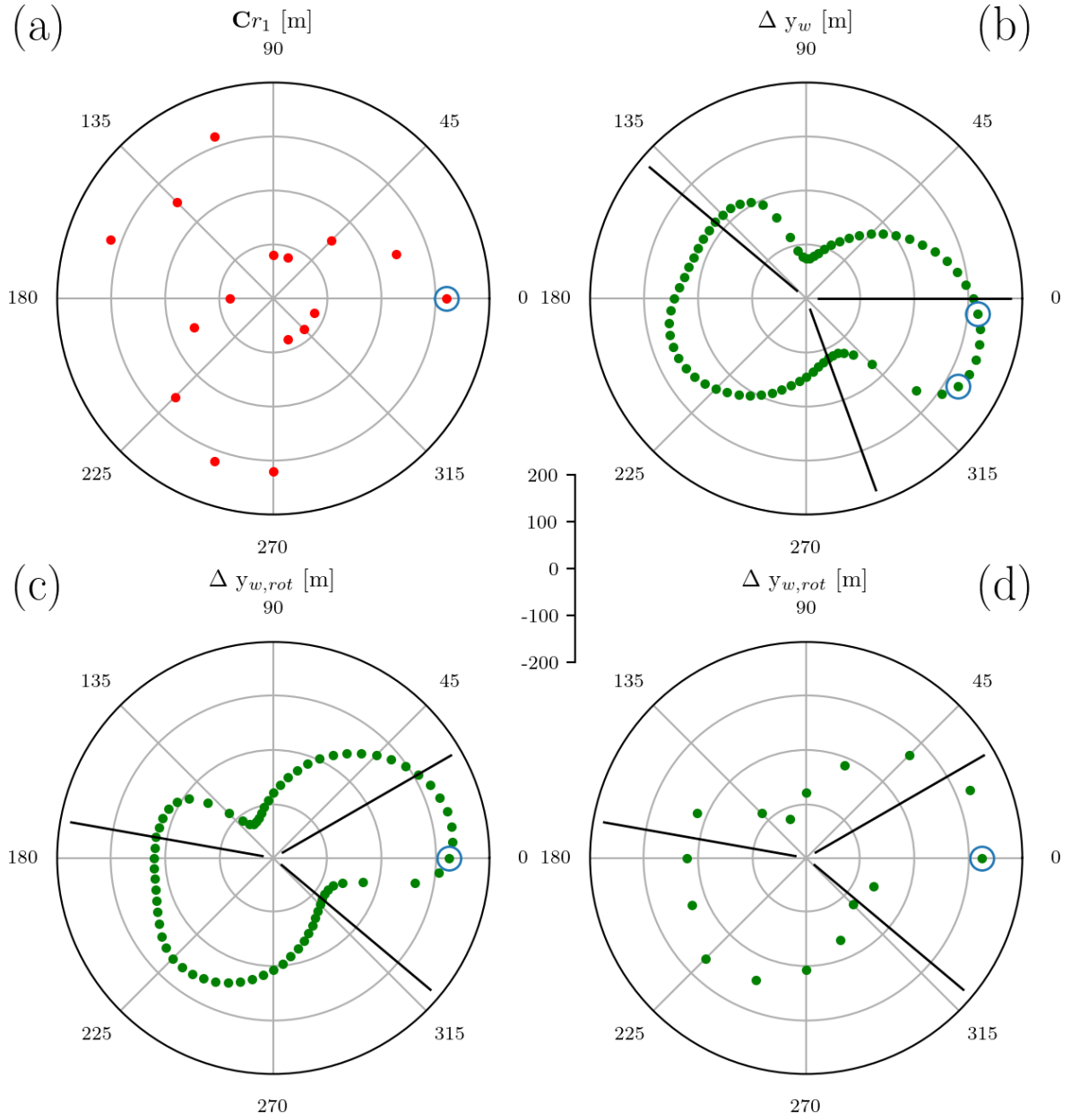


Figure 3.25: An example of the steps used to find the list of possible MS designs

headings. Afterward, in subplot (d), I dropped the wind directions that only exist in the rotated crosswind displacement $\Delta y_{w,rot}$ but not at the targeted crosswind displacements Cr_1 of turbine 1. Finally, $diff$ is calculated by subtracting every subplot (d) point from every corresponding subplot (a) value and summing them up. The difference is stored, and the same process is repeated for the second possible orientation in Figure 3.24 subplot (b). This is repeated for all MS designs in the MS_{temp} list, and the $diff$ value of each possible design is stored.

After I have the $diff$ value of the FOWT i at the wind direction j , I choose only one design from each unique value of MS design line headings from the MS_{temp} list, which achieves the lowest value of $diff$. Since the MS database has only 31 unique values of MS headings, the possible designs for each FOWT at a single wind direction cannot exceed 31 MS designs. Since there are 16 wind directions in the wind rose, the possible customized MS designs could not exceed 496 MS designs. Therefore, I reduced the number of potential designs from the size of the entire MS database of 17862 designs to a maximum of 496 designs while considering the effect of the MS orientation.

I choose only a unique value of the MS headings as Figures 3.10, 3.11, and 3.12 show that the shape of the watch circle depends on the MS headings and the rest of the design parameters only tune the watch circle. Therefore, I assumed that if the value of $diff$ is the smallest compared to the required targeted displacement, then this MS is the best option. This assumption treats all the targeted displacements at different wind directions equally. It assumes all displacements have the same effect on the targeted energy gain, but one FOWT displacement can lead to a higher gain depending on the wind direction probability and the position of the FOWT within the wind farm. However, the results in Chapter 4 show that this assumption is valid and satisfies the research goals. My goal in this work is not to find the global optimum design; my main goal is to show the potential of integrating MS designs as part of the FWF design and its effect on AEP. The effect of this simplification is checked in Chapter 4.

3.5.2 MS design for each FOWT in the FWF

After narrowing down the number of possible MS designs that can be coupled to each FOWT, I iterate over these designs following the steps shown in Figure 3.26. First, I assign an MS design from the list to each FOWT in the FWF before I start the iteration. Then, I iterate over each FOWT in the FWF. The first step in the iteration process is to calculate AEP_0 , which is the AEP of the FWF at 10 m/s, at the beginning of the iteration process. In this step, the movements of the FOWT are considered when calculating the AEP. Therefore, the locations of the FOWT inside the FWF are updated according to the wind direction. After calculating AEP_0 , I iterate over each possible MS design for $FOWT_i$, and whenever an MS leads to an AEP value higher than AEP_0 , the design is coupled to the $FOWT_i$, and AEP_0 is updated to the new value of AEP. This iteration process is repeated for all FOWTs in the FWF till the value of AEP converges, and changing the MS design coupled to the FOWTs in the FWF does not lead to a change of the AEP. Finally, I end up with a customized MS design for each FOWT in the FWF that maximizes the AEP of the FWF at a constant wind speed of 10 m/s.

Although considering the change of the positions of the FOWTs according to the wind direction, the effect of the wakes on the relocation was not considered. When a FOWT is in the wake,

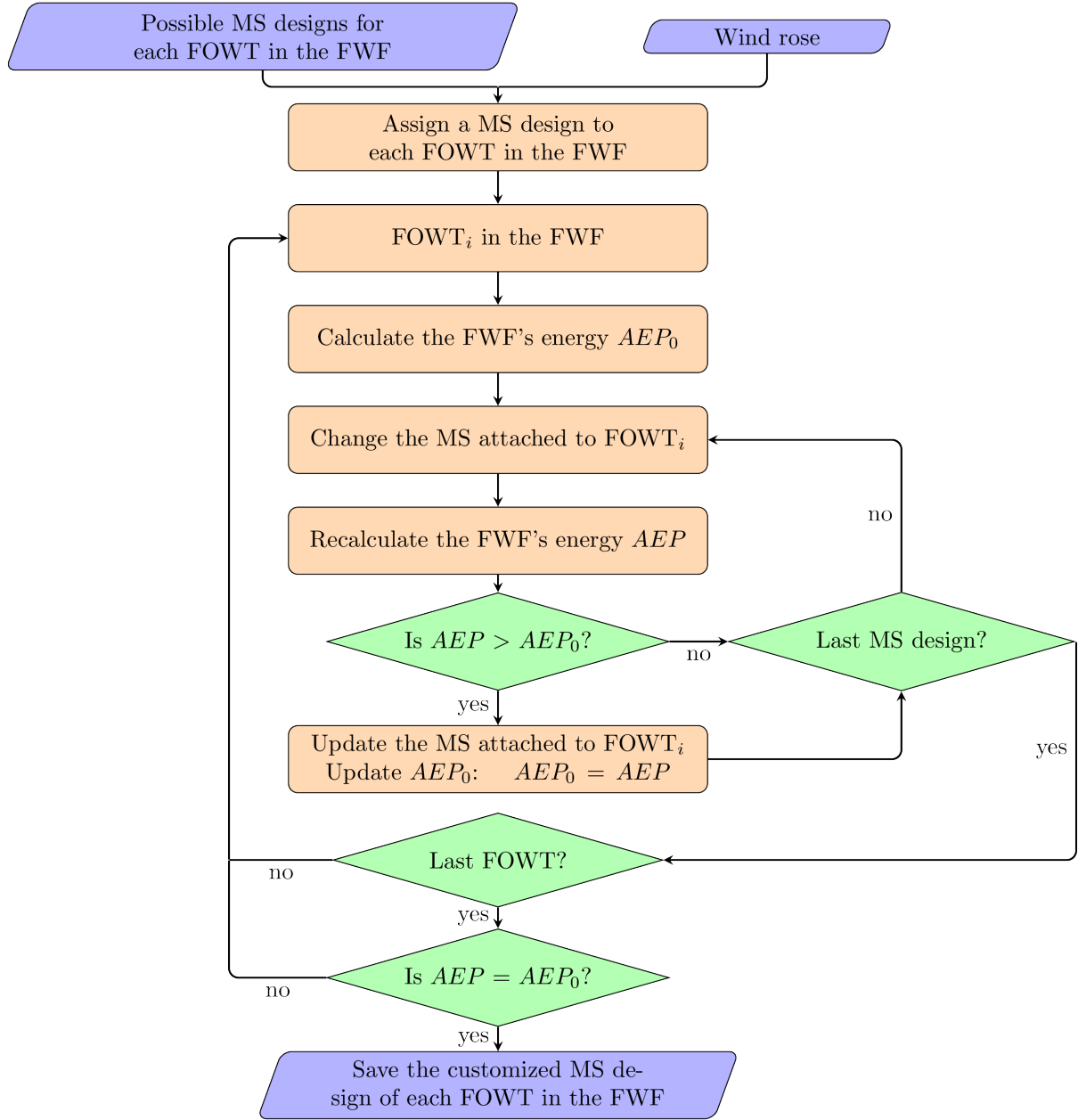


Figure 3.26: Method used to find a customized MS design for each FOWT in the FWF

it sees a lower wind speed than the FOWT when it sees the free stream; hence, the magnitude of the relocation will be lower. However, in this work, I neglected this and assumed that all FOWTs coupled to all MS follow the same watch circle as the watch circle produced at 10 m/s. This assumption simplifies the optimization process and makes it much faster, as the velocity distribution of the wind over the FWF is not calculated at each step of the iteration. Since this work does not aim to find a global optimum design but to prove the concept and show the potential of relocating the FOWTs in the FWF, this assumption is considered valid during the

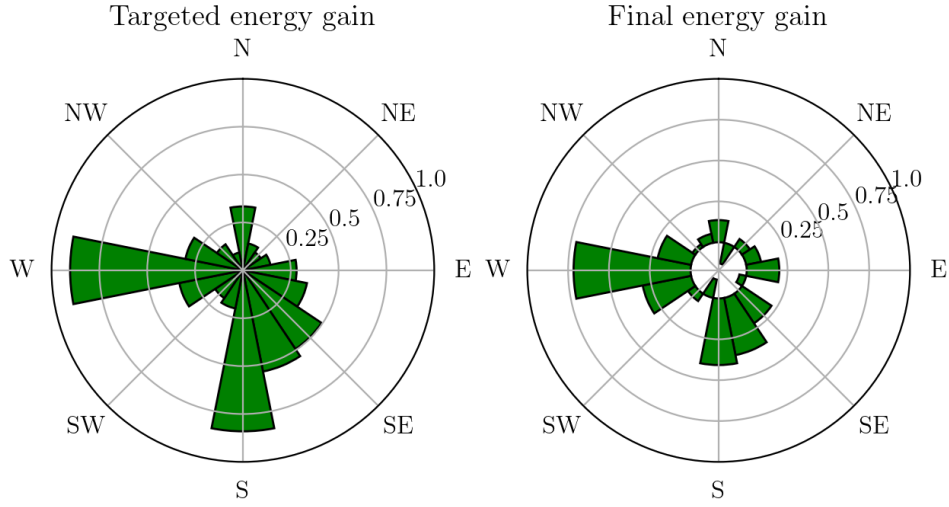


Figure 3.27: Target gain and final gain achieved

design phase. The wake effects on the motions will be calculated when dynamic simulations are done in Chapter 6.

The total final energy gain of the FWF with the customized MS designs is shown in Figure 3.27. The value of the gain is calculated using equation 2.17 and is equal to 2.54%. The wake losses of the final layout compared to all layouts starting from the gridded layout are shown in Table 3.4. The wake losses of the final design are -3.53% , which is 40% less wake losses compared to the BWFL.

Table 3.4: Wake losses of the gridded wind farm layout, BWFL, targeted layout, and final layout

	Gridded layout	BWFL	Targeted layout	Final layout
W_{loss}	-21.31%	-5.92%	-0.83%	-3.53%

3.6 Checking the minimum distance between mooring lines

According to the API (2005) standard, the distance between mooring lines at all operation conditions should not be less than 10 m, except when two mooring lines are hanging and crossing each other, the vertical distance between them should not be less than 20 m. Therefore, for all my designs, I ensure the distance between any two mooring lines is more than 20 m for all wind directions. If the distance between two lines is less than 20 m in any wind direction, I rotated the MS only once by a value of 5° . Afterward, if the minimum distance between the mooring lines is still less than 20 m, I repeated the design process, increasing the minimum accepted distance

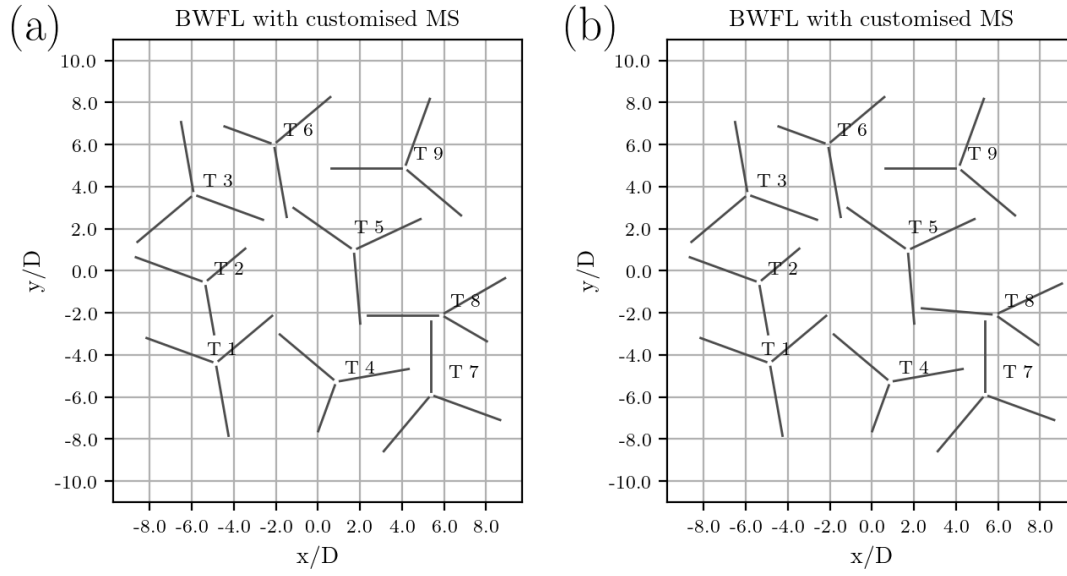


Figure 3.28: Layout before rotating the line headings of turbine 8 (left) and after rotating turbine 8 (right) to achieve a minimum distance of 20 m between mooring lines

between the turbines in the BWFL. Hence, I increase the value of $dist_{min}$ in the constraint in equation 3.1.

Figure 3.28 (a) shows the FWF layout at equilibrium (in the absence of aerodynamic forces) after checking the minimum distances between all mooring lines for all wind directions. The increment for the wind directions is 5° ; hence, 72 wind directions are considered. The distance between the mooring lines of FOWTs 7 and 8 is 17 m at a wind direction of 210° ; for the remaining wind directions, the minimum distance was always higher than 20 m. Therefore, the MS design of FOWT 8 is rotated by 5° . Figure 3.28 (b) shows the FWF layout at equilibrium after the MS of FOWT 8 is rotated. The minimum distance between the mooring lines becomes 28 m, and the MS designs for the layout are accepted. However, the energy gain at a constant wind speed of 10m/s is decreased by 0.04% to become 2.5% instead of 2.54%. Keeping in mind that the targeted layout, which is impossible to achieve, has an energy gain of 5.41%, the simplified method achieves 46% of the absolute optimum targeted layout, proving the methodology is simple yet robust.

3.7 MS costs and energy gain for full wind rose

The costs of the customized MS and the BMS for the FWF were calculated using equations 2.2 and 2.3. The cost of the customized MS designs is 13.8% less than the cost of the BMS. The values of the total BMS cost and the customized MS design costs are shown in Table 3.5.

Therefore, relocating the FOWTs decreases the wake losses and the MS costs as they are less stiff. If the customized MS design cost were higher than the BMS cost, I would have added more constraints to the MS design database. This will be explained in detail in Chapter 4.

Table 3.5: MS costs of the FWF coupled to the BMS and the customized MS

BMS [\$]	Customized MS [\$]
$3.85e + 07$	$3.31e + 07$

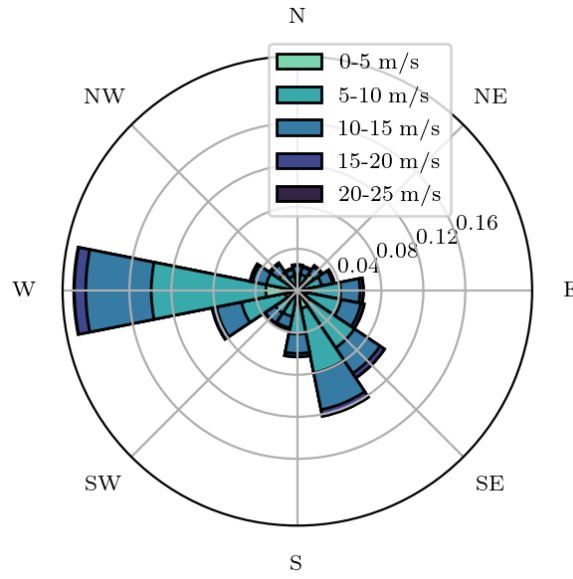


Figure 3.29: Wind rose of the IEA Task 37 with Weibull distribution shape parameter $k = 2.5$, and a scale parameter $\lambda = 10m/s$

The energy gain of the FWF with the customized MS designs is 2.5% at a wind speed of 10 m/s. This gain will decrease once I account for all wind speeds because wakes do not lead to power losses for above-rated wind speeds. Additionally, the energy gain is lower for low wind speeds as the displacements of the FOWTs are smaller at low wind speeds, as the thrust force acting on the rotor decreases. To calculate the energy gain for all wind speeds, I assumed the same Weibull distribution for all wind directions for the wind rose introduced in Figure 3.1. The Weibull distribution has a shape parameter $k = 2.5$ and a scale parameter $\lambda = 10$ m/s to produce the wind rose in Figure 3.29. Moreover, I calculated the watch circle of the customized MS designs at all wind speeds, as the displacements of the FOWTs are smaller for lower wind speeds and highest at rated wind speeds. The AEP gain for the entire wind rose is 1.2%.

Changing the Weibull distribution parameters affects the final AEP gain. For example, decreasing the scale parameter $\lambda = 8m/s$ increases the AEP gain to 1.7% as this shifts the distribution to the left and reduces the probability of occurrence for above-rated wind speeds. The following

two chapters will use the wind rose with Weibull distribution with shape parameter $k = 2.5$ and a scale parameter $\lambda = 10m/s$ as this is more conservative.

3.8 Conclusion

This chapter introduced the method I developed to assess the potential of relocating the FOWT and its effect on AEP and MS costs. The method explained in this chapter is implemented in the open-sources tool FloatingWAYS, which can be accessed here [Mahfouz \(2024\)](#). The results show an increase in the FWF's AEP due to the FOWTs' relocation and a decrease in the MS costs. However, the results presented in this chapter used a low-fidelity model; hence, verifying the results is needed to reach a solid conclusion. Additionally, the loads on the FOWTs due to relocation are not quantified, as the tools used are static tools. Dynamic tools are used in Chapter 5 to check the effect of the relocation on the loads and in Chapter 6 to verify the AEP gain due to relocation.

Additionally, this chapter showed the effect of the line headings, the mooring line diameter, length, and anchor radius on the ability of a FOWT to relocate. The line headings define the shape of the watch circle, while the other parameters can be used to tune the watch circle. Moreover, the crosswind displacement is larger if the difference between two mooring line headings is large for the wind directions between the two mooring lines. If the difference between two mooring line headings is lower than 90° , no crosswind displacement occurs when the wind direction is between the two mooring lines. The line length has the largest effect on the magnitude of the FOWT's relocation, followed by the mooring line diameter, and the anchor radius has the lowest effect on the magnitude of relocation.

PARAMETRIC STUDY

4.1 Overview

In Chapter 3, I introduced the methodology to benefit from the ability of the FOWTs to relocate their position to increase the AEP of the FWF. While using the proposed method, the user makes three decisions that can affect the output of the process. In this chapter, I will analyze the effect of these user inputs on the final energy gain and the costs of MS designs. These three decisions are:

1. Optimizing the BWFL

I assumed in Chapter 3 that the user would optimize the baseline layout to increase the AEP. In reality, this is not always possible, as the layout optimization can be restricted by several constraints, such as the number of turbines compared to the lease area or the shape of the lease area. Or just to ease the marine navigation for ships inside the offshore wind farm. These constraints hinder the optimization process, leading to a gridded-shaped wind farm layout similar to wind farms in the North Sea, such as Horns Rev 1 wind farm. If the BWFL is not optimized, the wake losses are higher, and relocating the FOWTs will lead to higher gains in the FWF's AEP. Since grid-shaped layouts are more realistic and common, I will check the effect of using a grid layout for the rest of the work.

2. Creating the MS database

The motions of the FOWTs depend on the MS database and the parameters of the full factorial design matrix. Moreover, it depends on the constraints I added to the MS designs added to the database. The cost of the MS is also affected by the design parameters. While creating the MS database, I made it less stiff than the current state-of-the-art MS designs

to allow the relocation of the FOWTs. Since this is the purpose of my work here, I will keep the full factorial design parameters the same but will change the constraints to increase the stiffness of the database and check the effect of this on the AEP gain.

3. Choosing the tolerance value

In subsection 3.5.1 (Figure 3.24), I chose a tolerance of ± 5 m. Changing the tolerance value can lead to choosing different MS designs. Therefore, in this chapter, I will analyze the effect of changing the tolerance on the energy gain.

In addition to these three decisions made by the user, in subsection 3.5.1 (Figure 3.25), the method narrows down the number of possible MS design by choosing a single design from each possible MS headings for each wind direction. In this chapter, I will investigate the effect of increasing the possible MS designs on the final energy gain. These are not all the parameters affecting the method's performance, but they are the dominant ones. In my work in Mahfouz and Cheng (2023b), I checked the effect of the farm layout size, the shape of the farm boundaries, and the wind change on the method performance. These aspects are not discussed further in the current dissertation.

4.2 Effect of the value of tolerance

The tolerance value defines the acceptable difference between the targeted layout matrix $\mathbf{Cr}$ in Table 3.2 and the crosswind displacement of the MS design chosen in section 3.5.1. I used a tolerance of 5 m in Chapter 3. In this section, I will set several tolerance values between 5 m to 200 m to check the effect of changing the tolerance on the energy gain at 10 m/s. This will be done for the same optimized BWFL presented in Chapter 3.

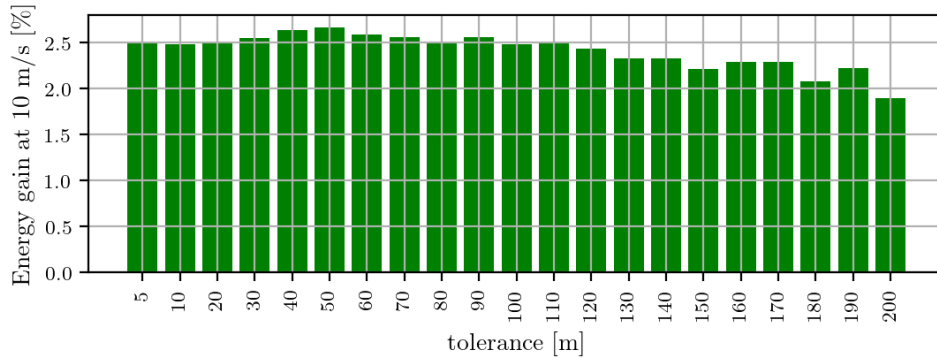


Figure 4.1: Effect of the value of the tolerance on the energy gain at wind speed of 10 m/s

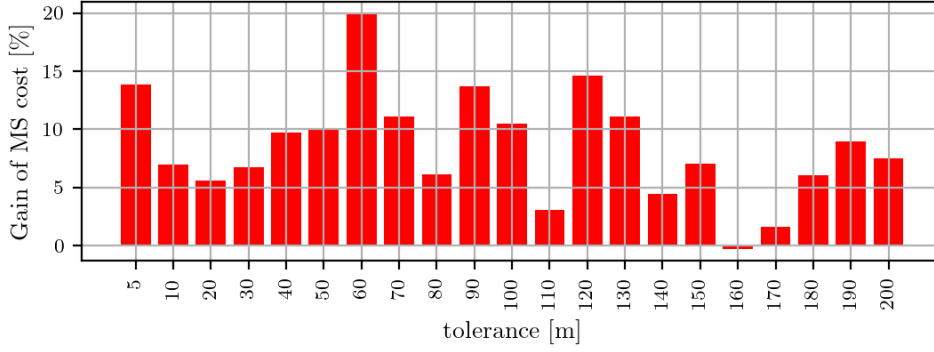


Figure 4.2: Effect of the value of the tolerance on the cost of the customized MS design compared to baseline MS cost

Figure 4.1 shows the effect of the tolerance value on the energy gain due to relocating the FOWTs at a fixed wind speed of 10 m/s. The highest value of energy gain occurs at the tolerance of 50 m with an energy gain of 2.67%. The lowest energy gain of 1.9% occurs when the tolerance is set to 200 m. The Figure shows that the effect of the tolerance value on the energy gain is small for tolerance values less than 120 m. However, as the tolerance increases, the gain decreases as the difference between the targeted layout and the displacements of the FOWTs increases. Despite having higher energy gain at a tolerance of 50 and 40 m, the MS designs do not satisfy the constraints of having a minimum distance of 20 m for all wind directions. The highest gain where this constraint is achieved happens at a tolerance of 5 m.

The effect of the tolerance on the MS design cost is shown in Figure 4.2. The cost for the MS designs is always below the baseline MS design cost except for a tolerance of 160 m. The optimization process only aims for a higher energy gain, and the cost of the MS design is not included in the objective function. However, if an MS design cost is higher than the cost of the baseline design, the design is rejected, and the process is repeated with more constraints on the MS database.

Throughout the rest of this chapter, I will run tolerances for all the cases I will analyze from 5 m to 120 m. I will choose the design with the highest energy gain that satisfies the constraint of keeping the minimum distance between mooring lines less than 20 m without increasing the cost of the MS in the FWF.

4.3 Effect of increasing the possible MS designs

One of the main uncertainties of the method introduced in Chapter 3 comes from decreasing the number of possible MS designs for each FOWT in the farm and how much this affects the energy gained due to relocating the FOWTs. Therefore, I increased the number of possible MS designs

by considering not only unique headings but also unique orientations at which the MS design achieves the tolerance value. For example, in Figure 3.25, I had two possible MS designs in subplot (b), and I chose only one with the minimum difference from the targeted layout matrix. In this section, I will consider both designs, adding the unique orientation as a parameter to filter MS designs. This increases the number of possible MS designs exponentially, making the process computationally expensive, so I will only use it in this section.

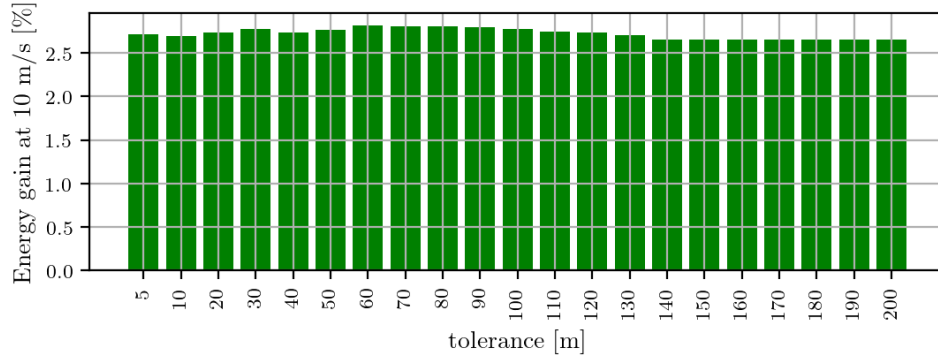


Figure 4.3: Effect of increasing the number of possible MS designs on the energy gain at wind speed of 10 m/s

The energy gain at 10 m/s due to increasing the possible MS designs is shown in Figure 4.3. The maximum energy gain of 2.82% occurs at 60 m tolerance. The minimum energy gain occurs at tolerance values of 140 m higher with a value of 2.65%. Increasing the tolerance for values higher than 140 m does not affect the energy gain, as the MS design change is almost negligible. This is due to the methodology used, which chooses the designs with unique headings and orientation but with the smallest difference to the targeted design matrix, so as the tolerance increases, the possible MS designs for each FOWT are not affected. Therefore, the customized MS design chosen stays the same.

The results of increasing the possible MS designs show that the assumption used to decrease the number of possible MS designs is valid. The comparison between the results of Figures 4.1 and 4.3 shows that the difference is less than 0.2%. Since the goal of this paper is to prove the concept and not to find the global optimum solution, and as increasing the number of MS designs makes the problem computationally expensive, I will use the simplified method as presented in Chapter 3 for the rest of this work.

The effect of increasing the number of possible MS designs on the cost of the customized MS is shown in Figure 4.4. The cost of the MS design is always below the cost of the baseline MS design.

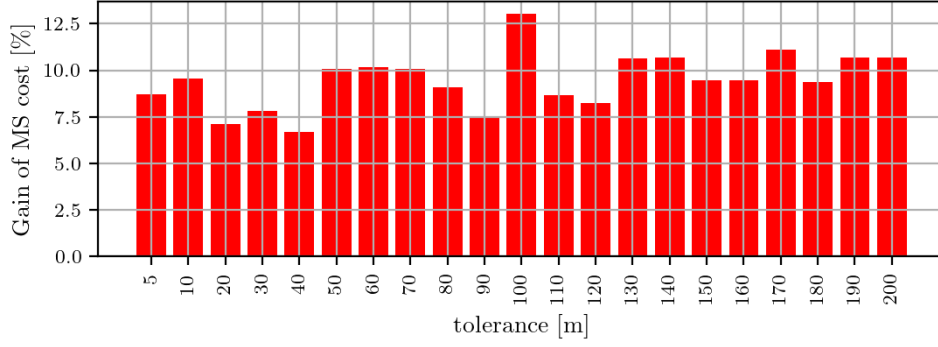


Figure 4.4: Effect of increasing the number of possible MS designs on the cost of the customized MS design

4.4 Effect of changing constraints on MS database

Allowing larger FOWT displacements means the customized MSs are less stiff for surge, sway, and yaw DoFs. As I assume in this work that there is no yaw controller to control the platform yaw movement, the MS is solely responsible for providing enough yaw stiffness for the FOWT to keep it facing the wind. Yaw stiffness is crucial for above-rated wind speeds where the pitch controller is active. As the blade pitch angle increases, the aerodynamic torsion acting on the FOWT increases, which can lead to a larger FOWT's yaw angle. This then leads to a higher moment around the x-axis, increasing the platform roll angle and increasing the loads on the tower base. Setting the maximum allowable yaw angle to $\pm 5^\circ$ in the MS database does not always mean it will stay within this range for the entire operation region. Since the highest aerodynamic torsion happens at above-rated wind speeds and the MS database is created at 10 m/s, the yaw angle will increase for above-rated wind speeds.

In this section, I check the effect of increasing the constraint on the maximum allowable yaw angle to increase the yaw stiffness of the accepted MS designs in the mooring database. In Chapter 3, the maximum allowable yaw angle was set to $\pm 5^\circ$. I decrease the maximum allowable yaw angle to $\pm 4^\circ$ and $\pm 3^\circ$ and see how this affects the cost, the energy gain at 10 m/s, and AEP gain using the full wind rose. The results are shown in Table 4.1, where the energy gain decreases as I increase the yaw stiffness. Moreover, the costs of the customized MS designs at maximum allowable yaw $\pm 3^\circ$ increase and are only 0.8% lower than the baseline MS design. The details of all MS designs for the BWFL considering the costs are introduced in appendix B in Tables B.1, B.2, and B.3. The BWFL when each FOWT is coupled to its customized MS is shown in Figure 4.5.

The minimum tolerance value that can be used increases as the stiffness of the MS increases. This is because as the MS gets stiffer, the value of the maximum displacement in the crosswind direction decreases and becomes less than the required values in the targeted displacement matrix

Table 4.1: The energy gain and the cost of the customized MS designs at three different yaw angle constraints

Constraint on platform yaw [°]	5	4	3
Energy gain at 10 m/s [%]	2.5	2.2	1.8
AEP gain (full wind rose) [%]	1.2	1	0.8
Cost gain [%]	13.8	17.9	0.8
Tolerance [m]	5	80	80

(*Cr*). For example, for the MS database with the constraint of the yaw angle set to ± 3 , the minimum tolerance value increases to 30 m. This means the maximum crosswind displacement

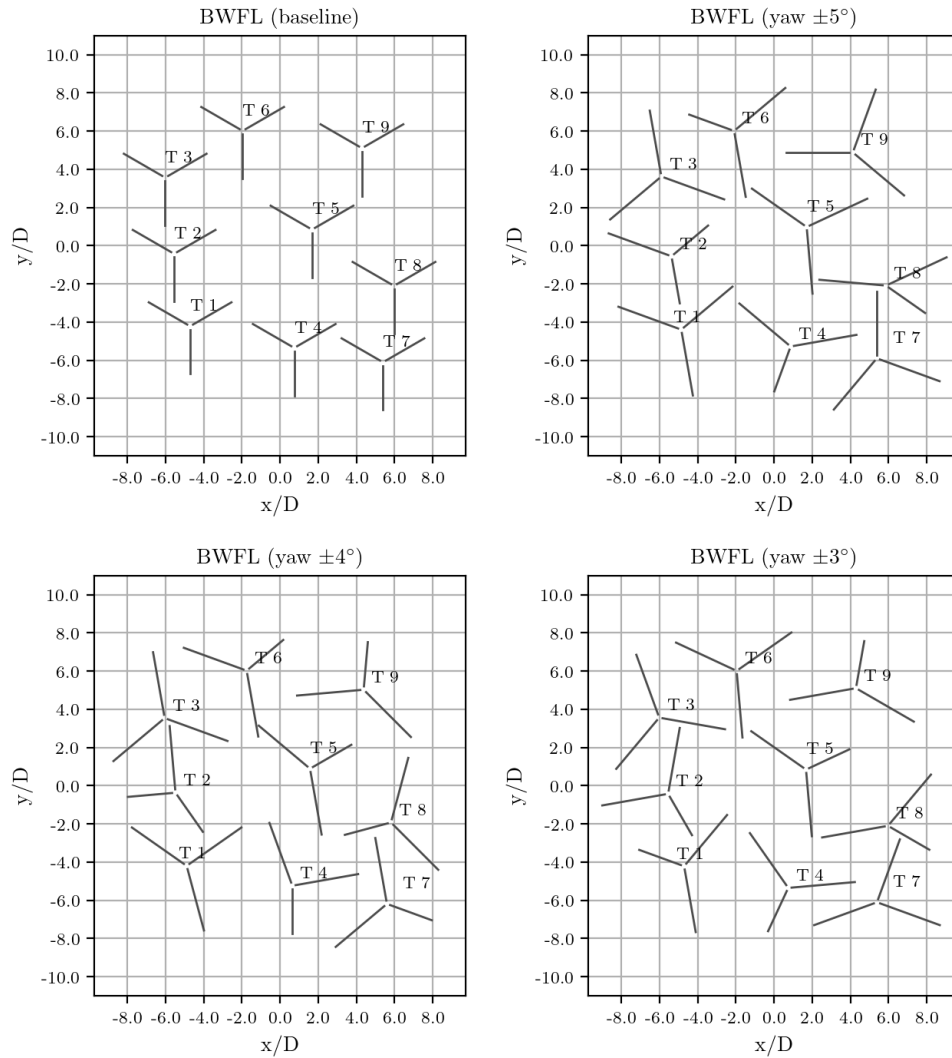


Figure 4.5: BWFL coupled to the baseline MS design and the customized MS designs

is around 90 m instead of the targeted displacement of 120 m. This also explains the decrease in AEP gain as the constraint of the maximum yaw angle decreases.

4.5 Effect of using a grid-shaped layout as a BWFL

Due to constraints on the layout optimization, many wind farms have grid shape layouts such as Horns Rev 1, and Nysted. With these gridded layouts, relocating the FOWTs offers an additional DoF that can mitigate the constraints on layout optimization and decrease wake losses. Therefore, I will use a gridded wind farm layout (GWFL) as a baseline layout instead of the BWFL and apply the same method introduced in Chapter 3 to show how the FOWTs displacement increases AEP. The GWFL and the targeted energy gain (considering the full windrose) are introduced in Figure 4.6. The wake losses of the GWFL and its targeted layout are shown in Table 4.2. The total AEP gain of the targeted layout of the GWFL is 11.6%, where the highest gain happens in wind directions from west to east.

Table 4.2: Wake losses of the GWFL and its targeted layout considering the full wind rose

	Gridded layout	Targeted layout GWFL
W_{loss}	-13.9%	-3.8%

I used the same MS database with the three different constraints for the maximum allowable absolute platform yaw angle, and the results are shown in Table 4.3. The results show that none of the MS designs currently have a cost lower than the cost of the baseline MS designs. Since I do not have a full cost model of the FOWT, I reject the MS designs with costs higher than the

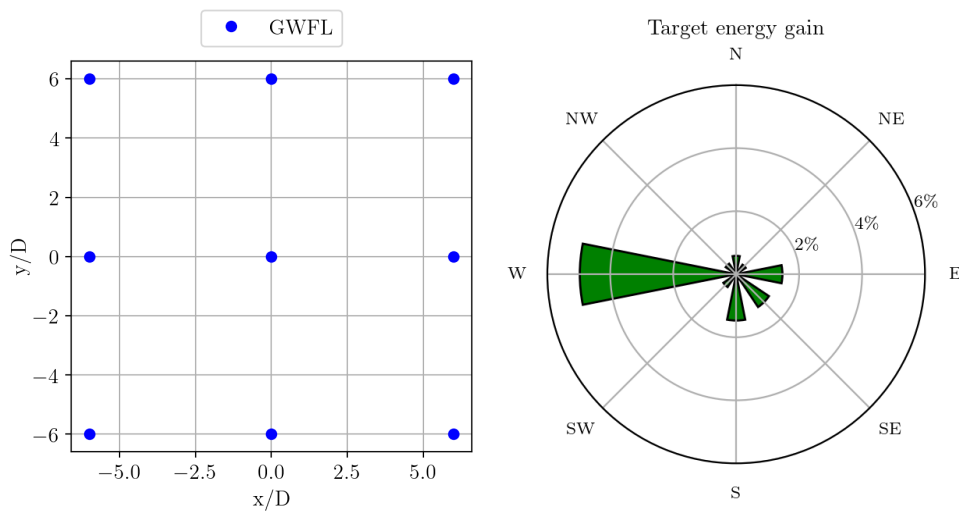


Figure 4.6: GWFL and the targeted energy gain considering the full wind rose

baseline MS costs. A full LCOE model will allow the user to choose MS designs that cost more than the baseline if the gain in AEP compensates for the loss in material cost.

Table 4.3: The energy gain and the cost of the customized MS designs of the GWFL at three different yaw angle constraints

Constraint on platform yaw [°]	5	4	3
Energy gain at 10 m/s [%]	13.1	10.9	7.2
AEP gain (full wind rose) [%]	8.1	6.7	4.7
Cost gain [%]	-6.7	-10.3	-14.6
Tolerance [m]	10	30	20

As none of the MS designs chosen by the method chose an MS design that costs less than the baseline MS design, I added more constraints on the MS database. The first constraint I added was that the maximum angle between two mooring line headings has to be less than 160° . This constraint was enough for the MS databases with yaw angle ranges between $\pm 5^\circ$ and $\pm 4^\circ$. Another constraint was added for the stiffer MS database with the yaw angle range between $\pm 3^\circ$: no MS design should have all three lines with a diameter of 0.18 m. These two constraints aim to decrease the mooring lines' length and diameter. When the difference between two mooring line headings is larger than 160° , this allows higher displacement but also means that the diameters and line lengths of such system will have to increase to achieve the minimum required stiffness. The cost increased for the gridded layout because there is a dominant wind direction where the gain is highest. Choosing MS designs with large differences between the mooring line headings ensures that the crosswind displacement is higher for a wind direction and negligible for the rest of the wind directions. Therefore, the optimization method chooses MS designs with larger differences between the mooring line headings. After applying these constraints, the results are shown in Table 4.4. The details of all MS designs for the GWFL considering the costs are introduced in appendix B in Tables B.4, B.5, and B.6.

Table 4.4: The energy gain and the cost of the customized MS designs of the GWFL at three different yaw angle constraints and cost constraints

Constraint on platform yaw [°]	5	4	3
Energy gain at 10 m/s [%]	9.9	8.6	5.8
AEP gain (full wind rose) [%]	6.3	5.4	3.6
Cost gain [%]	1.5	9.6	4.2
Tolerance [m]	30	20	50

All three cases of the customized MS with different yaw stiffness values for the GWFL will be used during the dynamic verification of the results to complete the proof of concept in the next

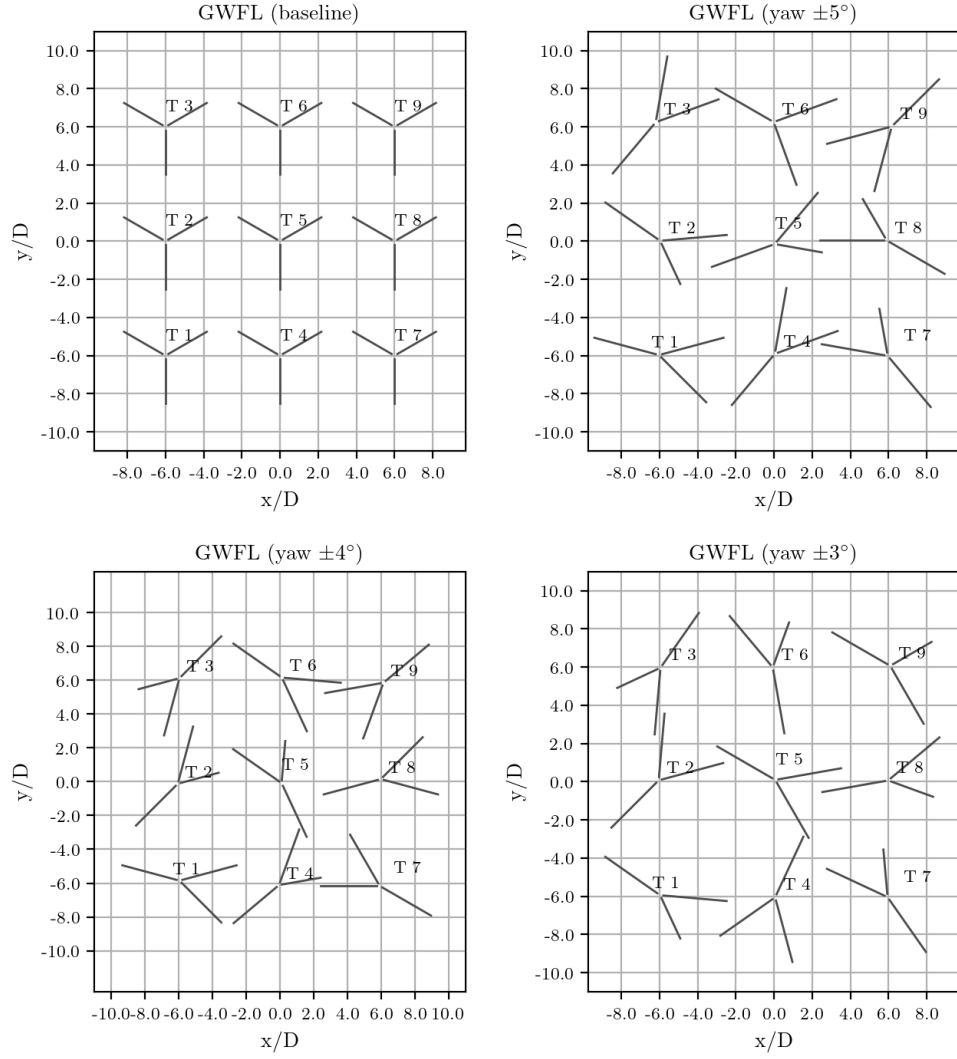


Figure 4.7: GWFL coupled to the baseline MS design and the customized MS designs

chapter. The layouts with the baseline MS design and the customized MS designs from Table 4.4 are shown in Figure 4.7. The AEP gain distribution of each of the three designs with the different yaw stiffness is introduced in Figure 4.8.

The AEP gain decreases as the constraint on the yaw angle increases. This is directly connected to the maximum crosswind displacement the MS design can achieve. The maximum crosswind displacement at a wind speed of 10 m/s of the MS designs with yaw constraint $\pm 5^\circ$ is 139 m, and of the MS designs with yaw constraint $\pm 4^\circ$ is 108 m, and for the MS designs with yaw constraint $\pm 3^\circ$, it is 87 m.

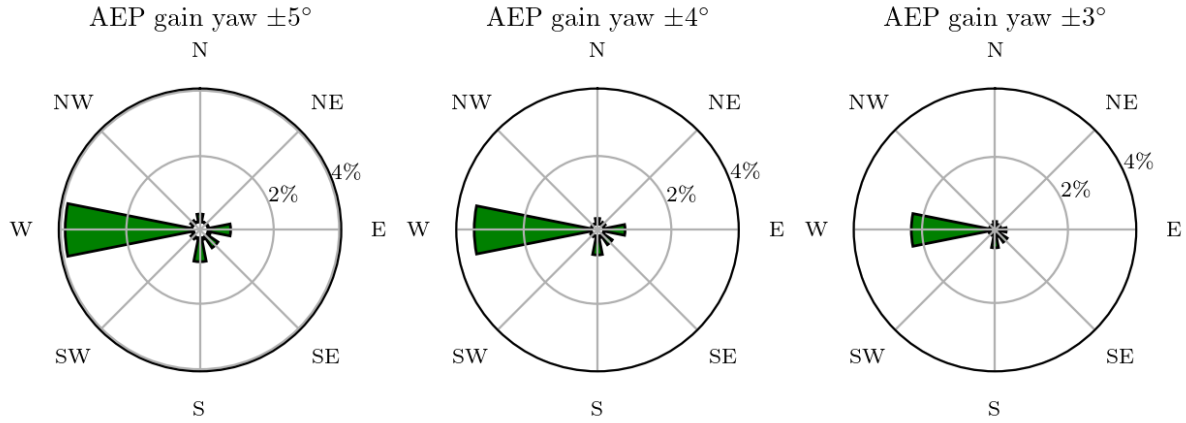


Figure 4.8: The AEP gain with for the three customized MS designs with different stiffness

4.6 Conclusion

In this Chapter, I checked the effect of changing three user input parameters on the AEP gain that can be achieved by relocating the FOWT. The first user parameter checked was the tolerance value; increasing the tolerance value by more than 120 m decreased the energy gain, but the results were comparable below this value. There is no direct relationship between the MS costs and the tolerance value. The second parameter checked was the MS database; a stiffer database with a smaller maximum allowable crosswind displacement decreases the AEP gain. Finally, a GWFL as a baseline increases the AEP gain due to relocation. Additionally, I checked the validity of the assumption used to decrease the MS designs considered for each FOWT in the FWF. The results show that despite being simple and computationally efficient, the tool gives robust results and is close to those obtained from a brute-force optimization technique. For the next two Chapters, I will use the GWFL designs presented in Figure 4.7 in my load analysis and power gain verification because GWFL is closer to most installed offshore wind farms.

EFFECT ON FOWT'S LOADS

5.1 Overview

In the last section, I introduced three variations of MS designs for the FOWTs inside the GWFL. Each of these designs had a different yaw stiffness, and I introduced the effect of changing the yaw stiffness on the MS costs and the AEP gain using steady wake models. In this chapter, I will analyze the impact of each of these designs, with the different yaw stiffness, on the dynamics of the wind turbine. An MS design with a lower yaw stiffness will suffer from more considerable yaw misalignment. This is more significant in the current work due to the lack of a yaw controller for my FOWTs model. Therefore, this chapter is dedicated to analyzing the effect of MS yaw stiffness on FOWT's loads. First, I compare the customized MS stiffness to the BMS. Then, I will compare the difference in the MS watch circles achieved using the static tool MoorPy and the dynamic tool OpenFAST. Afterward, I will analyze the fatigue loads in operation conditions on the mooring lines, rotor blades, and the tower base during operation. Finally, I analyze the loads in extreme conditions with the FOWT parked.

For the GWFL design from Figure 4.7, I will refer to the FWF layout design produced when an MS database with a constraint of $\pm 5^\circ$ as Yaw 5. Similarly, I will refer to the FWF layout designs produced with yaw constraints of $\pm 4^\circ$ and $\pm 3^\circ$ as Yaw 4 and Yaw 3, respectively. The results discussed in this chapter are based on my work in Mahfouz and Cheng (2025).

5.2 MS' Stiffness

The mooring stiffness of the BMS and the customized designs for the different GWFL designs are calculated using MoorPy. MoorPy produces a 6x6 stiffness matrix $\mathbf{K}$, from which I extracted the first two diagonal components (K_{11} and K_{22}) to get the stiffness in the x and y directions. I calculated the stiffness matrix of each MS design at each wind direction with an increment of 5° and at every wind speed between 4 m/s and 25 m/s with an increment of 1 m/s. After calculating the stiffness of each MS design, I calculated the natural frequency in the x and y directions; since the MS is responsible for station keeping and providing stiffness in the x and y directions, this represents the natural frequency of the FOWT in surge and sway DoFs when coupled to each of the MS designs. The x and y axes are the global reference frame axes and do not rotate with the wind direction. The natural frequencies of the BMS and the Yaw 5, Yaw 4, and Yaw 3 designs are shown in Figures 5.1, 5.2, 5.3, and 5.4. Since each turbine in the Yaw 5, Yaw 4, and Yaw 3 FWF layouts have a different MS design, I chose the MS coupled to Turbine 8 as an example.

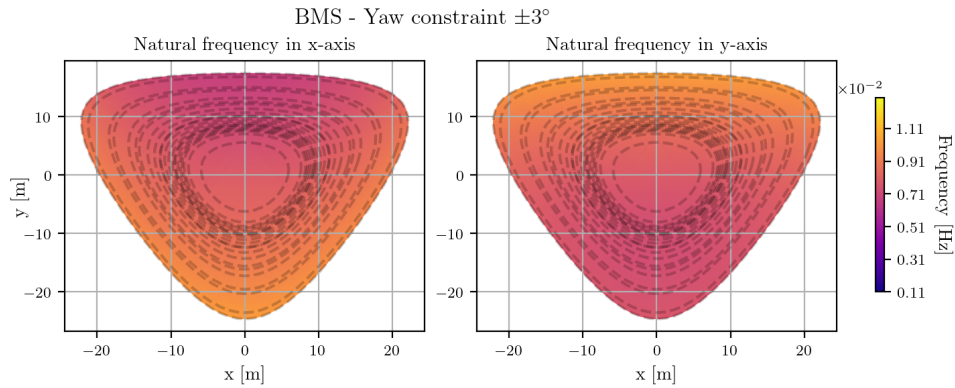


Figure 5.1: FOWT's natural frequency in x and y axis for BMS

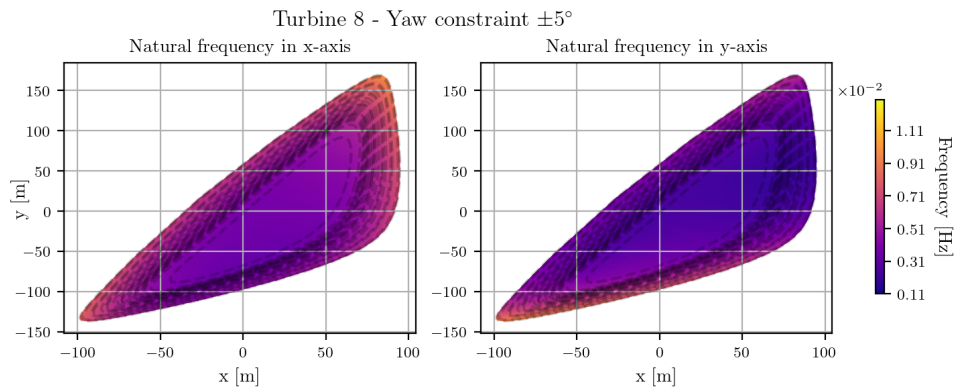


Figure 5.2: FOWT's natural frequency of Turbine 8 when the yaw constraint is $\pm 5^\circ$

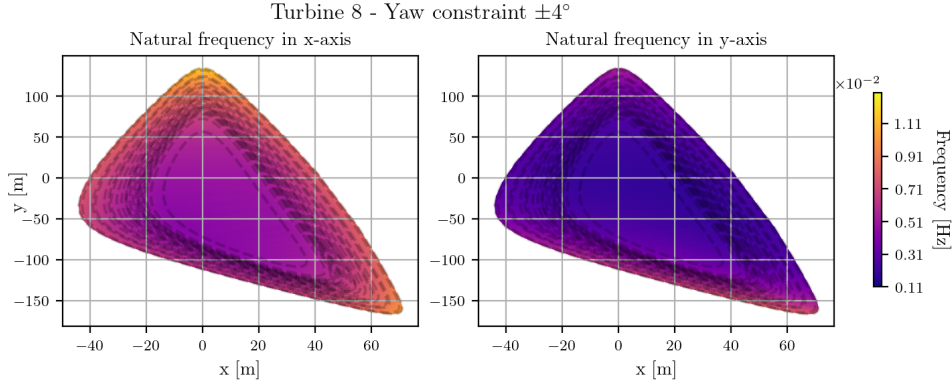


Figure 5.3: FOWT's natural frequency of Turbine 8 when the yaw constraint is $\pm 4^\circ$

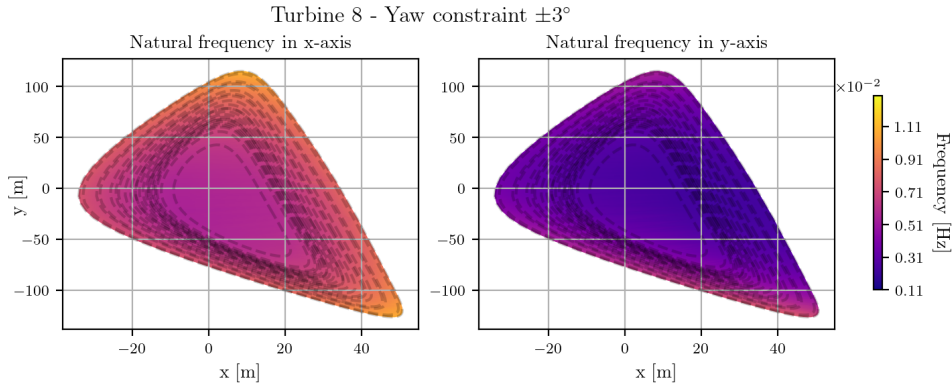


Figure 5.4: FOWT's natural frequency of Turbine 8 when the yaw constraint is $\pm 3^\circ$

The dashed lines in Figures 5.1, 5.2, 5.3, and 5.4 represent the watch circles of each MS at all wind speeds between 4 m/s and 25 m/s. The innermost dashed line is the watch circle at the lowest wind speed of 4 m/s. The outermost watch circle is at rated wind speed, while for higher wind speeds, the watch circle decreases again as the thrust force decreases.

Figure 5.1 shows that the natural frequency of the BMS has a small range of values, which indicates that the BMS' stiffness also has a small range of values. The natural frequencies for the BMS range from 0.01 Hz to 0.0074 Hz, so the natural period ranges from 100 s to 136 s. The plot also shows that the maximum displacement allowed by the BMS is small, with a value of 25 m. For the flexible MS designs, the range of the natural frequencies of the FOWT is wider; this is clarified in Figures 5.2, 5.3, and 5.4. The MS stiffness highly depends on the wind speed and direction. As a result, the range of natural frequencies of the FOWT becomes larger, ranging between 0.01 Hz and 0.0023 Hz, so the natural period ranges from 100 s to 437 s. The Figures show that the natural frequencies of the FOWT in surge and sway are not affected by the yaw stiffness. The surge and sway natural frequencies are within the same range for the BMS, but this is not true for the customized MS designs. For some designs, the surge natural frequency is

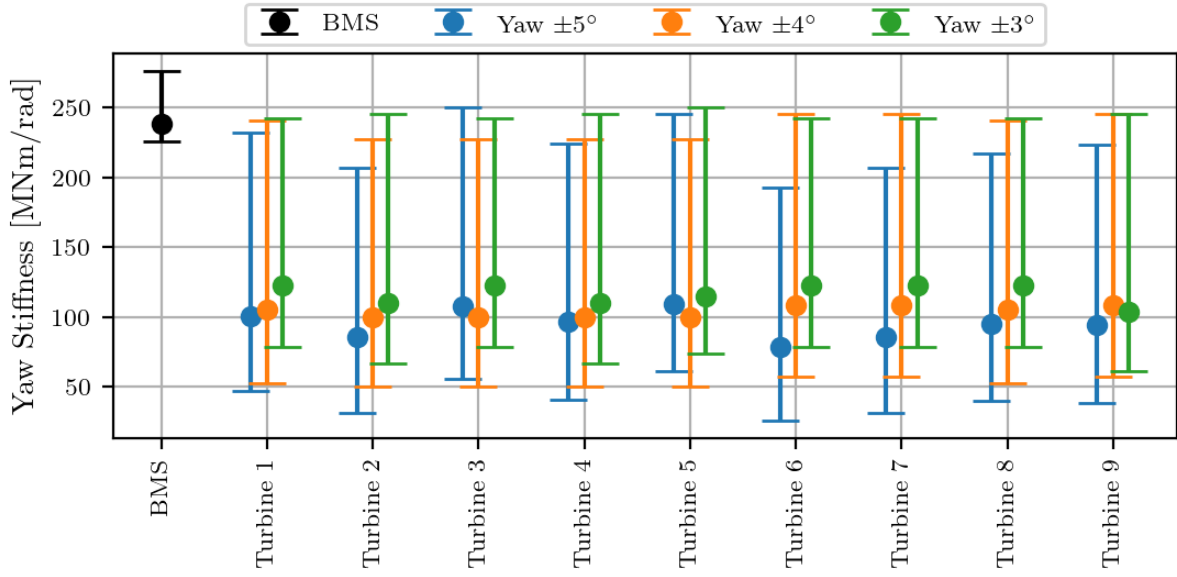


Figure 5.5: Yaw stiffness range of the MS designs in the three FWF layouts

lower; for others, the sway natural frequency is lower. The range of natural frequencies for the designs in layouts Yaw 3, Yaw 4, and Yaw 5 is equal.

The yaw constraint affects the range of the yaw stiffness considerably. Figure 5.5 shows the range of the yaw stiffness (K_{66} in the stiffness matrix) of the FOWT coupled to the BMS design and when coupled to each MS design in the layouts Yaw 5, Yaw 4, and Yaw 3, respectively. The dots represent the mean stiffness of each MS for all wind speeds and directions, and the range extends from the minimum to the maximum stiffness. The stiffness of the BMS design has a small range as it ranges from 226 MNm/rad to 276 MNm/rad. For the Yaw 5 layout, the stiffness range considering all MS designs is between 26 MNm/rad to 250 MNm/rad, with the lowest stiffness occurring at the MS coupled to Turbine 6. The stiffness ranges between 50 MNm/rad and 245 MNm/rad for the MS designs in layout Yaw 4, with the lowest stiffness occurring at Turbines 2, 3, 4, and 5 as they share the same MS design. Finally, for layout Yaw 3, the yaw stiffness ranges between 62 MNm/rad and 250 MNm/rad, and Turbine 9 has the lowest stiffness value. The maximum stiffness values for all designs occur at the rated wind speed when the thrust force is highest. The highest values are comparable and within the same range. Hence, we can predict that the performance of all MS around the rated wind speed will be similar in terms of yaw stiffness and natural frequencies. However, for the wind speeds with a small thrust value, the MS stiffness of the customized MS design is very small. For all MS designs, including the BMS design, the lowest MS stiffness occurs at wind speeds of 4 and 5 m/s below rated, followed by wind speeds of 25 m/s and 24 m/s above rated. The effect of these lower stiffness on the loads is analyzed throughout the rest of this Chapter.

5.3 Comparing watch circles

The watch circles used to choose the MS design for each FOWT were obtained using the static tool MoorPy. Therefore, the first step was to compare the watch circle I used from MoorPy to that from OpenFAST. This section aims to show that the MS relocation predicted by MoorPy matches when the full FOWT is considered in OpenFAST. Otherwise, the steady-state method used to choose the customized MS designs becomes invalid, as the FOWTs do not move as predicted, and the uncertainty of the results increases drastically.

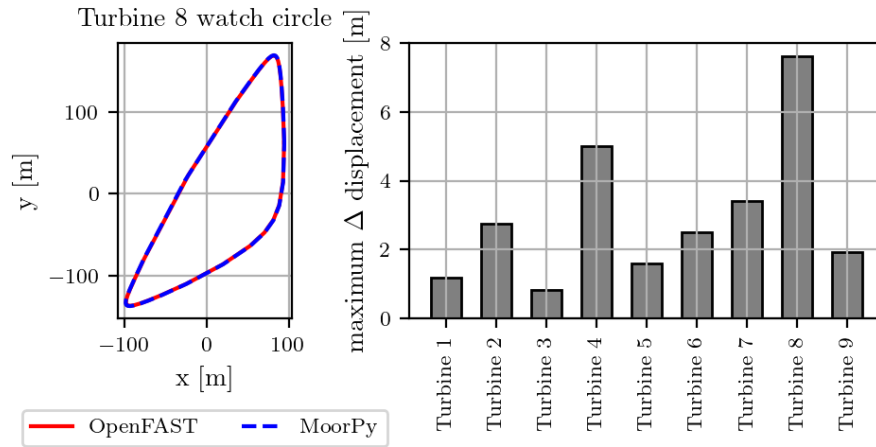


Figure 5.6: Watch circle in OpenFAST and MoorPy on the left. The maximum difference between the displacement of the FOWTs in OpenFAST and in MoorPy on the right. Yaw constraint is $\pm 5^\circ$

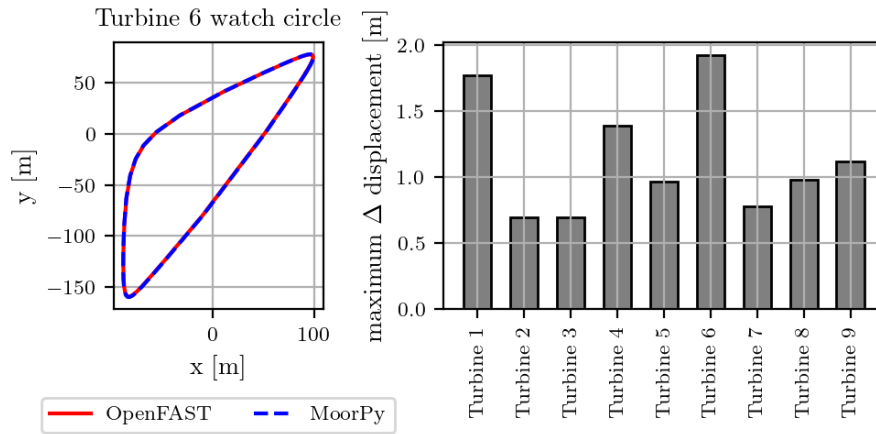


Figure 5.7: Watch circle in OpenFAST and MoorPy on the left. The maximum difference between the displacement of the FOWTs in OpenFAST and in MoorPy on the right. Yaw constraint is $\pm 4^\circ$

To achieve this, I used steady wind of 10 m/s in OpenFAST without waves and turbulence to calculate the different watch circles for all the MS designs with different yaw stiffness. The

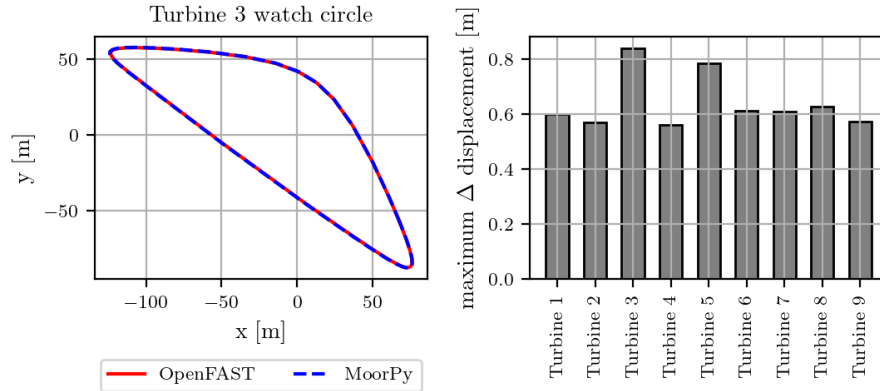


Figure 5.8: Watch circle in OpenFAST and MoorPy on the left. The maximum difference between the displacement of the FOWTs in OpenFAST and in MoorPy on the right. Yaw constraint is $\pm 3^\circ$

steady-state simulations in OpenFAST were done for 4200s, and the first 600 s were omitted to remove transient effects. The simulations were done for 36 wind directions with an increment of 10° . The mean of the surge and sway values between 600 s and 3600 s was obtained and compared to the results from MoorPy. Each FOWT, coupled with its customized MS design in the Yaw 5, Yaw 4, and Yaw 3 layouts, was considered. This means that 324 steady-state simulations were carried out for each layout. I chose the wind speed of 10 m/s as this is the wind speed I used while creating the MS database in section 3.4 and for choosing the MS design to be coupled with each FOWT in the FWF.

Figures 5.6, 5.7, and 5.8 show the maximum difference in displacement between OpenFAST and MoorPy for each FOWTs in the layouts Yaw 5, Yaw 4 and Yaw 3 respectively. The watch circle of the turbine, where the difference in displacement is maximum, is plotted on the left side of each Figure. The total displacement is calculated by calculating the norm of the x and y components of the watch circle for each wind direction. Then, the difference between the displacement in OpenFAST and MoorDyn was calculated.

It is clear from the figures that the Yaw 3 layout has the lowest difference in displacement, with a difference of less than 1 m. That layout Yaw 5 has the highest difference in displacement with approximately 8 m for Turbine 8. This is expected as a higher yaw angle will affect the aerodynamic force components in surge and sway, which are better captured when the full FOWT is modeled, and the structure dynamics and the aerodynamic forces are coupled. This does not happen in MoorPy, as the aerodynamic forces are applied as an external vector at MSL. The method I used to transfer the aerodynamic forces from the hub to the sea level is explained in section 3.4.2, and it does not fully capture the structure dynamics. However, the difference of 8 m is minimal and will have limited effect on the AEP gain as 8 m is only 3% of the 15MW turbine rotor diameter. Therefore, the results show that the difference between the

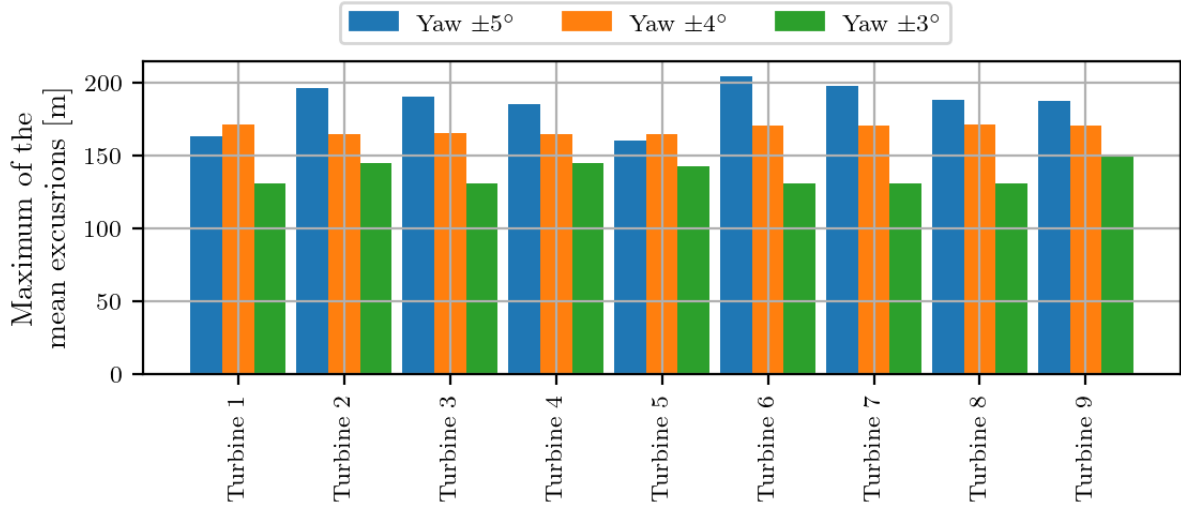


Figure 5.9: Maximum of the mean excursions of each FOWT in layouts Yaw 5, Yaw 4, and Yaw 3

watch circle in OpenFAST and MoorPy is small and can be considered negligible.

Figure 5.9 shows the maximum of the mean excursions of each MS design in the three different layouts. The mean excursion was calculated for each MS design at each wind speed and direction. The mean excursion is the norm of the mean of the surge displacement and the sway displacement. The maximum mean excursion for layout Yaw 5 is for Turbine 6 and equals 204 m. The maximum value for layout Yaw 4 is for Turbines 1 and 8 with 171 m. Finally, the maximum value for layout Yaw 3 is at Turbine 9 with 151 m.

5.4 Effect of relocating the FOWTs on the loads

In this section, I analyze the effect of allowing the FOWTs to have larger displacements on the loads of the mooring lines, the tower base, and the blade root. The loads are analyzed under operational conditions and extreme conditions. For operation conditions, sixteen wind directions were considered with an increment of 22.5° corresponding to the wind directions of the IEA wind rose presented in Figure 3.29. The wind speeds between 4 m/s and 25 m/s were considered with an increment of 1 m/s. The simulation time was set to 4200 s, and the first 600 s were omitted to remove transient effects. In addition, to decrease the transient effects, the initial states of the platform displacements were calculated using MoorPy and used as input to the dynamic load cases. The wind field was created using the Mann turbulence box generator (Liew, 2022), with a turbulence intensity of 6%. The duration of the wind field is 3600 s, and only one seed for each wind speed and direction was used. The resolution of the wind field is 2 m in the x direction and 5 m in the y and z directions. Due to the lack of information on sea state as the

IEA wind rose is not a real wind rose, we used the same sea states used during designing the Activefloat platform as defined in Mahfouz et al. (2020); Vigara et al. (2020). The significant wave height H_s was set to 2 m, and the wave period T_p was set to 6 s, which coincides with the site conditions used during the design of the Activefloat platform. Choosing a constant wave height and wave period will affect the fatigue damage calculated within this chapter. However, the work of Mahfouz et al. (2020) shows that the Activefloat platform motions are dominated by the aerodynamic rather than the hydrodynamic forces. Therefore, I believe this simplification will not significantly affect the results of this chapter. Especially since the wind rose used here is not connected to a site with known wave conditions. The second-order wave loadings were considered, and the wave and wind were aligned for all wind directions.

The results of the simulations in operation conditions for the new MS designs are used to calculate fatigue damage, using equation 2.10, and the lifetime DELs, using equation 2.8, compared to the FOWT when coupled to the BMS, which does not allow large motions of the FOWT. In addition, the maximum value of each load case is checked and compared to the MBL of the mooring lines and yield strength for the tower base. The probability of occurrence of each wind speed and wind direction for each load case is taken from the probability distribution of the IEA wind rose which covers all the wind speed and wind directions checked in this chapter.

The extreme load cases were modeled using the extreme 50-year values of winds and waves to design the Activefloat platform as defined in Mahfouz et al. (2020). The extreme wind is 28.35 m/s, and the extreme sea state H_s and T_p equal 6 m and 11 s, respectively. The turbines were shut off during the extreme event simulations by pitching the blades 90° out of the wind. The extreme wind field was created using the Mann turbulence box generator (Liew, 2022), with a duration of 3600 s and a turbulence intensity of 11% as recommended by the IEC standard (IEC, 2019). The extreme load cases simulations were carried on for 36 wind directions with an increment of 10°. The simulation time was set to 4200 s, and the first 600 s were omitted to remove transient effects. The results were used to check the maximum loads on the mooring lines and the tower base in extreme loading conditions and ensure they were below the maximum allowable loads.

5.4.1 Loads on the MS designs

I used the T-N curve presented in the API standard (API, 2005) and presented in equation 2.11 to calculate the mooring lines' 25-year fatigue damage. According to the API standard, a safety factor 3 should be used while using the T-N curve. This means a mooring line with a 25-year fatigue damage of less than 0.33 will survive the expected lifetime. The results of the 25-year damage for the mooring lines for the different FWF designs with different yaw stiffness are shown in Figure 5.10. The Figure shows the 25-year fatigue damage of the customized MS

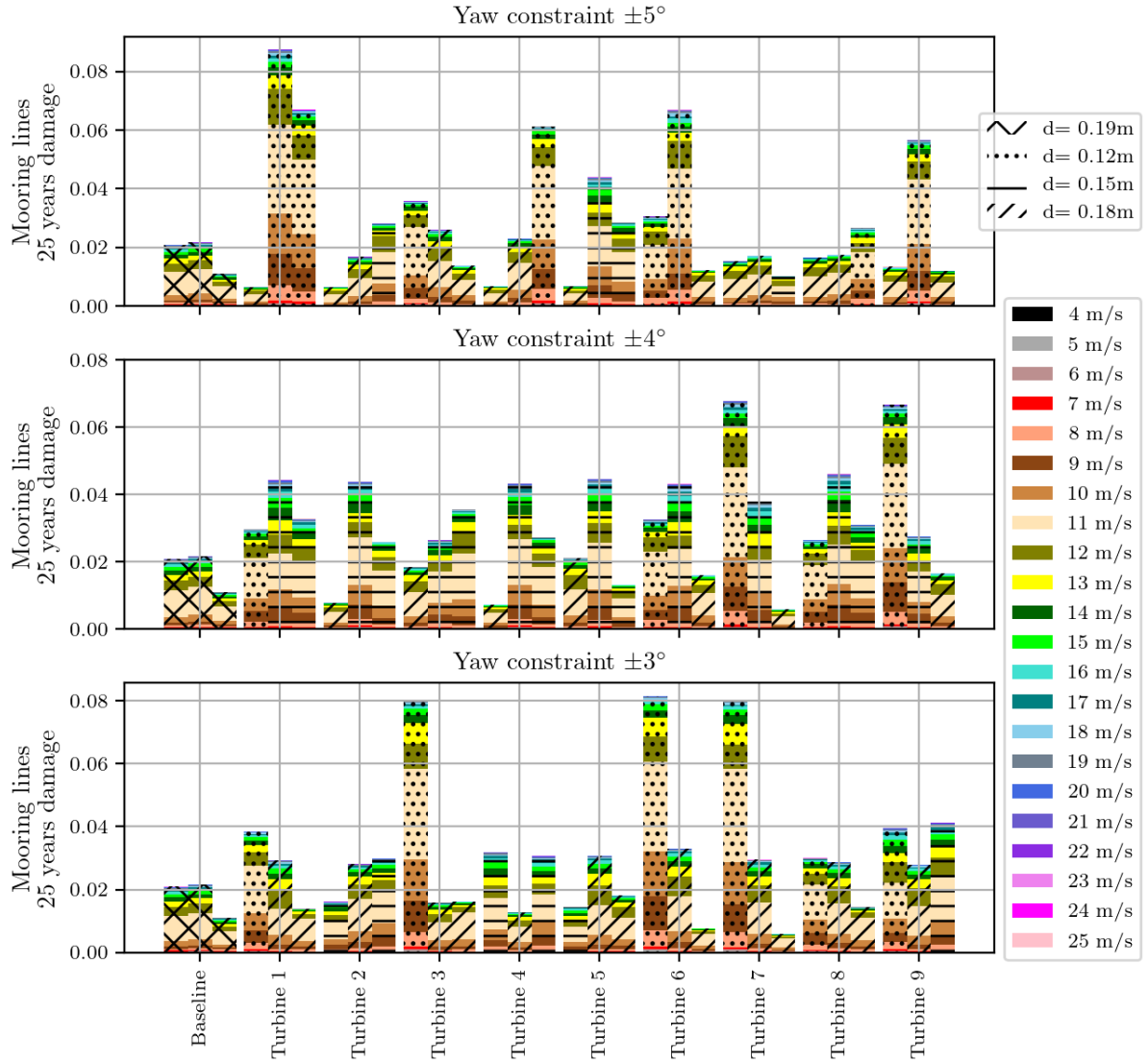


Figure 5.10: Fatigue damage assuming a 25-year lifetime for the FWF designs of Yaw 5, Yaw 4, and Yaw 3. Each bar in each turbine represents one mooring line. The colors represent the damage done at each wind speed

designs of each turbine, where each MS is represented by three bars, each representing a single mooring line. The patterns on each bar represent the diameter of the mooring lines. The fatigue damage on a mooring line is highly affected by the diameter of the line; a line with a small diameter will suffer from greater damage than a mooring line with a larger diameter when both lines are loaded equally. This is because the MBL is a function of the mooring line diameter. The colors of each of the bars in Figure 5.10 represent the fatigue damage at each wind speed. When analyzing the mooring fatigue loads, I focus on the effect of four parameters: the mooring lines' diameters, the wind speeds, the MS orientation, and the mooring lines' headings.

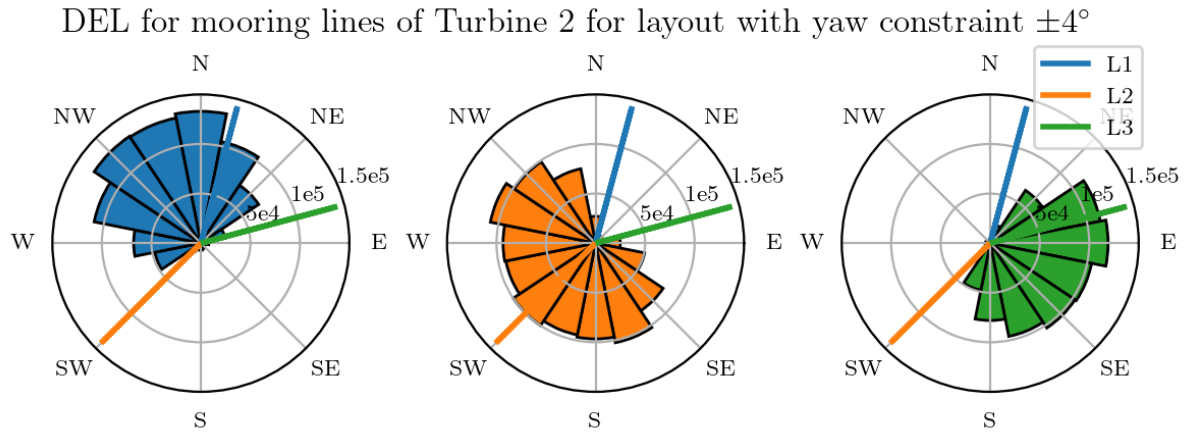


Figure 5.11: 1Hz DEL for MS design of turbine 2 for FWF design Yaw 4

All MS designs in Figure 5.10 are lower than the threshold of 0.3. The Figure shows that the fatigue of the mooring lines is not affected by the constraint on the maximum allowable platform yaw angle. The mooring designs of the three layouts with the different yaw constraints show similar damage values, where the damage value depends on the mooring lines' diameters. The maximum damage of the mooring lines in the three cases is four times higher than the mooring lines of the BMS, but all these cases occur for the smallest mooring line diameter of 0.12 m. The mooring lines with diameters 0.15 m and 0.18 m have fatigue damage within the same range as the BMS despite having a smaller diameter. This shows that allowing a less stiff MS with higher excursion can have a smaller diameter than a stiff MS design and still withstand the fatigue loads. A smaller diameter leads to a lower material cost for the MS design.

Figure 5.10 shows that the rated wind speed has the largest contributions to the 25-year fatigue damage for all cases, where most damage occurs between 9 m/s and 12 m/s. The below-rated wind speeds lower than 9 m/s cause negligible damage for all MS designs. On the other hand, the above-rated wind speeds contribute significantly to fatigue damage of the mooring lines. This is due to the higher rotational motions of the FOWTs at the above-rated wind speed. This will be discussed in detail when analyzing the fatigue loads on the tower base.

The fatigue performance of the MS is related to its stiffness, which is the slope of the force-displacement response at a given offset. The FOWTs are displaced to a mean position by the thrust force of the wind turbine, with the wind turbulence and the waves causing oscillations in position and tension around this mean. The stiffness, represented by the slope of the tension-displacement response, indicates the amplitude of wave-frequency tension fluctuations. The customized MS designs have much lower overall stiffness than the baseline, resulting in lower tension amplitudes and reduced fatigue damage. In other words, in a system with lower stiffness, the energy is dissipated through the FOWTs displacements rather than the increase in the

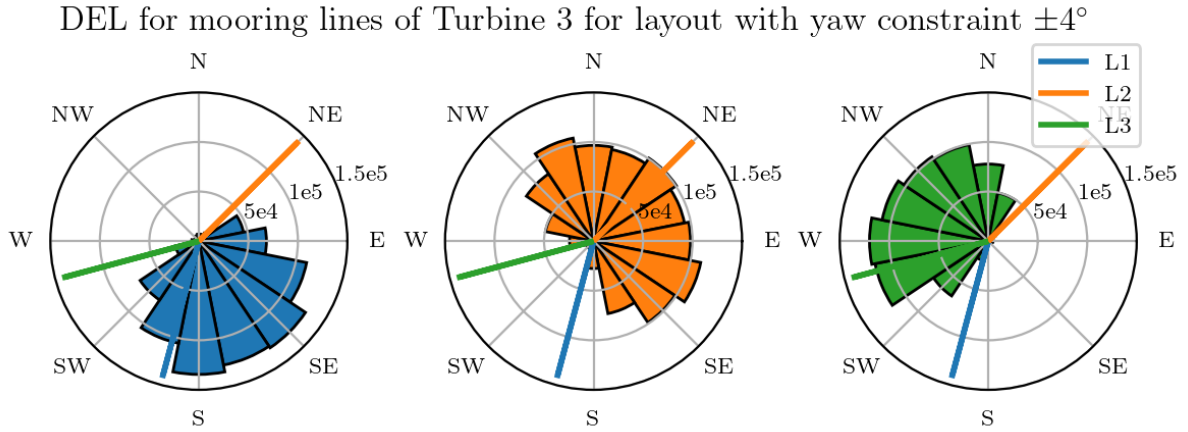


Figure 5.12: 1Hz DEL for MS design of turbine 3 for FWF design Yaw 4

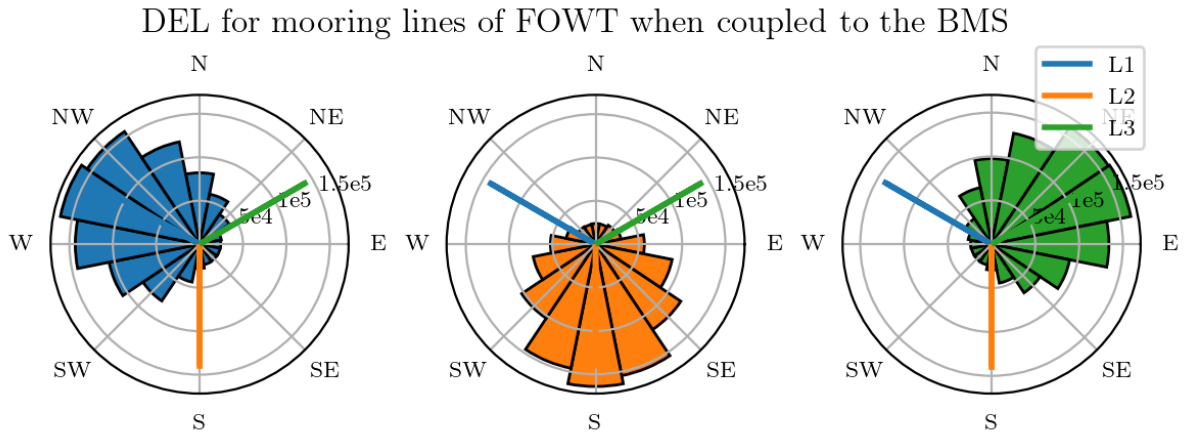


Figure 5.13: 1Hz DEL for MS design of the FOWT coupled to the BMS

tension cyclic amplitudes. This also coincides with the findings in Figure 5.5, where the highest stiffness is at rated wind speeds, and so is the fatigue damage. Additionally, the reduced stiffness decreases platform motion responses to first-order wave forces, moving the system farther from resonance. This has a small effect in this case as the Activefloat platform is less sensible to wave excitation forces than wind forces, as shown in Mahfouz et al. (2021).

Finally, identical MS designs with different orientations have a different value for the damage. For example, for the Yaw 4 design, by checking Table B.5, we can see that the MS design for Turbines 2, 3, 4, and 5 are identical, just with different orientations. Similarly, the MS design of turbines 6, 7, and 9 are identical with different orientations. However, the value of the damage of the mooring lines of these identical designs in Figure 5.10 varies due to the difference in orientation. I will use Turbines 2 and 3 from the Yaw 4 layout as an example to analyze the effect of the difference in orientation on fatigue damage. Figures 5.11 and 5.12 show the 1Hz DELs of each mooring line at a wind speed of 11 m/s. Changing the orientation of the MS

changes the wind direction at which the highest values of the DEL take place. For Turbine 2, the mooring line with the highest damage is line 2, as it has high DEL values coinciding with the main wind direction of the wind rose. The second highest damage is for line 3, as the high DEL value coincides with the second most probable wind direction. Finally, the damage of line 1 is the lowest of the three mooring lines coupled to Turbine 2 as the DELs coincide with the least probable wind direction. This differs for Turbine 3, where the damage is highest for mooring line 3 as its DELs coincide with the most probable wind direction.

To ensure that the comparison between the BMS design and the customized MS design is fair, I used a conservative approach to ensure that the orientation of the BMS is adapted to avoid having any of the mooring lines in the most probable wind directions. The orientation of the BMS is shown in Figures 4.7 and 2.5. The DELs of the BMS at each wind direction at 11 m/s are shown in Figure 5.13.

Another observation in Figures 5.11, 5.12, and 5.13 is how the mooring lines' headings affect the DEL distribution and the span at which the mooring line DELs are high. For the symmetric BMS design, the highest DEL of each line is always when the mooring line is upwind and aligned with the wind direction. Moreover, the span of wind direction at which the DEL is highest is equal for the three lines and equal to 120° . This is not the case in the asymmetric MS designs where the span of wind direction through which the mooring line DEL is high depends on the angle between the mooring lines' headings. In Figure 5.11, the span of wind direction at which the DELs of line 2 is high for a span of 180° , meaning that 50% of the wind directions will cause high DEL loads on line 2. This makes it harder to avoid the most probable wind directions. This can be explained by checking the difference in headings between line 2 and its neighboring mooring lines. The angle between line 2 and line 1 is 150° , and the angle between line 2 and line 3 is also 150° . Since line 2 has an equal heading difference between its two neighboring lines, the highest DEL is when the mooring line is upwind. So when the headings between a mooring line and its neighboring lines are large, the DELs are high for a bigger span of wind directions.

On the other hand, the span of wind directions at which the DELs are high for mooring lines line 1 and line 3 is smaller as the difference between the lines heading is smaller. However, as the difference between the headings of lines line 1 and line 3 and the neighboring lines are unequal, the highest DEL does not occur when the lines are upwind but shifted towards the neighboring line where the difference in the heading is larger. We can predict from the mooring design where the highest DELs will be and implement this as a constraint while choosing the MS design orientation. In future work, we can benefit from this knowledge by decreasing the diameter of the mooring line upwind from the least probable wind direction and increasing the mooring line diameter for the lines upwind from the most probable wind direction to decrease mooring costs. This was not implemented in the method presented in Chapter 3.

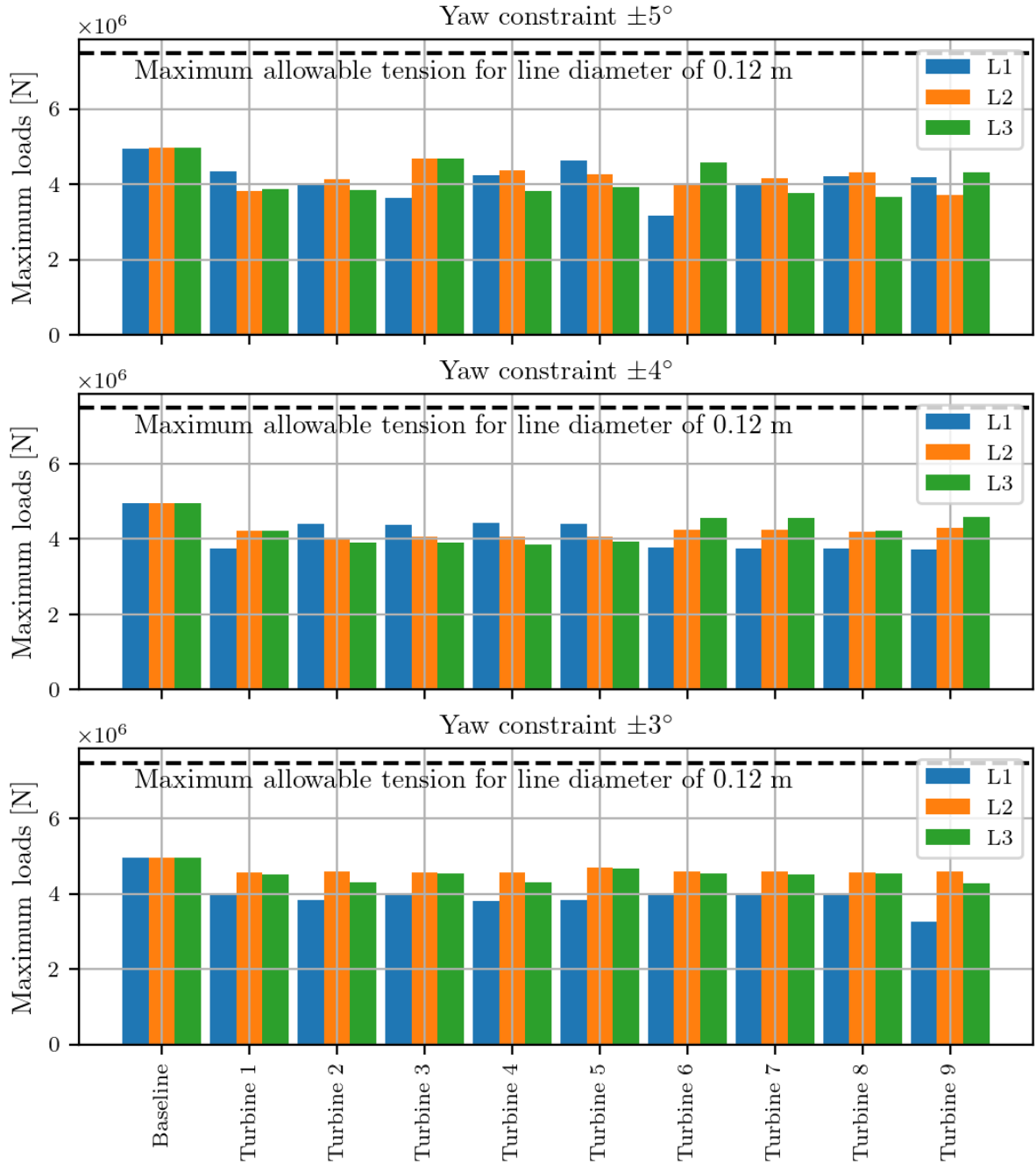


Figure 5.14: Maximum load on each mooring line in each FWF design in operation conditions

Figure 5.14 shows the maximum tensile load on each mooring line during operation, considering all wind speeds and directions. The Figure shows that all mooring lines are far from the maximum allowable tension with a safety factor of 2. The mooring line diameter of 0.12 m is a reference as this is the smallest diameter allowed in the MS database and, hence, in the MS designs. The Figure also shows that the orientation does not affect the maximum tension the

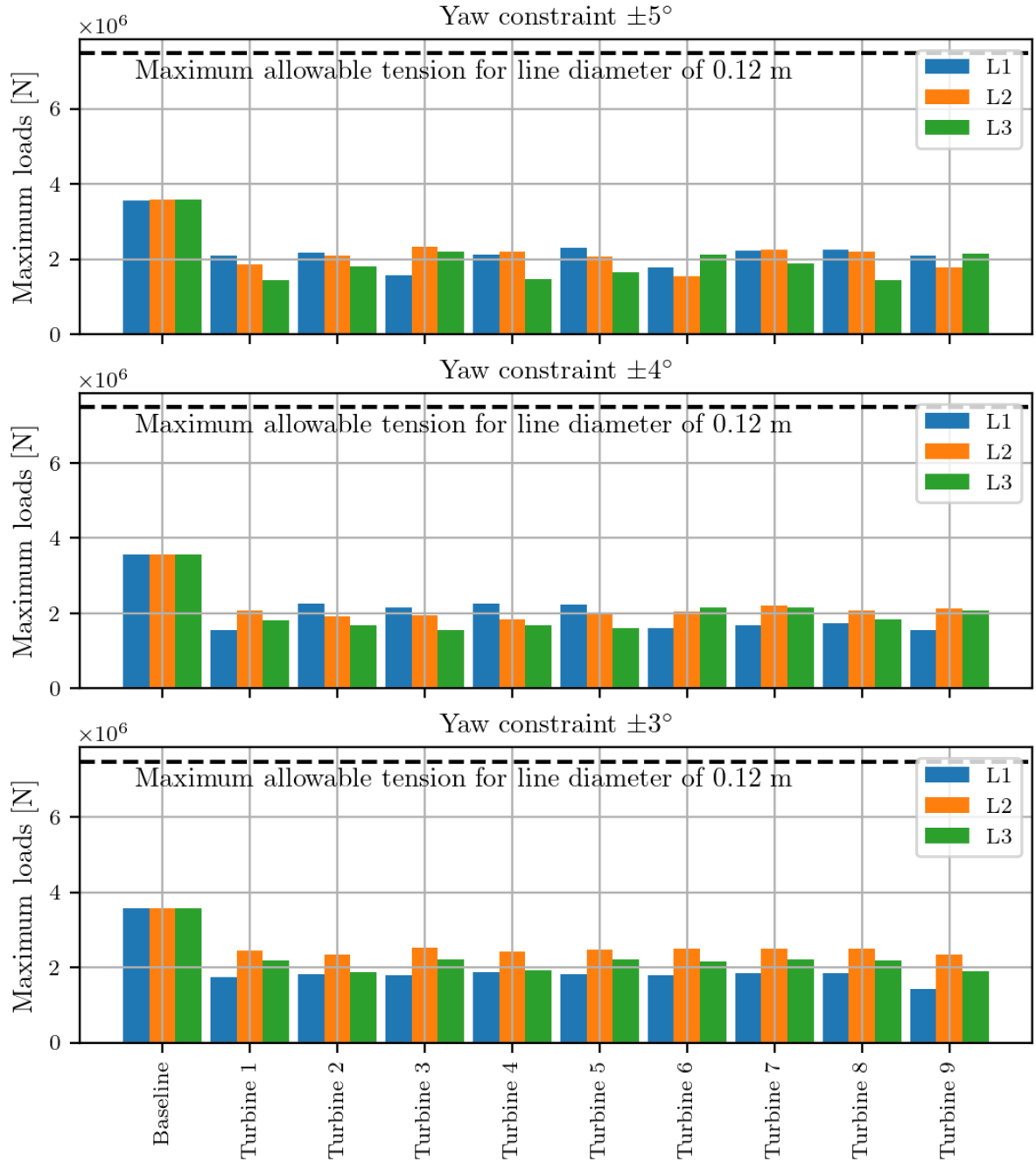


Figure 5.15: Maximum load on each mooring line in each FWF design in extreme wind and wave

mooring line suffers from during operation, where Turbines 2, 3, 4, and 5 in the Yaw 4 design have the same values of the maximum tension, although they have different orientations. This is expected as the wind rose, and the probability of occurrence of each wind direction does not affect the maximum loads. Therefore, the maximum tension value is independent of the orientation and only depends on the MS design. This is true for our results as the wind and wave are

always aligned; wind and wave misalignment can make the maximum loads dependent on the MS orientation. Since the three lines in the BMS are identical, they suffer from the same values of maximum tension. Finally, all the customized MS designs have lower maximum tension than the BMS. The maximum loads on the customized MS designs are always lower than the BMS mooring design, regardless of the mooring lines' diameters.

All the designs were checked against slackness by checking the tension at the anchor to ensure it did not reach zero. None of the mooring lines in any MS design had zero tension at the anchor at any operational load cases I checked.

The maximum loads on each mooring line in extreme wind and wave are shown in Figure 5.15. The loads are lower than the maximum loads the mooring lines suffer from during operation from Figure 5.14. This is probably due to the low value of extreme wind used 28.35 m/s. The maximum loads on the customized MS designs are always lower than those on the BMS design. All mooring lines are safely lower than the minimum breaking load value with a safety factor of 2 as recommended by the API standard (API, 2005). It is also clear that an MS with the same design suffers from the same value of the maximum loads in extreme conditions regardless of the MS orientation. This is again valid for these load cases where wind and wave forces were aligned and can differ for other load cases with wind and wave misalignment. The maximum load cases on all the mooring lines of the BMS design are equal as the mooring lines are identical, and the design is symmetric. The mooring lines also passed the slackness check, as the forces at the anchor were never zero for any mooring line in extreme conditions.

5.4.2 Loads on the tower base

In this section, I first analyze the loads at the tower base during operation for the three different farm designs, Yaw 5, Yaw 4, and Yaw 3, and compare them to the FOWT when coupled to the BMS. The loads on the tower base were analyzed by calculating the axial stress on the tower base at 12 different locations along the tower circumference with an increment of 30° , and the results in this section shown are for the location with the maximum fatigue damage. The axial stress was calculated using equation 2.12. For damage calculation, I used the S-N curve of steel as defined by DNV GL (2014) standard. Figure 5.16 shows the damage at the tower base of each FOWT inside the three FWF designs. The colors show each wind speed's contribution to the 25-year damage.

The fatigue damage at the tower base is high for above-rated wind speeds, especially wind speeds higher than 20 m/s for the Yaw 5 and Yaw 4 FWF layouts. This is due to the low MS stiffness at these wind speeds and the higher aerodynamic yaw moment in the above-rated region. As the wind turbine controller pitches the blades to keep the turbine's power and the rotational speed constant, the aerodynamic yaw moment increases. Since the MS design yaw stiffness is

low for FWF designs Yaw 5 and Yaw 4, this leads to higher yawing of the platform. The higher yaw misalignment increases the platform pitch and roll motion fluctuation. As the pitch and roll fluctuations increase, the tower top masses create a higher fluctuation in the tower base bending moments, increasing the tower fatigue loads. Due to the large tower length, a few degrees of pitch and roll are enough to create a large moment arm for the tower top gravitational forces.

In Figure 5.16, the 25-year fatigue damage on the Yaw 3 design for all FOWTs inside the FWF is lower than the fatigue damage on the tower base of the BMS. Although the platform yaw is higher than the BMS design for high wind speeds, the MS can provide enough yaw stiffness to overcome the higher aerodynamic yaw moment for the above-rated wind speeds. The fatigue

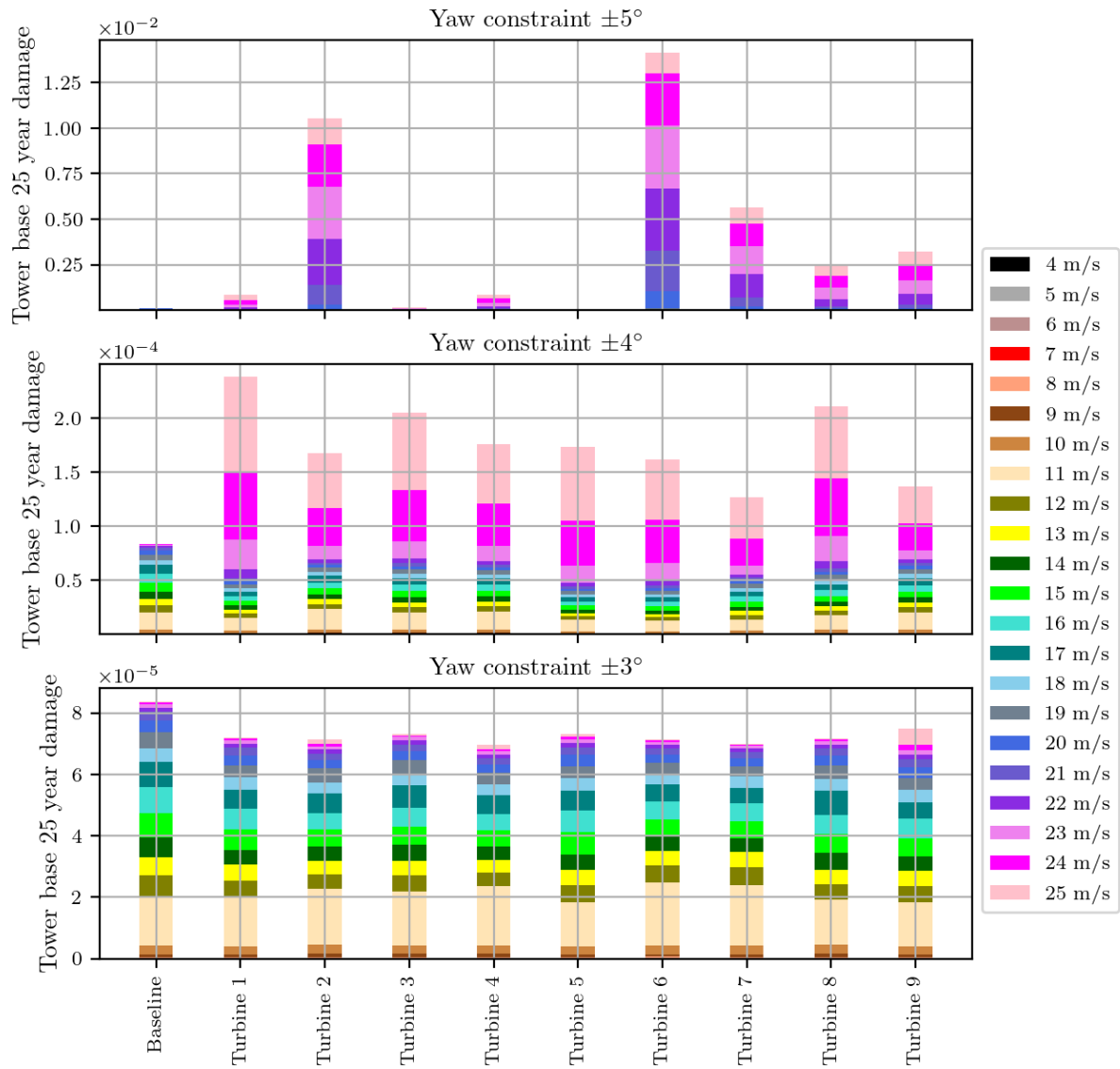


Figure 5.16: Damage at the tower base for the FWF designs Yaw 5, Yaw 4, and Yaw 5

damage results of the tower base are very small, showing that the tower design is driven by the maximum loads rather than fatigue loads. This agrees with the work of Ma et al. (2019), which shows from historical data that the tower failure is due to extreme loads. On the other hand, fatigue failures are less common and occur at connection points due to the failure of bolts due to human errors during installation or welding. The fatigue results in Figure 5.16 only represent the material failure due to the cyclic loading.

The fatigue damage at the tower base differs when the FOWT is coupled to two identical MS designs with different orientations. For layout, Yaw 4, Turbines 2 and 3 have different tower damage because the MS orientation is different. The difference is because the yaw stiffness differs with changing the direction of the wind. Lower stiffness in a more probable wind direction will cause higher tower base fatigue damage.

Figure 5.17 shows the maximum axial stress at the tower base during operation conditions. The results show the maximum value considering the 12 locations over the tower radius where the axial stress was calculated. When the FOWT is coupled to the BMS design, the maximum tower base stress load is 94 MPa. The tower base stress for Yaw 5 of design for Turbine 6 is 198 MPa, which surpasses the yield strength with a safety factor of 2. This means this design will fail as the stress exceeds the yield strength. The yield strength is 350 MPa, so the tower base stress should not exceed 175 MPa. The maximum tower base stress for Yaw 4 designs is 118 MPa, while the maximum tower base axial stress for Yaw 3 designs is 101 MPa. This means that even if we increase the safety factor on the yield strength to 3, the Yaw 4 and Yaw 3 designs will still achieve the design criteria. The Yaw 3 design's maximum tower base load is 7% higher than the BMS, while the Yaw 4 design's maximum tower base load is 22% higher than the BMS

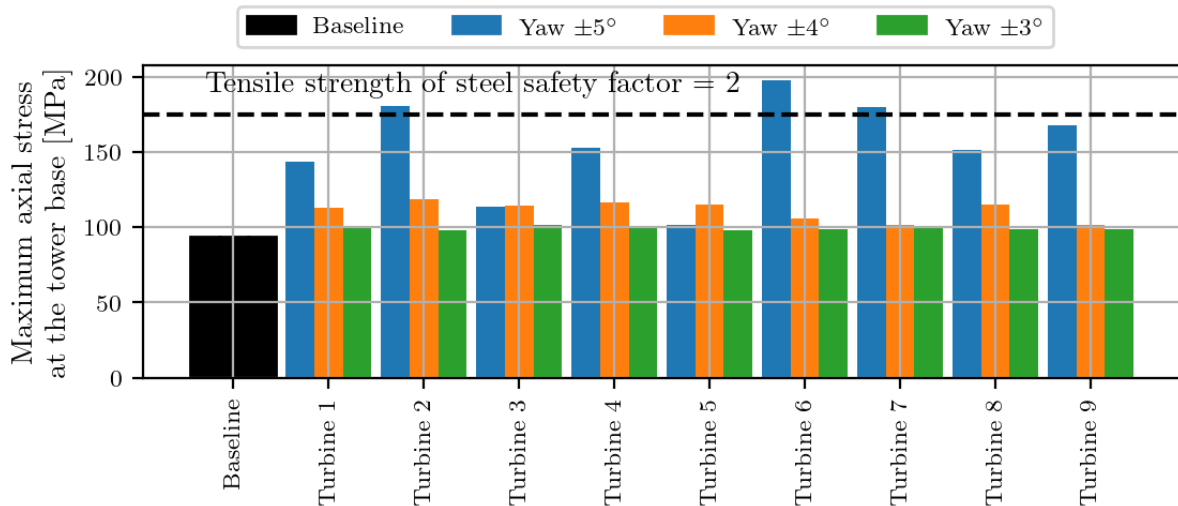


Figure 5.17: Maximum tower base axial stress at operation for the FOWT coupled to the BMS and the three FWF designs Yaw 5, Yaw 4, and Yaw 3

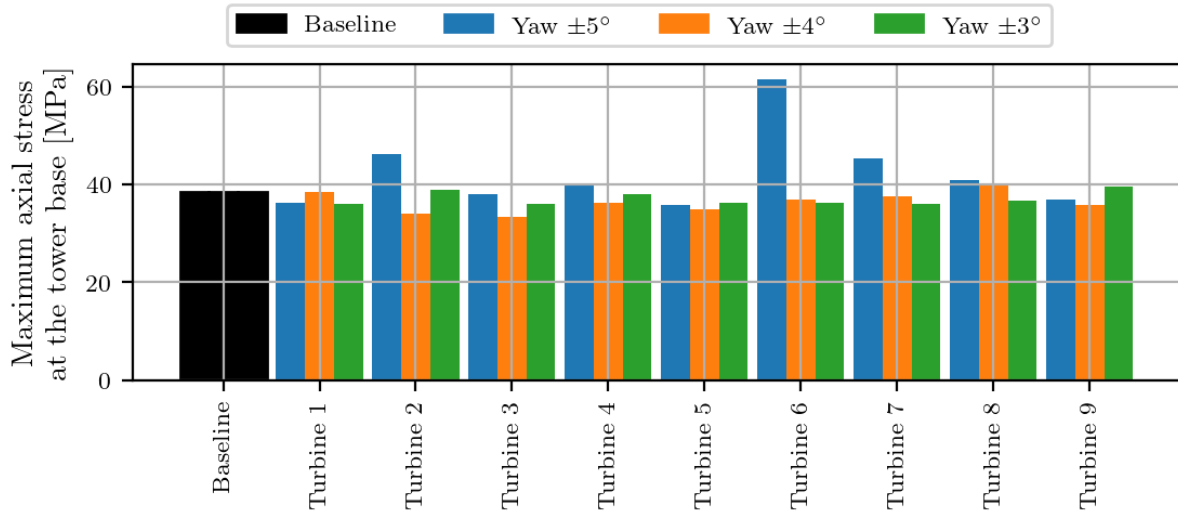


Figure 5.18: Maximum tower base axial stress at extreme wind and wave for the FOWT coupled to the BMS and the three FWF designs Yaw 5, Yaw 4, and Yaw 3

design. The connection between the maximum tower base stress in Figure 5.17 and the MS yaw stiffness in Figure 5.5 is clear. For layouts Yaw 4 and Yaw 5, the maximum stress happens at the turbines coupled with the lowest MS stiffness.

The maximum loads on the tower base in extreme wind and waves are shown in Figure 5.18, where all the designs are far below the yield strength. Turbine 6 of the Yaw 5 design has the maximum axial stress value of 62 MPa. This shows that for the load cases checked in this work, the maximum loads on the tower base are dominated by the operational load cases rather than extreme load cases.

5.4.3 Loads on the blade root

Figure 5.19 shows the percentage change of the lifetime DELs of the blade root of each turbine in layouts, Yaw 5, Yaw 4, and Yaw 3 as a percentage difference to the lifetime DEL of the FOWT coupled to the BMS. Similar to the fatigue damage at the tower base, layout Yaw 5 has the highest increase in blade root fatigue load. Turbines 6 and 2 have the highest increase in fatigue load with an increase of around 12.5%. These are the same turbines with the highest tower base fatigue damage, and the maximum load at the tower base surpasses the breaking load of the tower. These are also the turbines with the lowest yaw stiffness. Therefore, I investigate why the loads at these turbines are higher in the next section.

For layouts, Yaw 4 and Yaw 3, the blade root loads are within the same range as the baseline FOWT. In layout Yaw 4, the maximum fatigue load increase is slightly higher than 0.6% at

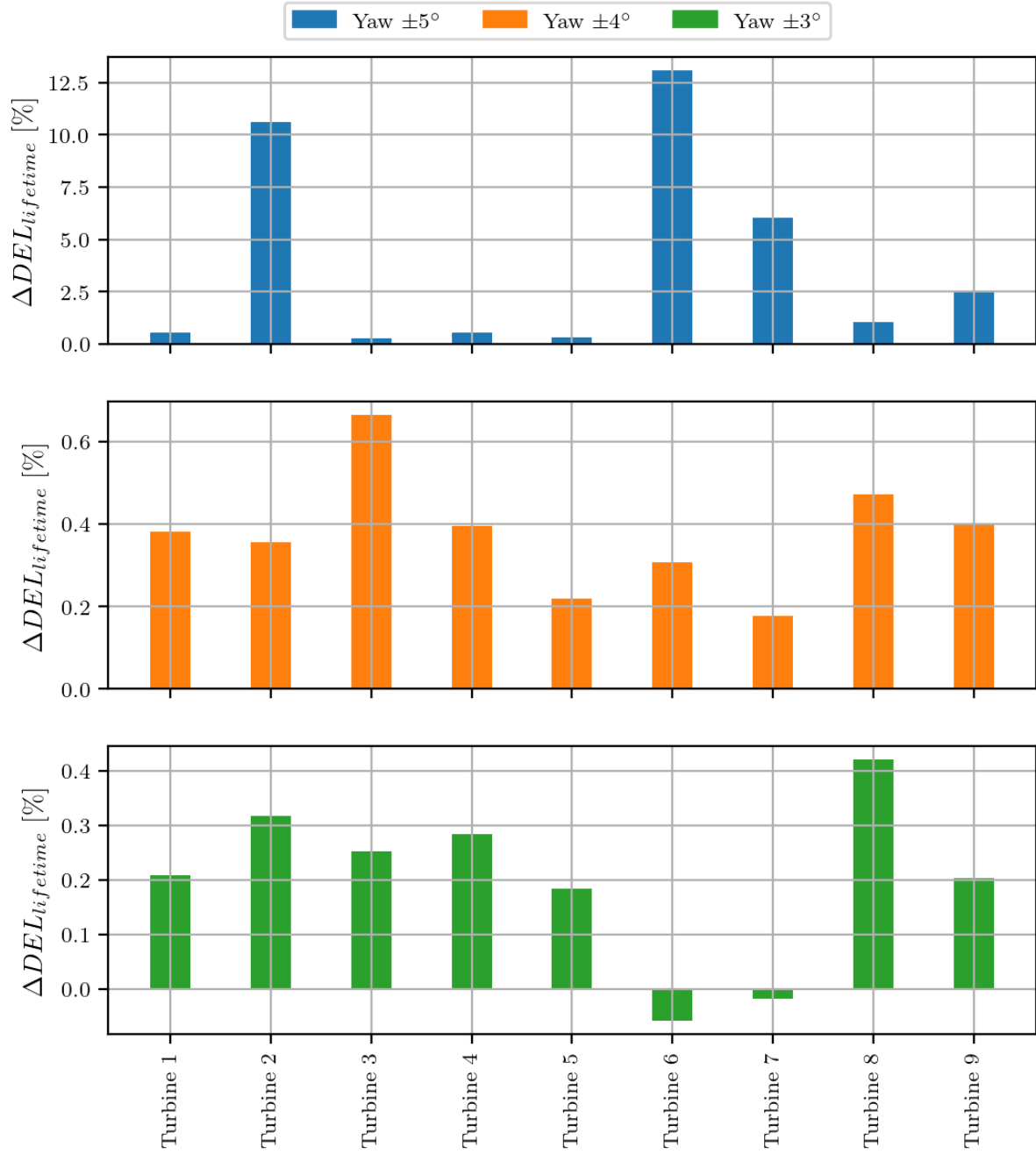


Figure 5.19: The lifetime DELs for blade root moment. The results are shown as a percentage difference to the baseline FOWT. With positive indicating the loads are higher than the baseline FOWT

Turbine 3, and the rest of the turbines have lower values. None of the turbines have lower fatigue damage than the baseline turbine. For layout Yaw 3, the maximum fatigue increase happens for Turbine 8 with a value slightly higher than 0.4%. For this layout, Turbines 6 and 7 have slightly lower fatigue damage than the baseline turbine.

Yaw 4 and Yaw 3 layouts have lower yaw stiffness than the BMS. Hence, these layouts will have higher yaw misalignment values, especially for above-rated wind speeds. As the yaw misalignment increases, I expected that the blade root fatigue loads would increase, but this was not the case for the OpenFAST results in operation conditions, as shown in Figure 5.19. The layout Yaw 4 and Yaw 3 results show very small differences compared to the baseline. This can be because the increase in the yaw angle is not large enough to cause an increase in the blade root fatigue loads. The other reason can be due to the uncertainty of the blade root moment of the BEM model used in OpenFAST in yaw misalignment conditions. The works of Shaler et al. (2023) and Muoz-Simón et al. (2020) have shown that the BEM model underestimates the blade root moments for yaw misalignment angles larger than 12° . Shaler et al. (2023) compared the results of the BEM model implemented in OpenFAST to actuator line LES results at wind speed of 8 m/s and steady uniform wind with no vertical shear. A higher fidelity aerodynamic model is needed to verify the results shown.

5.4.4 MS stiffness and FOWT loads

In this section, I discuss the results shown for the tower base and blade loads and explain the reason behind the higher loads for a softer MS design with a smaller yaw stiffness. Figure 5.20 shows the time series of the blade pitch, platform yaw, platform roll, and platform pitch. The time series shows the last 600 s of the simulations of the FOWT when coupled to the BMS, as well as the MS designs coupled to Turbine 6 in the FWF designs Yaw 5 and Yaw 3. The simulation is at operational conditions as defined earlier with a turbulent wind speed of 25 m/s and wind direction 0° . Although the time series in Figure 5.20 is produced considering turbulent wind and irregular waves, the wave frequency does not appear in the floater's response. This agrees with our work in Mahfouz et al. (2021), which shows that inertia and aerodynamic forces dominate the Activefloat platform's response.

Figure 5.20 shows that the mean yaw angle of the Yaw 5 and Yaw 3 designs are higher than the constraint values of 5° and 3° respectively. The constraint used to filter the results of the MS database is only done for wind speed of 10 m/s at which the MS database is created. This constraint no longer holds as the aerodynamic yaw moment is higher for the above-rated wind speed. Figure 5.20 shows the FOWTs displacements at 25 m/s where the aerodynamic yaw moment is at its highest value. Additionally, the MS database was produced using static tools that could not capture the dynamic effect of the controller on the rotor aerodynamics. Therefore, we cannot accurately predict the yaw angle of the platform using MoorPy at the wind speeds above rated.

The Figure shows that the less stiff MS design with the yaw constraint of $\pm 5^\circ$ causes a coupling between the aerodynamic forces and the floating platform dynamics. The blade pitch, platform

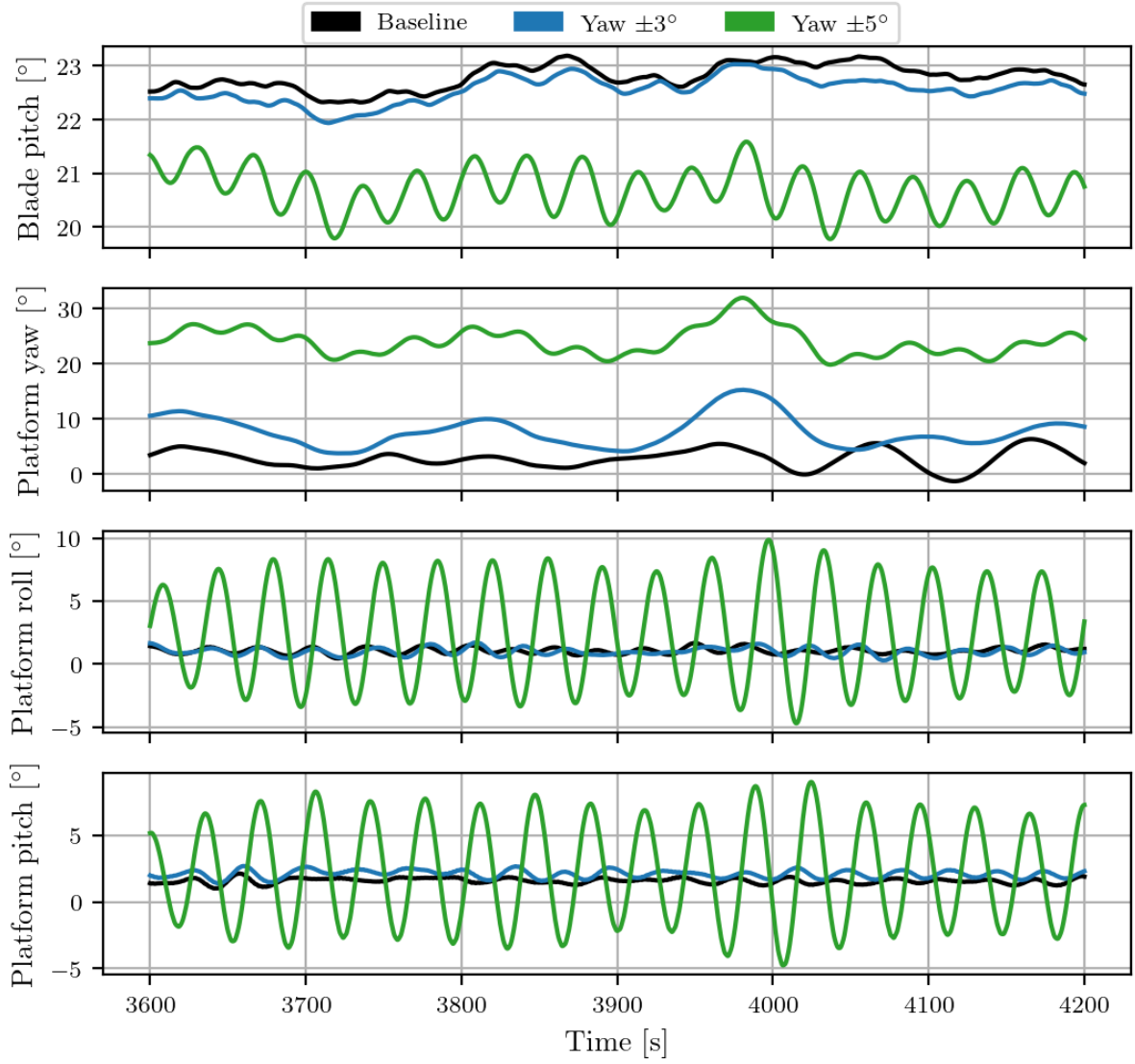


Figure 5.20: Time series of the FOWT when coupled to the BMS, Turbine 6 in the Yaw 3 and Yaw 5 layout designs. The time series is at a wind speed of 25 m/s and wind direction of 0°

roll, pitch, and roll oscillate with a frequency equal to the natural frequency of the pitch and roll DoFs. The oscillations also suggest that a FOWT coupled to an MS system with a low yaw stiffness can lead to instability. As the yaw stiffness is small and the torsional moment is high, the FOWTs start yawing with values higher than 15° , causing this resonance. At 25 m/s and wind direction of 0° , the yaw stiffness (K_{66}) of the MS design with Yaw $\pm 5^\circ$ is 35 MNm/rad, while the BMS K_{66} is 232 MNm/rad. In the following paragraphs, I analyze whether the roll-yaw or pitch-yaw coupling is causing instability.

Haslum et al. (2020), and Haslum et al. (2022) explain the aerodynamic coupling between roll and yaw. The FOWT yaw displacement creates a negative moment around the x-axis, leading

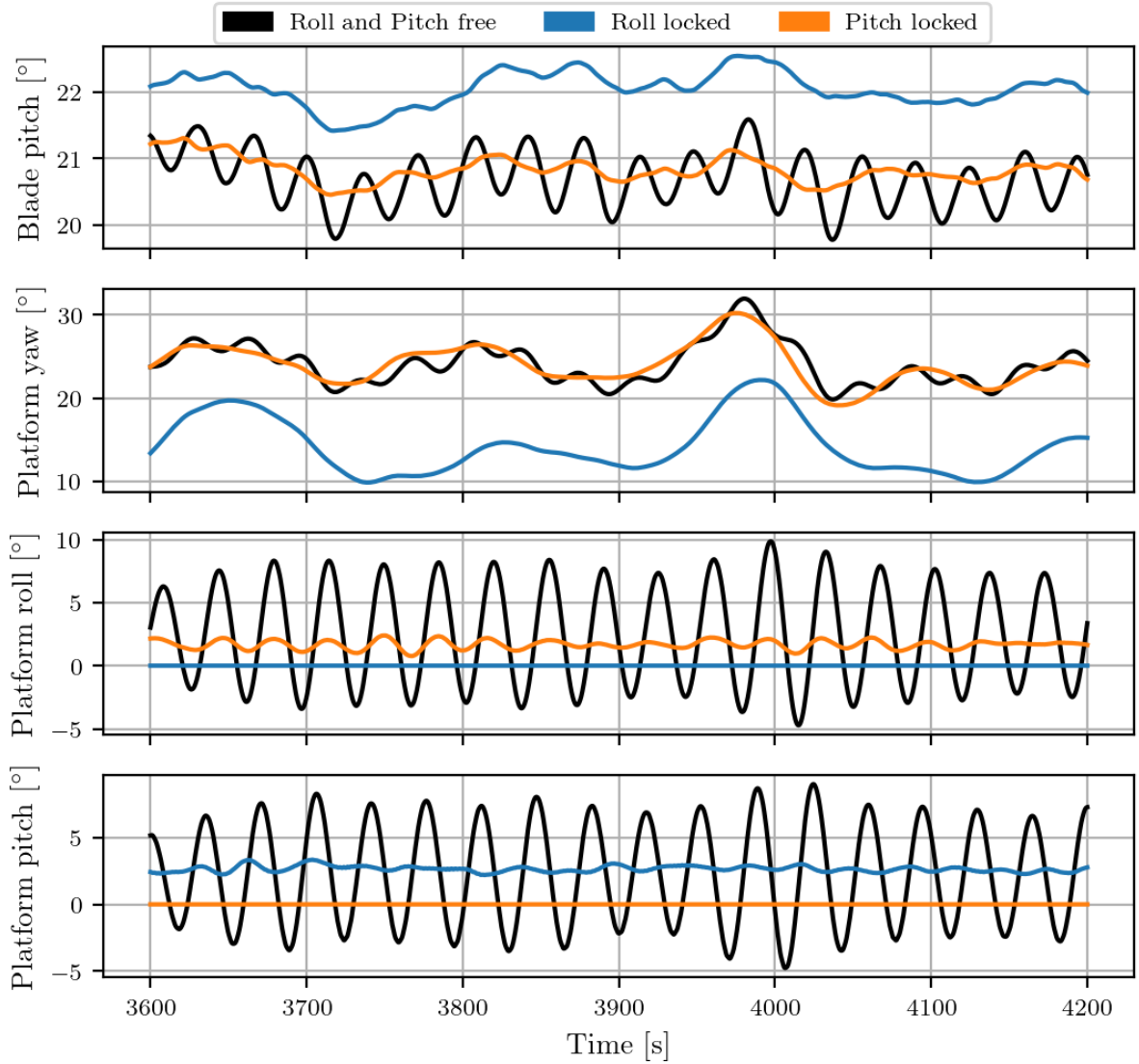


Figure 5.21: Time series of Turbine 6 in the Yaw 5 layout designs, with all platform DoFs free, pitch DoF locked, and roll DoF locked. The time series is at a wind speed of 25 m/s and wind direction of 0°

to a negative roll. On the contrary, the roll displacement creates a positive yaw moment around the z-axis, increasing the yaw displacement. The moments created in these cases are not due to the change of the aerodynamic yaw moment produced by the rotor aerodynamics but rather due to the mean thrust force acting on the rotor when it is rolled or yawed. The roll natural period is 31 s, while the yaw natural period is 212 s; the gap between the two natural frequencies makes it clear that the roll yaw coupling does not lead to any instabilities in the current work. The study also states that the instability occurs at the highest thrust force, which is not the case as the thrust at 25 m/s is low compared to the rated thrust.

The pitch motion can lead to either an increase or a decrease in the aerodynamic yaw moment due to the effect of the rotor tilt on the aerodynamic torsion, as explained in the work of Hansen (1992). The FOWT platform pitch motion changes the aerodynamic force distribution on the blades through one cycle, which changes the fore-aft moment at the blade root, which directly alters the aerodynamic yaw moment acting on the FOWT. I have checked the effect of increasing the platform pitch on the aerodynamic torsional moment using steady-state simulations at 25 m/s. The increase of platform pitch decreases the aerodynamic yaw moment; hence, the yaw angle decreases and vice versa. The change in the aerodynamic yaw moment due to the change in platform pitch is much smaller than the change in the aerodynamic yaw moment due to the change in the platform roll DoF. Since the pitch and yaw natural frequencies are well separated, energy transmission between the two DoFs is unlikely.

To investigate these oscillations further, Figure 5.21 shows the results when the roll and pitch DoFs are locked. The simulations are done at the same operation condition with a turbulent wind field with a mean wind speed of 25 m/s and a wind direction of 0° for Turbine 6 in the Yaw 5 layout. When the roll or the pitch DoFs is locked, the oscillations at the pitch and roll natural frequencies are no longer visible. When the roll DoF is locked, the mean platform yaw value is lower, and the mean blade pitch is higher. This is because when locked, the platform roll angle is zero, and it does not increase the mean aerodynamic yaw moment acting on the platform, leading to a higher yaw displacement. The oscillation effects are only visible at high wind speeds and low MS stiffness. The results prove that it is not yaw roll instability or yaw pitch instability but rather a coupling between the three DoFs, and when any of the three DoFs is locked, no oscillation occurs.

A final check was to check the response of a non-controlled system. Therefore, I turned off the controller dynamics and ran the same simulation with the floating platform, free to move in all six DoFs. The blade pitch and the rotor speed were fixed to the mean settings of 22.6° and 7.56 rpm, respectively. This matches the expected mean blade pitch value and rated rotor speed at a wind speed of 25 m/s. The simulation showed that the FOWT's platform yaw kept increasing until the simulation failed. This shows that if the MS stiffness in the yaw DoF becomes too small, the FOWT will rotate freely around the z-axis as the stiffness is too small to withstand the aerodynamic yaw moment at a mean wind speed of 25 m/s.

I also analyzed Yaw 4 and Yaw 3 layouts by checking the designs with increased tower base fatigue damage. It is visible for the layout Yaw 4, as shown in Figure 5.16, that the tower base fatigue damage is greater for above rated wind speeds, indicating the same effect for layout Yaw 5 is present. The low yaw stiffness increases the roll pitch oscillation and the tower base fatigue. Since the effect is obvious and the fatigue damage is much higher, I did not investigate layout Yaw 4 further.

For the layout, Yaw 3, the increase in the tower base fatigue damage is visible only in the fatigue damage results of Turbine 9 and only for certain wind directions. The fatigue damage of Turbine 9 is greater when the wind is directed upwind between line 3 and line 1 and when the wind is aligned upwind of line 2. However, the oscillation is most visible, and the fatigue damage is the highest when the wind is aligned with mooring line 2. The yaw stiffness of the MS design coupled to Turbine 9 in the layout Yaw 3 is shown in Figure 5.22. The lowest stiffness is at a wind direction of -30° when the wind is aligned upwind with mooring line 2, with a value of 67 MNm/rad.

The yaw stiffness changes significantly with the wind direction as the MS design is asymmetric. The yaw stiffness depends on the counter moment the mooring lines produce to counteract the aerodynamic torsion moment. Therefore, the yaw stiffness depends on the horizontal components of the tension of the mooring lines, the arm of moment between these forces, and the direction of the forces. For example, a large arm of the moment and large horizontal forces lead to high yaw stiffness. A small heading difference between two lines decreases the yaw stiffness for wind directions between the two lines. A large heading difference between a mooring line and its neighboring lines decreases the yaw stiffness when the wind is aligned with the line. As the heading between two lines decreases, their tension forces act in the same direction, and hence, the counter moment value decreases, and the stiffness decreases. The stiffness is also lower for lower thrust values, as the tension of the mooring lines is lower; hence, the counter moment is

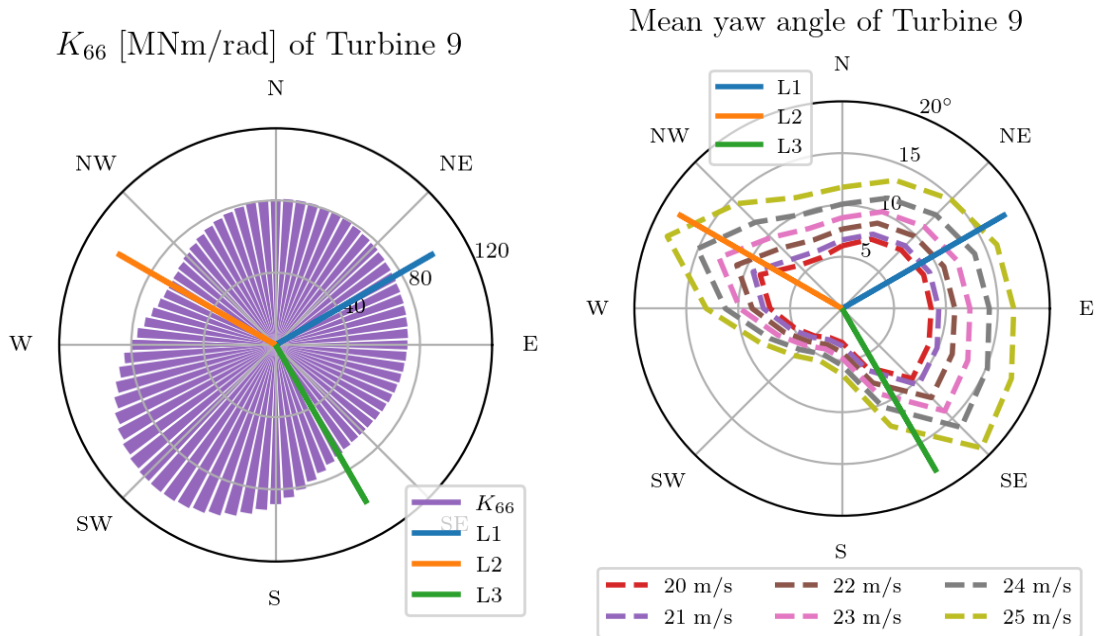


Figure 5.22: On the left is the yaw stiffness for each wind direction of the MS coupled to Turbine 9 in the layout Yaw 3. On the right is the mean platform yaw angle in OpenFAST for each wind direction

lower, and the MS stiffness is lower. The lowest values for stiffness are for wind speeds of 4 and 5 m/s, but as the aerodynamic yaw moment is small at lower wind speeds, no large yaw misalignment occurs.

For the wind direction -30° , the wind is aligned with mooring line 2, which carries most of the force, while the tensions in the other two lines are small as the heading difference is large. For wind directions with the wind blowing between line 3 and line 1, and as the heading difference between the two lines is small, they do not create a large counter moment as the tensions of the two lines are almost aligned and not opposite each other to create the moment. The stiffness is lower for all wind directions between the two lines. The stiffness is highest when the wind is between line 2 and line 3 as the angle between the two lines' headings is large and the two lines are opposite, creating a larger moment and a higher yaw stiffness.

Figure 5.22 shows the mean yaw angle in OpenFAST for the MS design coupled to Turbine 9 in the Yaw 3 layout for wind speeds between 20 and 25 m/s. The mean yaw angles are highest when the MS yaw stiffness is lowest and vice versa. The highest yaw angles occur at a wind speed of 25 m/s and for the expected wind directions. The main goal of the Figure is to show that for lower wind speeds in the above-rated region, the mean yaw angle is low and does not lead to higher fatigue or large amplitude oscillation. Except for two wind directions at 24 m/s, the yaw angle is always less than 15° and does not increase the fatigue load on the system or increase the platform oscillations.

Figure 5.23 shows the time series of Turbine 9 in the Yaw 3 layout for wind direction of 135° and wind speed of 25 m/s. The Figure shows the response with both pitch and roll DoFs free, with roll DoF locked, and pitch DoF locked. The result confirms again that locking either of the pitch or roll DoFs decouples the system, and no large oscillations are visible. Compared to Figure 5.21, the amplitude of pitch and roll oscillations in Figure 5.23 is small. The range of the oscillations in Figure 5.21 was 20° , while it is 10° for the stiffer MS design in the layout Yaw 3. This explains why the tower maximum load did not increase for Turbine 9 in the Yaw 3 layout. It also explains why the increase in fatigue damage is lower.

I checked the response of the uncontrolled system of the FOWT 9 in layout Yaw 3 at the wind direction with the lowest yaw stiffness values. I switched off the controller's dynamic response and simulated the system with a fixed blade pitch of 22.6° and fixed rotor rotational speed of 7.56 rpm. The wind field is a turbulent wind field with 25 m/s mean wind speed and the same wave loading conditions used for operational conditions. The results are shown in Figure 5.24, where the FOWT response shows an undamped oscillation in yaw, pitch, and roll DoFs. This shows that the stiffness of this MS system with a value of 67 MNm/rad is the minimum MS stiffness to withstand the aerodynamic yaw moment at 25 m/s, as the platform yaw angle does not increase further.

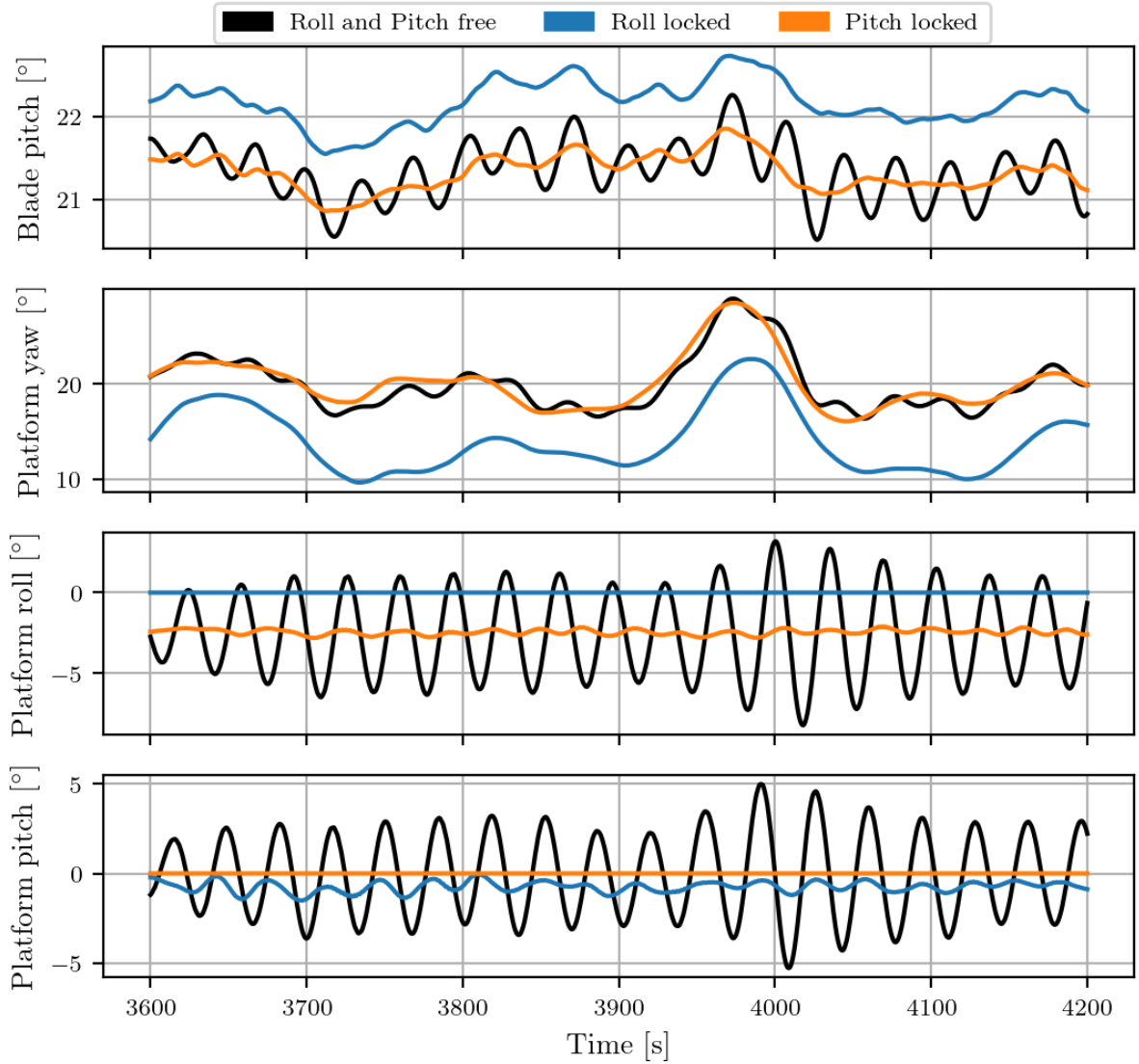


Figure 5.23: Time series of the response of Turbine 9 in the Yaw 3 layout when all DoFs are free, roll DoF is locked, and pitch DoF is locked

The results of layout Yaw 5, Yaw 4, and Yaw 3 show that the oscillation becomes more dominant as the yaw angle increases. The rotor thrust (F_t) is perpendicular to the rotor with component $F_{t,x}$ in the x direction and $F_{t,y}$ in the y direction, as shown in equation 5.1. These two forces, multiplied by the rotor height, cause the moments that excite the pitch and roll DoFs, respectively. As the platform yaw angle becomes larger, these two components become a function of the yaw angle, and small angle approximations are no longer valid. The high oscillations effect was seen in load cases where the yaw angle was higher than 15° . OpenFAST showed a warning message that small angle approximations are no longer valid for all the cases with high oscillations.

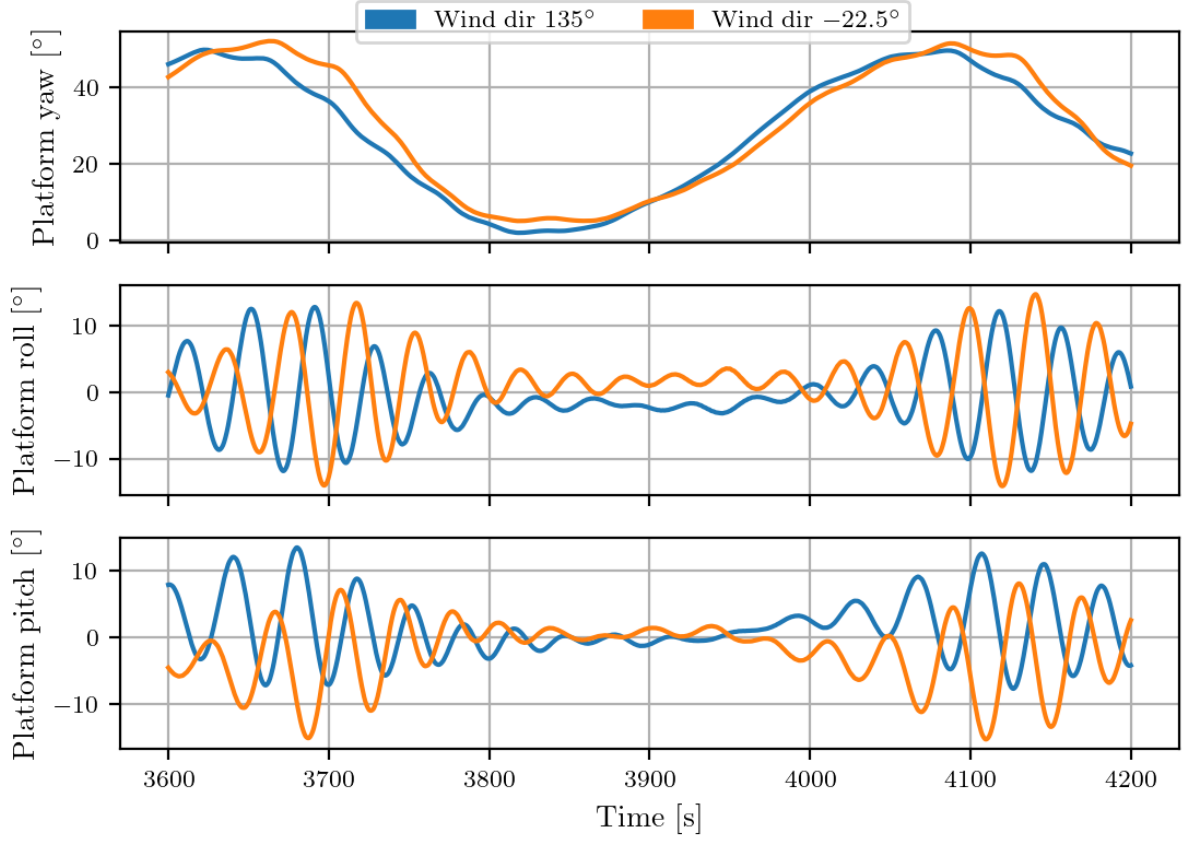


Figure 5.24: Time series of the response of the uncontrolled system of Turbine 9 in the Yaw 3 layout

$$\begin{aligned} F_{t,x} &= F_t \cos(yaw) \\ F_{t,y} &= F_t \sin(yaw) \end{aligned} \quad (5.1)$$

For the rotational motions of the FOWT, OpenFAST uses small angle approximations with correction for orthogonality; this affects the accuracy and reliability of the results when the platform yaw angle is higher. The effect of small angle approximations is very relevant to the results shown in this section, as the yaw angle directly affects the excitation forces for the pitch and roll DoF as shown in equation 5.1. As the yaw angle becomes larger than the limitations of small angle approximation, the roll and pitch displacement will become inaccurate. Therefore, this increases the uncertainty of the results and can be overestimating or underestimating the coupling effects I have shown in this section. Especially because results also show that the coupling effects only become significant when the yaw angle is outside the range within which the small angle approximation assumption is valid.

Additionally, it is vital to consider the BEM model's limitations, which overestimate the aerodynamic torsional moment at a higher yaw angle, as shown by Shaler et al. (2023) for fixed

bottom wind turbines. Therefore, to understand the limitations on minimum MS stiffness in the yaw DoF, a higher fidelity method is needed where the aerodynamic couplings with the FOWTs are captured. Moreover, at these coupled motions, the rotor might be operating in its own wake, which is also not captured by the BEM model within OpenFAST. There are two ways to avoid these higher oscillations: First, increase the MS stiffness to avoid getting larger yaw motion. When the platform yaw angle is below 15° , I saw that the oscillations are smaller and the coupling does not lead to higher loads. Second, individual pitch control (IPC) mitigates the yaw effect as shown in the work done by Sandua-Fernández et al. (2023) and Namik and Stol (2010), in which the IPC decreased the torsional moment acting on the FOWT at above-rated wind speeds. The results from Sandua-Fernández et al. (2023) show that even for a single point MS, the IPC controller could overcome the high torsional aerodynamic moment at above-rated wind speeds.

5.5 Conclusion

The chapter shows how relocating the FOWT affects the loads of the mooring lines, tower base, and blade roots. The loads of the mooring lines are dominated by their diameter: a lower diameter suffers from higher fatigue loads and lower maximum loads, and vice versa. The MS headings and orientations can be utilized to decrease the fatigue loads on the mooring lines.

The yaw stiffness greatly affects the tower base and blade root loads, especially for above-rated wind speeds. When the FOWT is coupled to an MS with small yaw stiffness, the loads at the maximum tower base loads can be higher than the tower's MBL, causing tower structural failure. The results are highly affected by the limitations of OpenFAST, which uses small angle approximation for the rotational motions of the floating platform. Therefore, no conclusions can be made for the cases where the yaw angle is larger than 15° . The aerodynamic torsional moment at above rated wind speeds can be mitigated by using an IPC or increasing the MS yaw stiffness. However, in this work here, I will not update the controller design to use IPC. Instead, I will only use MS designs that provide enough yaw stiffness to overcome the aerodynamic torsional moment for above-rated wind speeds.

Hence, for the rest of this work, I will use only the MS designs database with a constraint on maximum allowable yaw of $\pm 3^\circ$ at 10 m/s, as the results showed that these designs provide enough stiffness without increasing the loads on the tower or the mooring lines. The maximum loads are always within the same range as the baseline FOWT, and the fatigue load increase is negligible and only occurs at a mean wind speed of 25 m/s. Wind speeds above 20 m/s are rare, and at a mean wind speed of 25 m/s, the FOWT will not operate any longer and will be shut down as the turbulent field will go higher than the cut-out wind speed. The overall fatigue damage on the tower base for the Yaw 3 layout is always lower than the baseline FOWT.

FLOATING WIND FARM DESIGN - DYNAMIC VERIFICATION

6.1 Overview

The chapter's primary goal is to answer the first research question of this work: Can we benefit from the FOWT relocation to increase an FWF's AEP? The second goal is to compare the loads on the FOWT when operating inside the FWF to those on the FOWT when operating standalone. The steady-state results from Chapter 4 show that allowing the FOWT to relocate increases the FWF AEP. Still, these models are simple and cannot capture the wake dynamics, which can alter the results. Hence, I used the mid-fidelity tool FAST Farm v3.4 (Jonkman and Shaler, 2020) to model the novel FWF Yaw 3 layout from Chapter 4 in the time domain to capture the wake dynamics and the loads on the FOWT inside the FWF. The GWFL when the FOWTs are coupled to the BMS and when coupled to the newly designed customized MS designs were modeled in FAST Farm. A top view of the GWFL with the BMS and the customized MS design is presented in Figure 6.2. The customized MS designs are created with a constraint to ensure a higher MS stiffness by forcing the mean of platform yaw angle to be $\pm 3^\circ$ at a wind speed of 10 m/s. The customized MS designs' details are presented in Table B.6. I will refer to the GWFL coupled with the BMS design as the baseline FWF for the rest of the chapter. The results discussed in this chapter are based on my work in Mahfouz and Cheng (2025).

First, I calculate the AEP and the wake losses of the GWFL when coupled to the BMS to use as a reference for the rest of the chapter. Therefore, I modeled 160 load cases in FAST Farm covering wind speeds between 4 m/s and 13 m/s with a wind speed bin of 1 m/s and 16 wind directions with an increment of 22.5° similar to the IEA wind rose presented in Figure 3.29. At

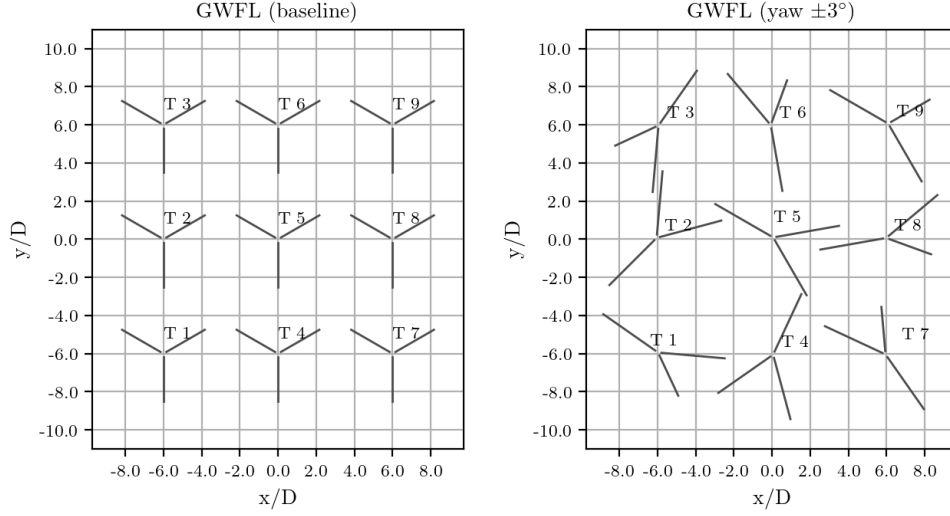


Figure 6.1: GWFL coupled to the baseline MS design and the customized MS designs

wind speeds equal to 14 m/s and higher, the FWF was assumed to operate at optimum power and was not modeled in FAST Farm. Then, I used the results to calculate the baseline FWF AEP.

After quantifying the AEP and the wake losses of the baseline FWF, I modeled the GWFL with the customized MS designs in FAST Farm. As verifying the AEP gain is the primary goal of this section, I modeled only 96 load cases in FAST Farm covering wind speeds between 8 m/s and 13 m/s with a wind speed bin of 1 m/s and 16 wind directions with an increment of 22.5° similar to the IEA wind rose presented in Figure 3.29. This range of wind speeds was chosen as this is the region where the AEP gain occurs, where at lower wind speeds, the AEP gain is small, and at higher wind speeds, there is no energy gain expected as all turbines operate at rated conditions.

Throughout this chapter, I used the curl wake model formulation of the DWM model implemented in FAST Farm. All the wake parameters were set to default in all load cases except for two parameters. The calibrated parameter for wake meandering ($C_{Meander}$) was set to 2.1, and the cut-off corner frequency (f_c) was set to 0.01 Hz. These parameters were tuned using the values from Carmo et al. (2024). The inflow wind field was created using the Mann turbulence box generator (Liew, 2022), with a turbulence intensity of 6%. The duration of the wind field is 3600 s, and only one seed for each wind speed and direction was used. The grid size of the wind field in x-y-z directions was set to 5 m to be smaller than the largest blade chord (Jonkman and Shaler, 2020). The high-resolution grid size for FAST Farm was equal to the resolution of the wind field. The high-resolution time step was set to 0.3 s, and the low-resolution time step was set to 3 s for all wind speeds and directions. The resolution of the low-resolution grid changed according to the wind speeds. The simulation time was set to 4200 s, and the first 600 s

were removed during post-processing to decrease the transient effects. For the baseline GWFL, the overall width of the high-resolution grid of each FOWT was set to $2D$. For the relocating GWFL with the customized MS designs, the width of the high-resolution grid was set to $3D$ to ensure that FOWTs remained inside the high-resolution grid. The wind and waves were always aligned. The significant wave height H_s was set to 2 m, and the wave period T_p was set to 6 s. The second-order wave loads were not considered in any load case in FAST Farm.

This chapter is organized as follows: First, I will show the increase in AEP due to relocating the FOWTs in the FWF. Afterward, I will compare the fatigue loads inside the farm to those on a standalone turbine presented in Chapter 5. However, I did not cover all wind speed ranges for the FWF as it is computationally expensive. The comparison will only look at the FOWT loads for wind speeds between 8 m/s and 13 m/s.

6.2 Energy gain and wake losses

I start by calculating the wake losses using the two tools, FLORIS and FAST Farm. The wake losses were calculated using equation 2.16. The AEP_{opt} values assuming zero wake losses between the two tools are unequal, as the AEP in FLORIS is higher than in FAST Farm. This is due to the difference between the two tools where the tilt of the rotor due to pitching and up-tilt angle are not considered in FLORIS but are considered in FAST Farm. The input power curve and thrust curve to FLORIS can be tuned and calibrated to ensure the power produced by a FOWT in FLORIS and FAST Farm is identical. Still, I decided not to calibrate the model as the pitch angle of the FOWT changes with the wind speed and also slightly with wind direction and mooring design so that I would have needed a different input file for each FOWT and wind direction. Since the difference between the AEP_{opt} is unrelated to the wake effects, I decided to use the AEP_{opt} of each tool for the wake losses. Therefore, the wake losses of FAST Farm are calculated using the AEP_{opt} from FAST Farm, and for FLORIS, similarly, the AEP_{opt} from FLORIS was used.

Using this method, the wake losses of both tools were almost equal as the FAST Farm losses were 14% and the FLORIS wake losses were 13.9%. The distribution of the losses for each wind direction is shown in Figure 6.2. The Figure shows that the distribution of the wake losses over the wind direction between the two tools is almost identical, with the highest wake losses for wind direction from west to east as expected.

From the FAST Farm results, wake losses of the baseline FWF and the FWF with the customized MS designs for wind speeds between 8 m/s and 13 m/s are introduced in Table 6.1. The results show that for these wind speeds, relocating the FOWTs decreases the wake losses of the baseline layout from 11.8% to 10.5%, which means that the losses decreased by a factor of 11%. The

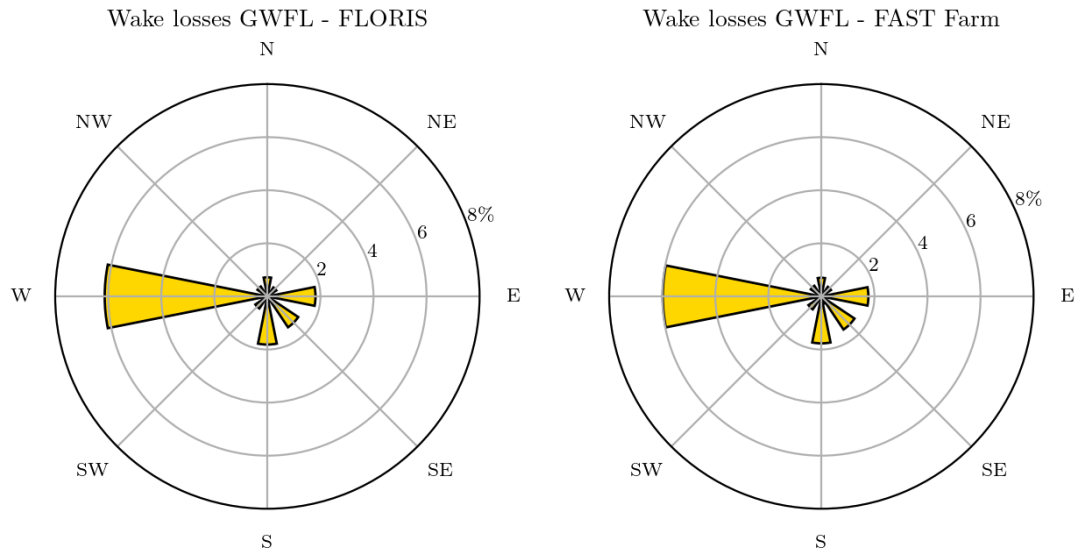


Figure 6.2: Wake losses of the GWFL coupled to the BMS in FLORIS and FAST Farm

wake losses are 11.8% between wind speeds of 8 m/s and 13 m/s; hence, for wind speeds below 8 m/s, the wake losses are 2.2%. However, since the loaded cases for the baseline FWF have the full range of speeds, the reference AEP of the baseline considers the entire wind rose. Therefore, these percentage wake loss values and all the percentage values presented in this section will not be affected if more wind speeds are accounted for.

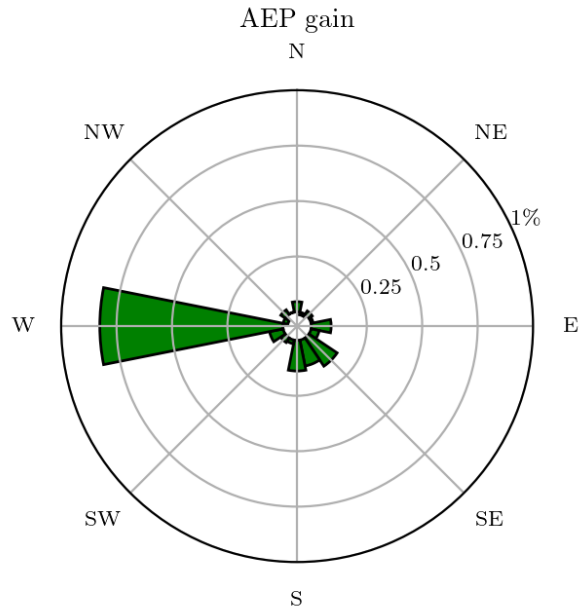


Figure 6.3: AEP gain from FAST Farm for wind speeds between 8 m/s and 13 m/s

Table 6.1: FAST Farm wake losses of the GWFL with the BMS and the customized MS design for wind speeds between 8 m/s and 13 m/s

	GWFL with BMS	GWFL with customized MS
W_{loss}	-11.8%	-10.5%

The AEP gain from relocating the FOWTs in the FWF is 1.5% for wind speeds between 8 m/s to 13 m/s. The AEP gain distribution over each wind direction is shown in Figure 6.3. This 1.5% AEP is less than the 3.6% AEP gain predicted by the steady-state results and presented in Table 4.4. This is mainly because of two reasons. First, the AEP gain in FLORIS presents the AEP gain for all wind speeds, which means wind speeds below 8 m/s are included, which is not the case for the FAST Farm results. Including wind speeds below 8, m/s will slightly increase the gain in AEP calculated in FAST Farm, which is not the main reason for the difference between the models.

The second reason that can cause the difference is the lack of a feedback loop between FLORIS and MoorPy in the current method presented in Chapter 3. In the steady model, if the inflow is 10 m/s, all the FOWTs in the FWF are assumed to displace by the displacement value at 10 m/s. However, a FOWT in the wake sees a lower wind speed due to the velocity deficit, displacing less. The effect of the velocity deficit on the magnitude of the FOWT's displacement is adequately captured in FAST Farm. The smaller displacements in FAST Farm due to the impact of the velocity deficit can be the reason for the lower AEP gain. I added a feedback loop between FLORIS and MoorPy to capture this effect while calculating the AEP in FLORIS. The position of a FOWT was determined by the average wind speed of the rotor calculated by FLORIS. When the impact of velocity deficit is included, the AEP gain calculated in FLORIS decreased to 3.2% AEP gain. The feedback loop between FLORIS and MoorPy was only used to calculate the AEP; it is not used while choosing the MS design as it will increase the computational costs exponentially. All the AEP results shown from now on will consider the coupling between FLORIS and MoorPy, including the feedback loop.

Table 6.2: AEP gain in FLORIS without feedback loop with MoorPy and with a feedback loop and the AEP gain in FAST Farm

	FLORIS no feedback loop	FLORIS with feedback	FAST Farm
AEP gain	3.6%	3.2%	1.5%

Despite including the effect of the velocity deficit on the FOWT motions, the difference between the AEP gain between FLORIS and FAST Farm for the relocating FWF is still high. The AEP gain values are summarized in Table 6.2. The positions of the relocating FOWTs inside the FWF when using FLORIS-MoorPy coupling and using FAST Farm are shown in Figure 6.4 for wind direction of 0° and mean wind speed at hub height equal to 10 m/s. The Figure

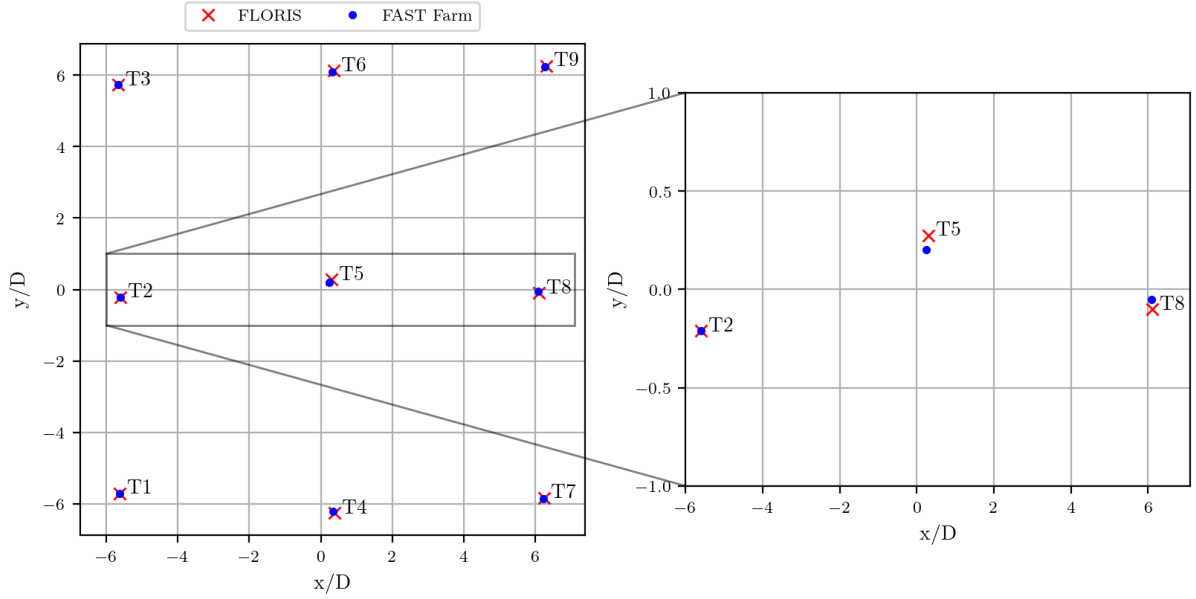


Figure 6.4: Position of the FOWTs inside the FWF when coupled to the customized MS designs. The Figure shows a wind direction of 0° and an average wind speed of 10 m/s at hub height

shows that the most significant difference between the FOWTs positions in FLORIS and FAST Farm is for the second row of turbines inside the FWF (i.e., turbines 2, 5, and 8). The largest difference is for the position of Turbine 5 in the two tools, which is 17 m. The Figure also shows that the upwind FOWT positions match perfectly between the two tools, as they do not suffer from velocity deficit and are loaded by the same wind speed. The difference in position of the FOWTs between FAST Farm and FLORIS indicates that the rotor average wind speed is different between the two tools, causing different displacements. Different rotor average wind speeds between the tools lead to different power production, hence the difference in AEP gain. To understand how this difference in the position of downwind turbines is connected to the difference in the wake models, I compared the horizontal and vertical velocity deficits calculated by the two tools.

Figure 6.5 shows the downwind velocity deficit behind each of the three turbines in the second row at hub height. The wind flow field at the rotor height was saved every 9 s in FAST Farm. The snapshots for the wind flow field covering the last 3600 s are used to calculate the average velocity deficit behind each FOWT. The velocity deficit is shown in three locations downwind at $4D$, $5D$, and $5.5D$ to see how the far-wake evolves and the wake recovery in each tool. The downwind wake of Turbine 2 at $5.5D$ is around 100 m in front of Turbine 5 and represents the inflow field at the rotor hub plane; similarly, the wake of Turbine 5 is the input flow field of Turbine 8. ΔU is the difference between the wind speed at the rotor at hub height and the ambient wind speed at the hub height $U_{amb,h}$. The result shows the velocity deficit of the two models when the GWFL is coupled to the BMS and when coupled to the customized MS design.

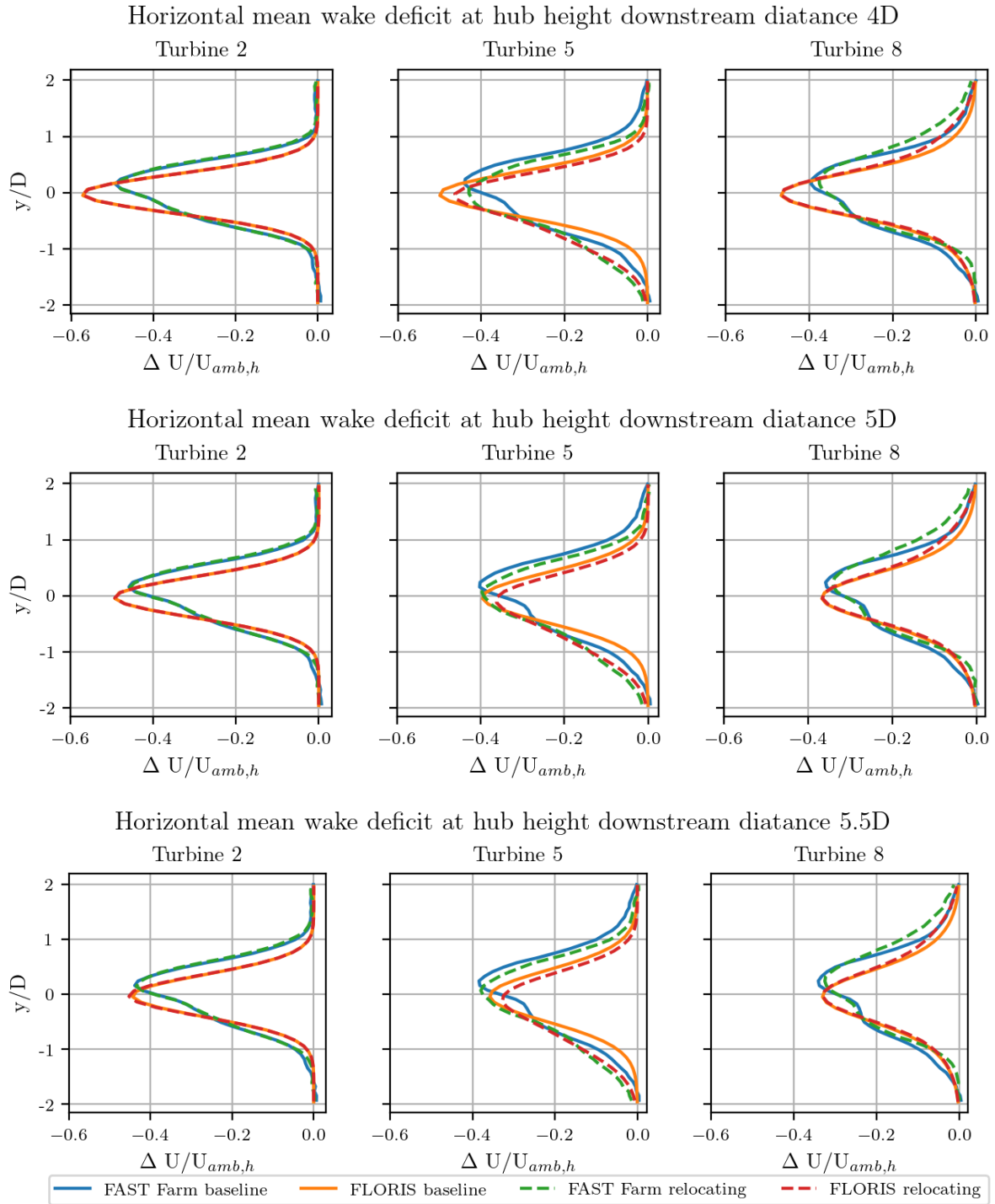


Figure 6.5: Horizontal velocity deficit at three downwind locations in FLORIS and FAST Farm

The Figure shows the following differences between the two wake models:

- The wake in FLORIS is symmetric around the rotor center, while in FAST Farm, the

velocity deficit is higher on one side (+ve side) of the rotor than the other (-ve side). The asymmetry increases as the wake evolves downwind.

- The velocity deficit distribution in FLORIS is always Gaussian, while in FAST Farm, the shape is skewed as it is affected by the movement of the yawing and pitching of the FOWT. The MS design affects the wake skew in FAST Farm as a different MS causes a different mean yaw value.
- The wake expands more in FAST Farm compared to FLORIS. This means that for a relocating FOWT, the required displacement to have the same rotor average wind speed is lower in FLORIS than in FAST Farm.
- FLORIS predicts a higher velocity deficit at the wake center at a downwind distance of $4D$. However, the wake recovery in FLORIS between $4D$ and $5.5D$ downwind is faster than in FAST Farm, so the deficit in FLORIS is lower at $5.5D$ downwind.
- The tails of the Gaussian distribution between the relocating FWF layout and the baseline layout are different for both FLORIS and FAST Farm. As the downwind turbine relocates, it is no longer in the wake's center; hence, the velocity deficit is slower on one side than another.

These observations mean that relocating the FOWT to the left or right side of the wake is different in FAST Farm due to the asymmetry of the velocity deficit. This effect is not considered in the method shown in Chapter 3 as FLORIS cannot capture it. This is why Turbine 5 relocation is much less beneficial in FAST Farm than in FLORIS, as it relocates to the less favorable side of the wake. Hence, the rotor average wind speed and energy gain due to relocation is lower. In both tools, Turbine 5 is partially in the wake of Turbine 2, but the percentage of the rotor out of the wake is higher in FLORIS compared to FAST Farm. This is because the wake asymmetry can only be captured using a dynamic wake model that captures the rotor's motions and not a steady-state static model. I have checked if this asymmetry exists in all three FWF rows, and all FWF rows have the same asymmetry.

Figure 6.6 shows the rotor average wind speeds of the GWFL. The results confirm the effect of the asymmetry on the rotor average wind speed. Turbine 4, which moves on the favorable side of the wake where the deficit is lower, has higher gains than Turbines 5 and 6, which have lower gains due to relocating. Therefore, the asymmetry of the wake and the difference in the wake expansion in FLORIS and FAST Farm are the two main differences leading to the significant difference between the energy gain results in the relocating FWF.

In Figure 6.7, the vertical velocity deficits for the three turbines of the second row are plotted at downwind distances of $4D$, $5D$, and $5.5D$ for the GWFL coupled to the BMS and the customized MS in FAST Farm and FLORIS. The vertical plane at the wind flow passing through Turbine 2

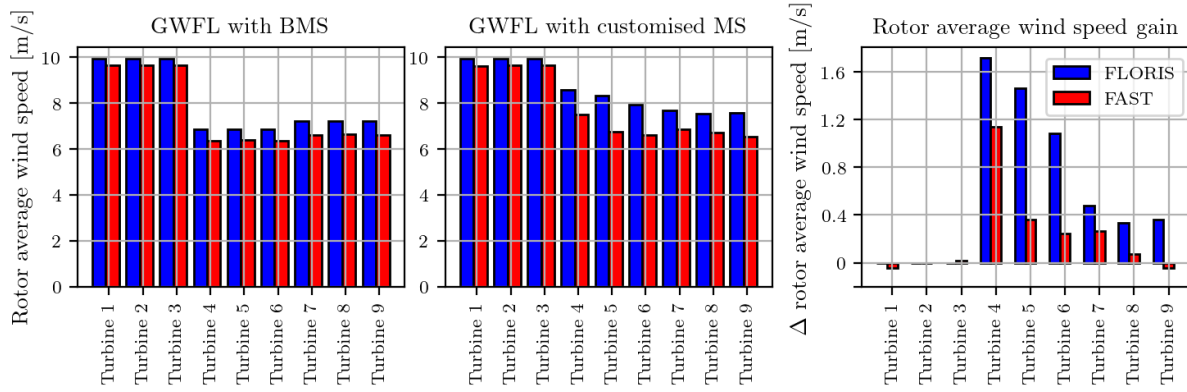


Figure 6.6: The rotor average wind speeds in FAST Farm and FLORIS for the GWFL coupled to the BMS and the customized MS for wind direction of 0° , and an inflow wind speed of 10 m/s. The change in the rotor average wind speed due to relocating the FOWTs is shown on the right side

is saved every 9 s of the simulations. The snapshots of the vertical wind field are used to calculate the average velocity deficit behind the FOWTs in the vertical plane. The wind speed at hub height is 10 m/s, and the wind direction is 0° . For all the plots, the vertical plane cuts exactly at the center of the rotor, except for the FAST Farm results when coupled to the customized MS designs. Due to the large displacements, the vertical planes do not follow the turbine and are at the initial positions of the FOWTs. Therefore, a comparison between the FAST Farm baseline and relocating layouts is impossible based on the Figure. The main observations from Figure 6.7 are:

- The largest velocity deficit for FLORIS is always at the hub height. This is not the case in FAST Farm, where the velocity deficit is largest at a higher altitude than the hub height. This is due to the vertical wake deflection, included in FAST Farm but not in FLORIS. As the FOWT pitches, the wake is shifted upwards, and since the platform pitching is not included in FLORIS, the vertical wake deflection is not accounted for.
- The wake recovery of the FLORIS model, especially for altitudes higher than the hub, is much faster than FAST Farm. The upper half of the rotor in FAST Farm suffers from higher velocity deficits. Therefore, the value of the velocity deficit between the two models at hub height is close, and the difference is significantly large for the upper half of the rotor.
- The wake recovery in FLORIS between $4D$ and $5.5D$ downwind is faster than in FAST Farm, so the deficit in FLORIS is lower at $5.5D$ downwind except behind the first turbine.

Figure 6.8 is a top view visualization for the wind flow field at hub height at wind speeds of 10 m/s and 12 m/s. The left side of the Figure is the GWFL coupled to the BMS, while the

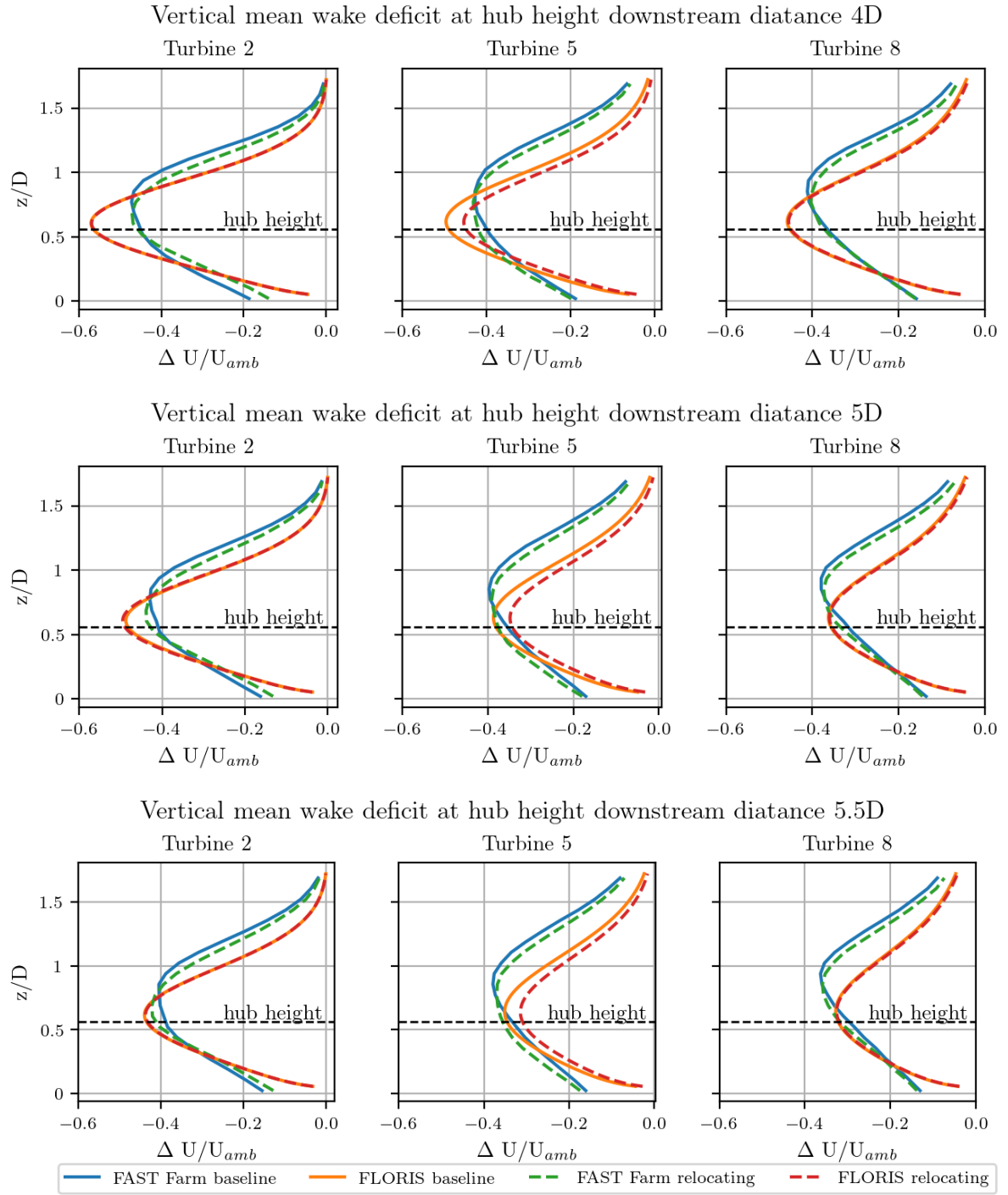


Figure 6.7: Vertical velocity deficit at three downwind locations in FLORIS and FAST Farm

right side is the relocating FWF layout design. The Figure shows how relocating the FOWTs decreases the wake losses within the FWF. The effect is clearer at a wind speed of 12 m/s, where the wake effects cause a high-velocity deficit of all the downwind FOWTs in the baseline design.

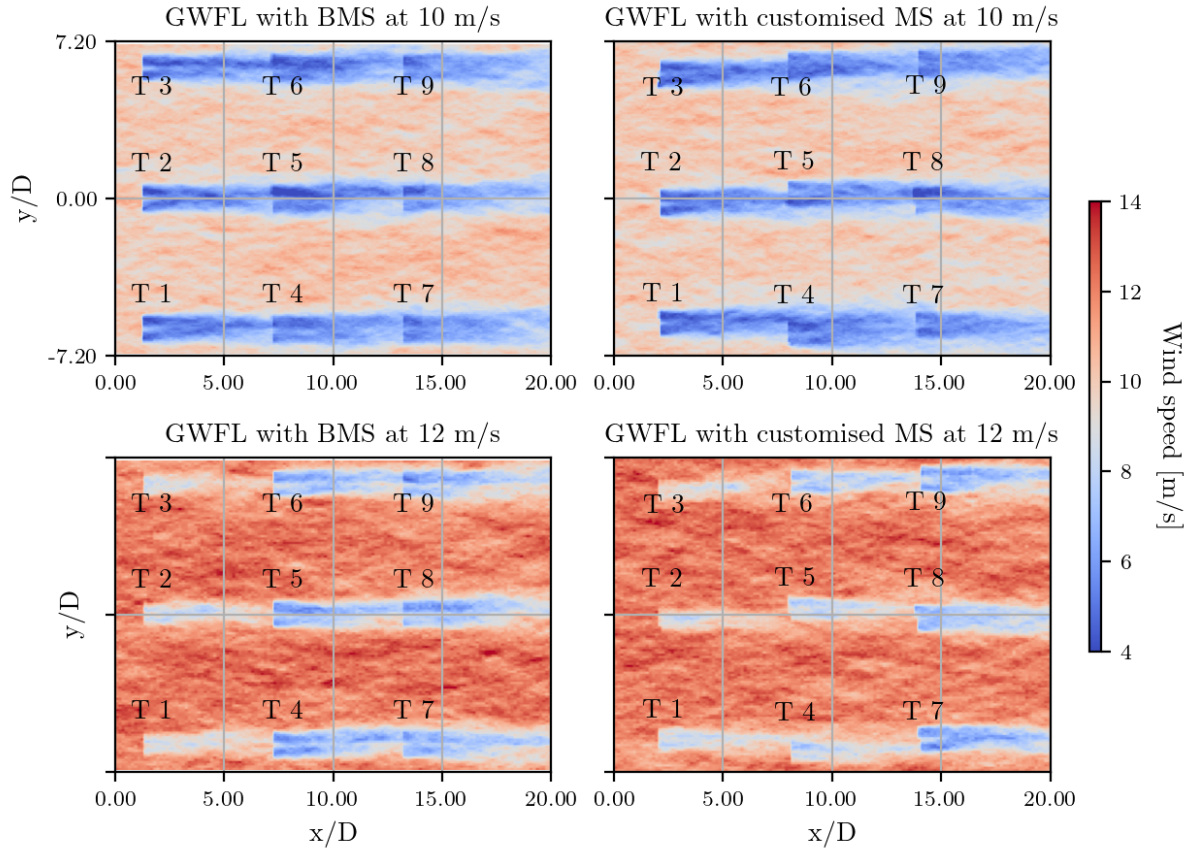


Figure 6.8: Visualization of the wind flow at hub height inside the GWFL with the BMS on the left and the customised MS on the right, for inflow wind speeds of 10 m/s and 12 m/s

The velocity deficit is lower when the FOWTs relocate out of the wake, decreasing wake losses.

Figure 6.9 shows the power production of the turbines behind each other in the GWFL at all wind speeds between 8 m/s and 13 m/s. Each subplot represents one row inside the GWFL when coupled to the BMS. Figure 6.10 shows the same results for the relocating GWFL when coupled to the customised MS design. In the baseline FWF for all three rows, the third turbine produces more power than the second for inflow wind speeds lower than 11 m/s. Starting an inflow wind speed of 11 m/s, the power produced by the third turbine becomes lower than that of the second. For a relocating FWF, the second turbine produces higher power than the third for wind speeds below 11 m/s and vice versa because the relocation leads to the second turbine seeing a larger wind speed. The exception is at 8 m/s, where Turbines 8 and 9 produce more power because, at 8 m/s, there is no power gain for Turbines 5 and 6. The energy distribution inside the flow differs as the turbines are no longer in the center of the wake, and the wake is not yet saturated. The effect of the relocation on the turbulence saturation is discussed in Chapter 7 as a larger number of wind turbines in each row is required.

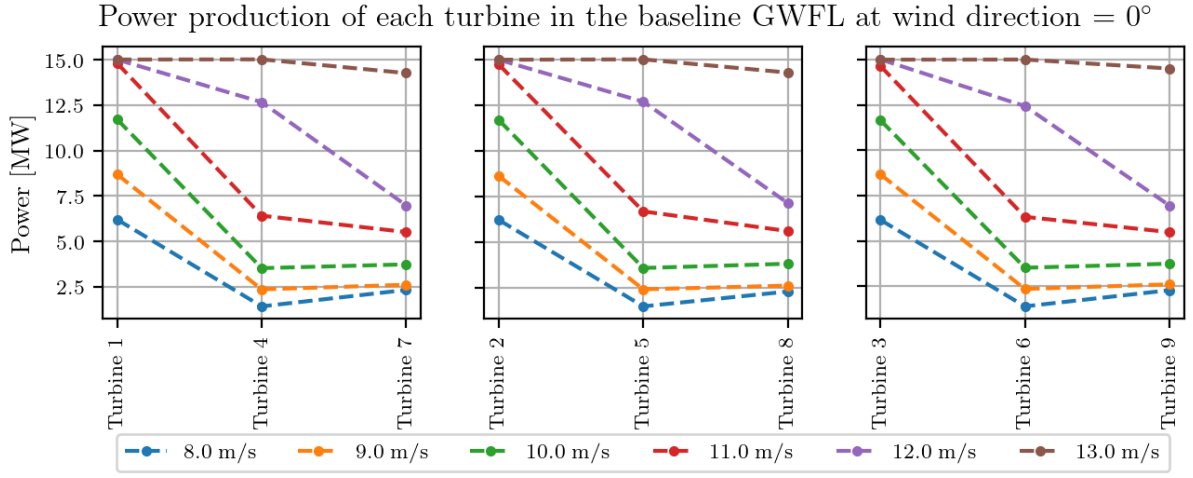


Figure 6.9: The power produced by each turbine in the GWFL when coupled to the BMS for wind speeds between 8 m/s and 13 m/s

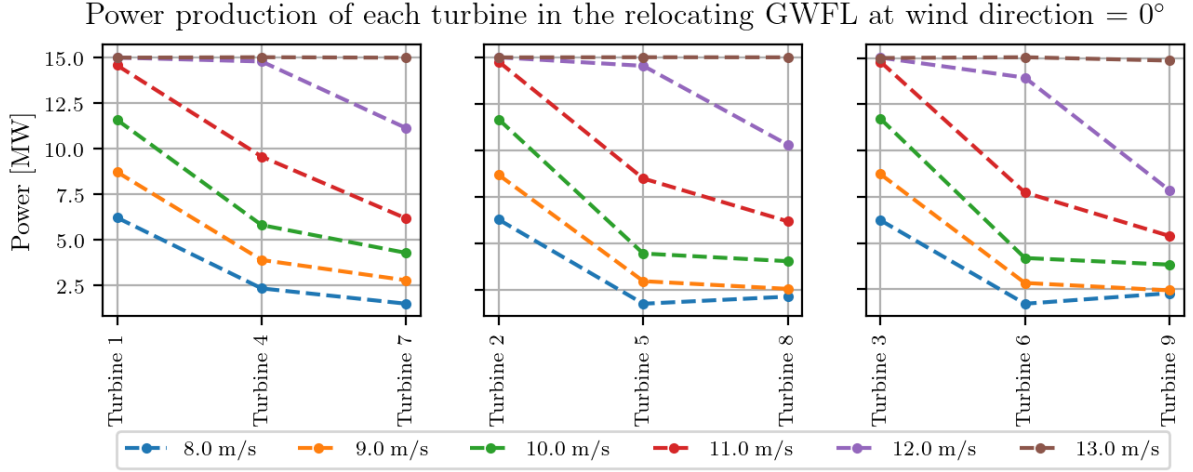


Figure 6.10: The power produced by each turbine in the GWFL when coupled to the customized MS for wind speeds between 8 m/s and 13 m/s

When comparing Figure 6.9 to Figure 6.10, it is clear that the first downwind turbine relocates out of the wake, and the increase in power due to the relocation is visible for all wind speeds. For the third turbine in the three rows, the increase in power becomes visible as the wind speed gets to the rated speed. This is because of the higher velocity deficit the turbines deeper in the relocating FWF suffer from. As the first turbine downwind relocates, the increase in the wake width and the energy distribution inside the wind field and the relocation of the second downwind turbine is negatively affected. As the velocity deficit increases, the thrust force acting on the FOWT's rotor decreases. Hence, the crosswind displacement is lower.

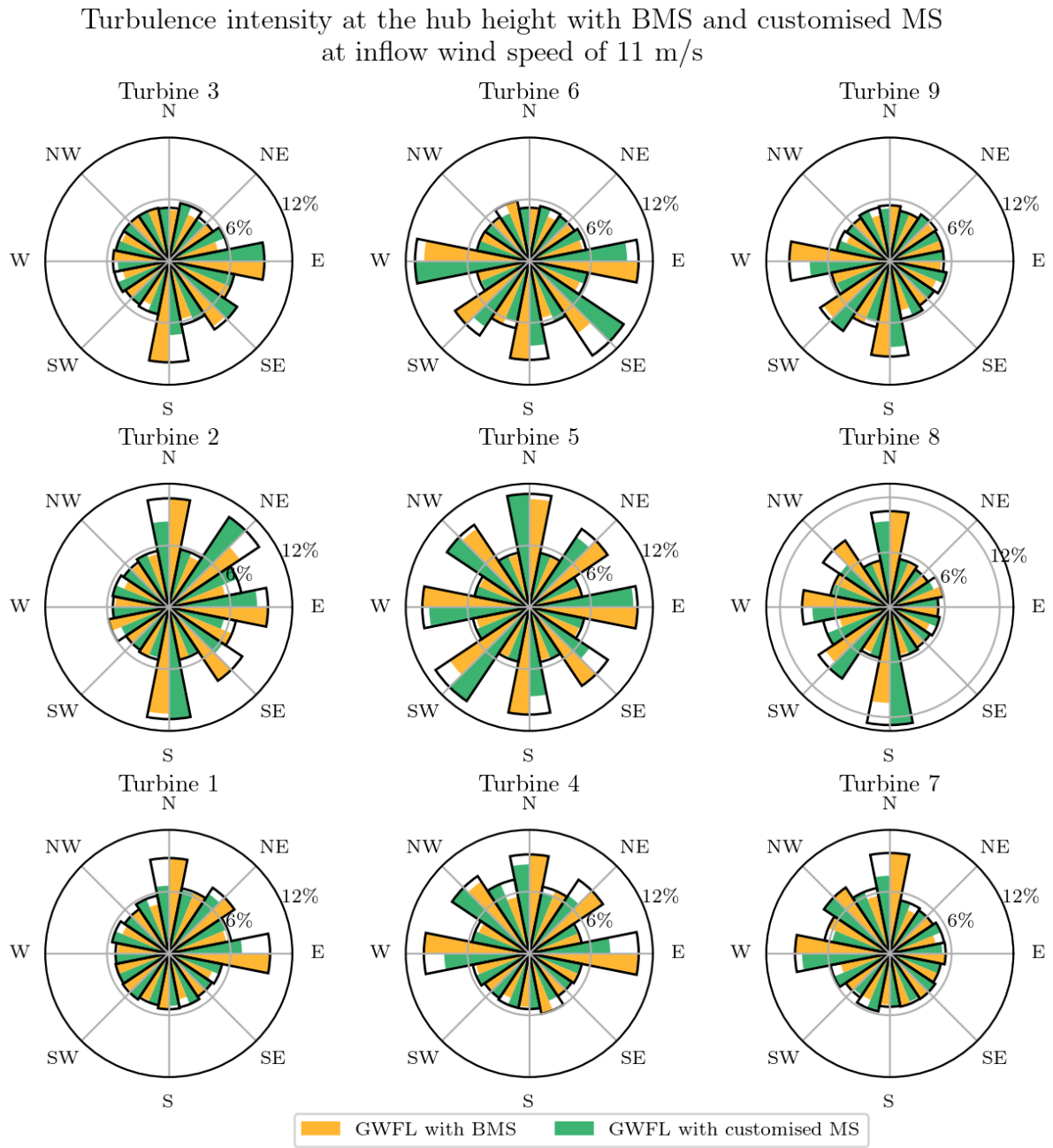


Figure 6.11: Turbulence intensity at the hub height of each turbine in the GWFL with the BMS and the customized MS designs at inflow wind speed of 11 m/s

6.3 Loads inside the FWF

6.3.1 Turbulence intensity and wind speed deficit

Before checking the loads inside the FWF, I will show how the turbulence intensity and the wind speed vary inside the farm as the wind direction changes. The wake leads to an increase in the turbulence of the wind field and a decrease in its speed. The change in the turbulence intensity and the rotor wind speeds are why the loads differ between a standalone FOWT and an FOWT inside the FWF. Figure 6.11 is the turbulence intensity at one point at the hub center of each turbine at an inflow wind speed of 11 m/s. Therefore, it is not the rotor's effective turbulence but rather an indication of the turbulence intensity inside the FWF. The value of turbulence intensity is shown for each wind direction for the GWFL with the BMS (in orange) and the GWFL with the customized MS (in green). For some wind directions, the turbulence intensity decreases by relocating the FOWTs, while for other wind directions, the turbulence intensity increases by relocating the FOWTs. Since this is only a single-point measurement at the hub center and not the rotor effective turbulence intensity, it is hard to conclude how the turbulence intensity changes between the two layout designs. The turbulence intensity is higher for the second turbine in the row than the third turbine, as it decreases until it saturates.

Figure 6.12 shows the rotor average wind speed for each wind turbine within the farm at an inflow wind speed of 11 m/s. Similar to Figure 6.11, the rotor average wind speed of the baseline and the relocating GWFL are shown for each wind direction. The increase in the average wind speed of the rotor is evident for wind turbines 4, 5, and 6, which are wind directions from west to east. For wind direction from south to north, the increase in the average wind speed of the rotor is visible for turbines 2 and 5. These differences in the rotor average wind speed lead to a rise in the turbines' power and, hence, the AEP gain.

It is clear from Figures 6.11 and 6.12 that the increase in the turbulence intensity always accompanies the highest velocity deficit (lowest wind speed). This is expected as the deficit indicates that the turbine is in the wake and hence suffers from higher turbulence intensity. In the following subsections, I will show how this affects the loads on the FOWTs for wind speeds ranging between 8 m/s and 13 m/s.

6.3.2 Fatigue damage of the mooring lines inside the farm

Figure 6.13 presents the mooring lines fatigue damage for the BMS design and the customized MS designs inside the GWFL. The fatigue damage is only for wind speeds between 8 m/s and 13 m/s. The Figure also shows the fatigue damage for a standalone (single FOWT).

The BMS design shows similar fatigue damage values for the single FOWT and the FWF results. This is because the MS fatigue damage is affected by both the turbulence and wind speed values, where higher turbulence and a higher wind speed will increase the fatigue damage. Although the turbulence intensity increases due to the wake effects in the farm, the wind speed acting on the FOWTs decreases. Hence, they balance out, keeping the value of the fatigue damage within the

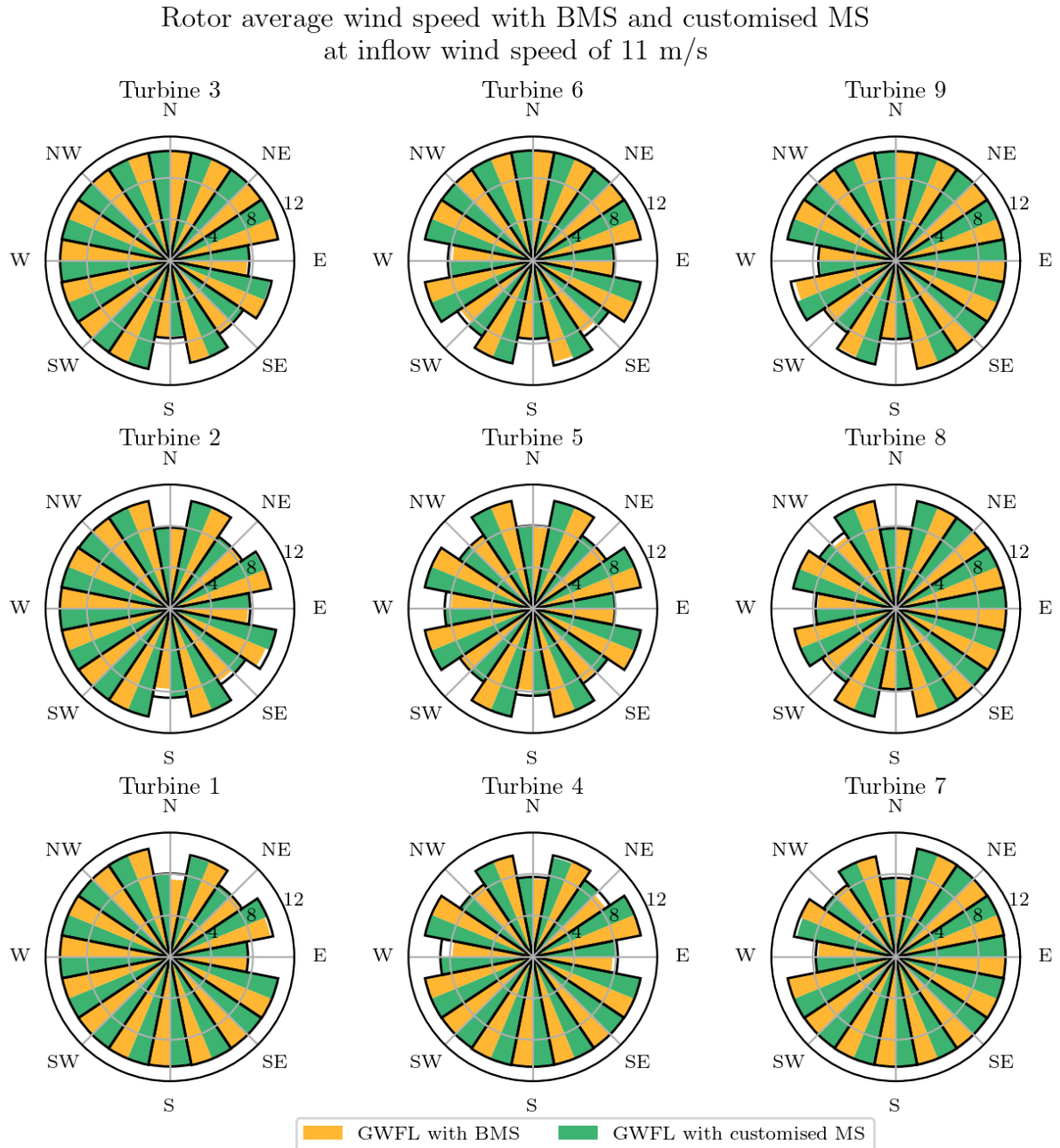


Figure 6.12: Rotor average wind speed of each turbine in the GWFL with the BMS and the customized MS designs at an inflow wind speed of 11 m/s

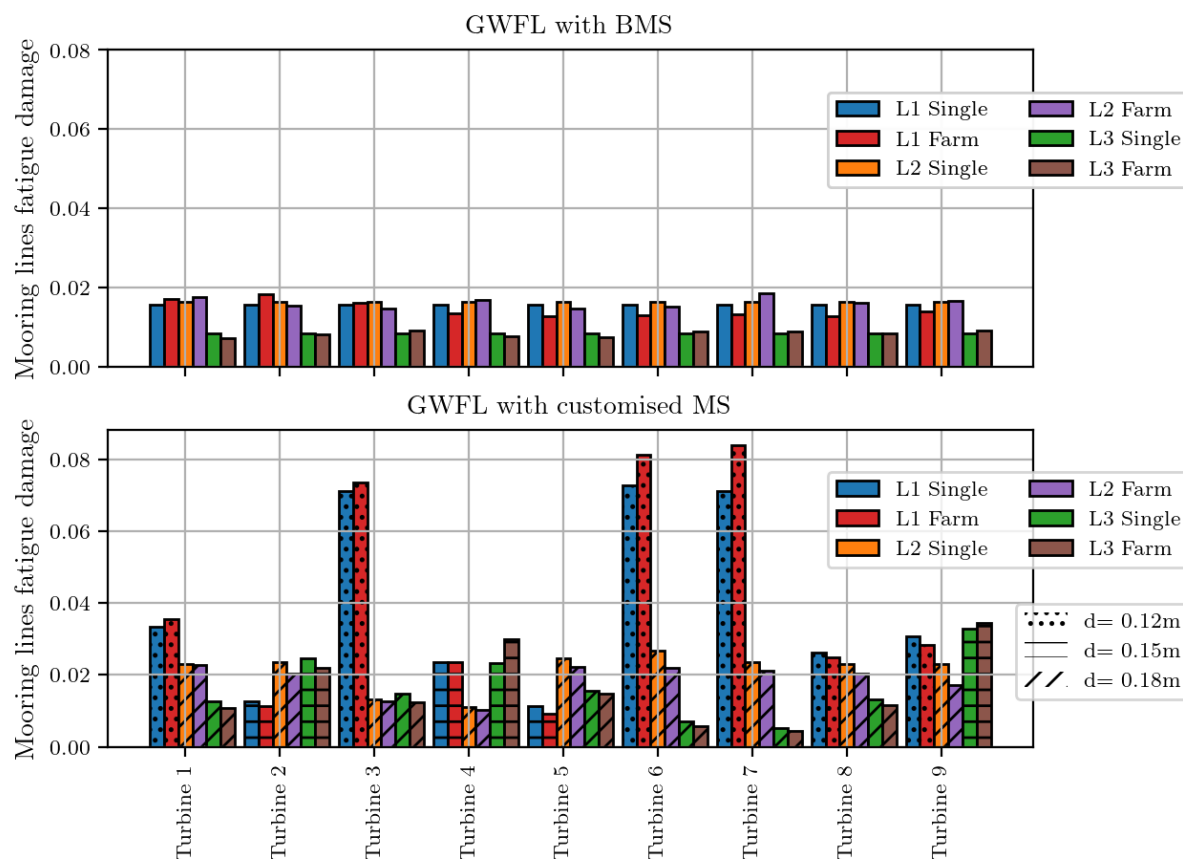


Figure 6.13: Mooring lines fatigue damage for wind speeds between 8 m/s and 13 m/s

same range. The same effect of the tradeoff between the increase in turbulence and the decrease in rotor average wind speed is shown for the customized MS design. The fatigue damage of all mooring lines remains within the same range for both the FAST Farm and the single FOWT case. The highest increase in fatigue damage is visible for the mooring lines with the smallest diameter of 0.12 m (Turbines 6 and 7). For the rest of the design, some mooring lines suffer more damage in the farm case, and others suffer more fatigue damage in the standalone case. The DEL distributions of the BMS and that of Turbine 7 for the customized FWF layout are discussed in the following paragraphs.

Figure 6.14 shows the DEL of the mooring lines of the BMS design for Turbine 5 in the baseline layout at wind speed 11 m/s. The effect of the wake is apparent as the DEL decreases when a turbine is in the wake due to the velocity deficit. It is clear for the DELs of line 2 of the BMS that the highest value is no longer when the line is upwind. The results of this Figure do not mean that the fatigue damage is always lower inside the FWF than a single FOWT; it just shows that the wind speeds are shifted for a turbine in the wake as the inflow wind speed differs from the effective wind speed at the rotor. Although the probability of occurrence used in the

fatigue damage calculation is that of a wind speed of 11 m/s, the effective wind speed velocity at the rotor is lower. The effect of the fatigue damage will change from one site to another according to the wind rose probability distribution. I have shown in Chapter 5 (Figure 5.10) that the greatest fatigue damage happens when the rotor's effective wind speed is around the rated wind speed of 11 m/s. If, due to wake effects, the load case causing the greatest fatigue damage is shifted to more probable inflow conditions, this will lead to greater fatigue damage; if the load case causing the greatest fatigue damage is shifted to less probable inflow conditions, it will lead to lower fatigue damage.

Figures 6.15, and 6.16 show the DEL of the MS design coupled to Turbine 7 as a standalone FOWT and inside the FWF at an inflow wind speed of 12 m/s. After the FOWT relocates at wind direction 0° , the rotor average wind speed of the turbine is 9.5 m/s, so the turbine

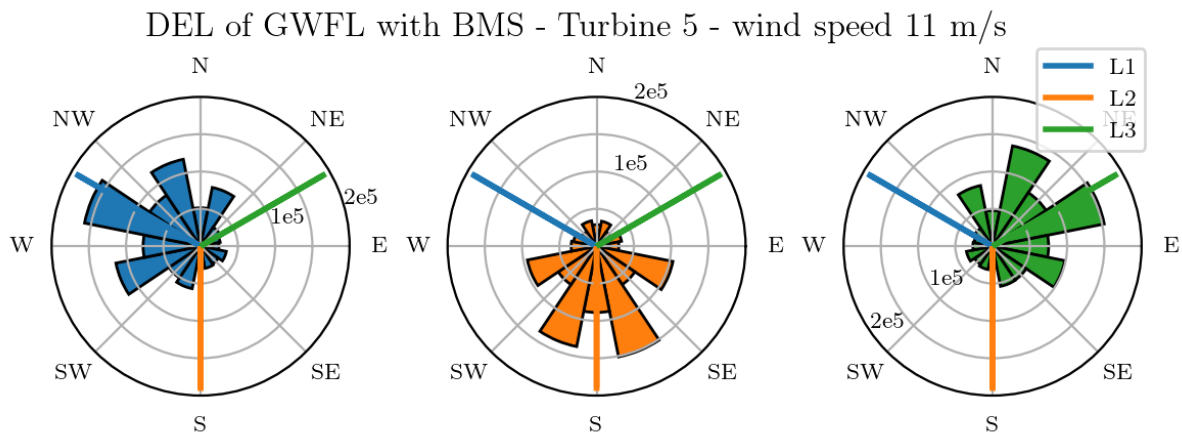


Figure 6.14: DELs of the BMS design for Turbine 5 inside the GWFL at an inflow wind speed of 11 m/s

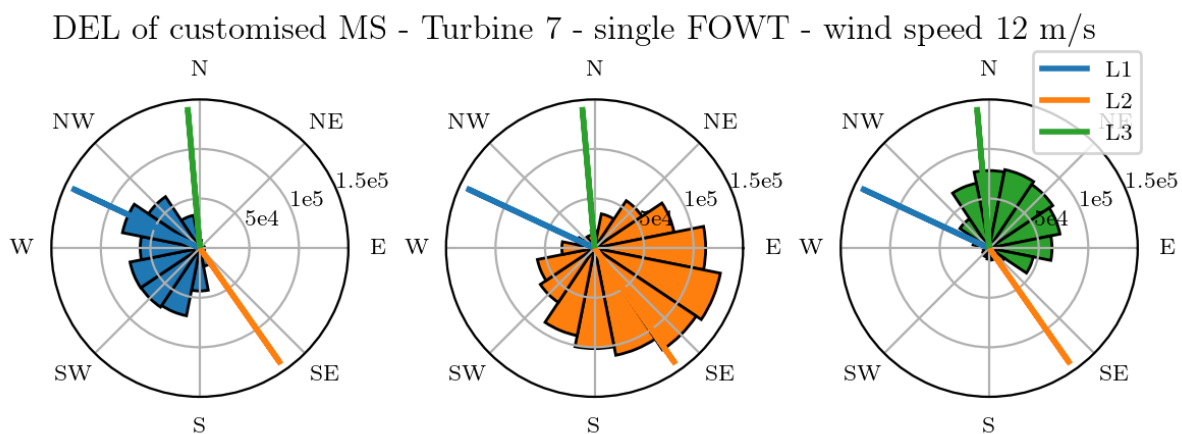


Figure 6.15: DELs of the customized MS design for Turbine 7 as standalone at an inflow wind speed of 12 m/s

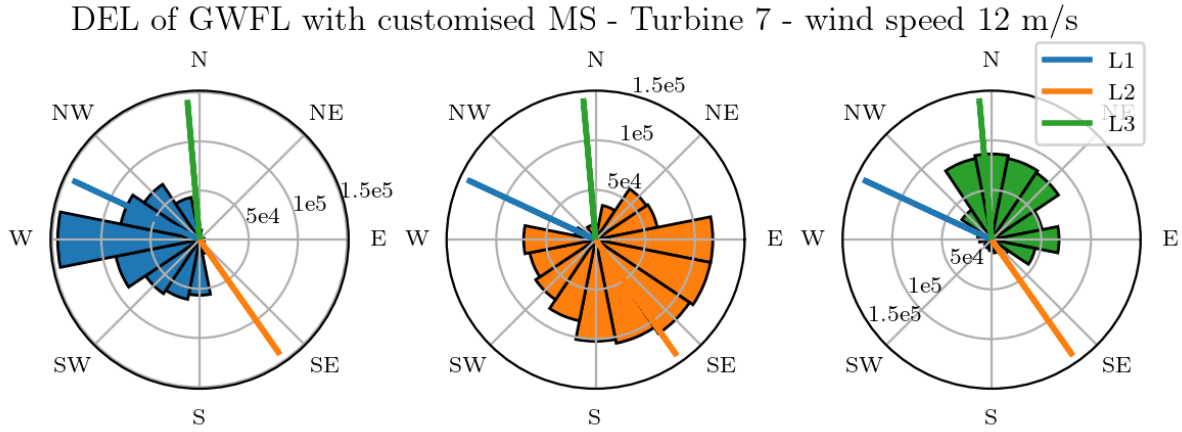


Figure 6.16: DELs of the customized MS design for Turbine 7 inside the GWFL at an inflow wind speed of 12 m/s

is partially in the wake, with high turbulence. This can be verified by checking the power production of Turbine 7 from Figure 6.10. The increase in turbulence and wind speed due to relocation led to an increase in fatigue damage. Since this increase happens at the most probable wind direction, the effect on the fatigue damage is significant, as shown in Figure 6.16. The DEL of Turbine 7 at wind direction west to east doubles compared to the single FOWT. This is mainly the effect of turbulence. This is the same effect that happens for Turbine 6. This again shows that the impact of the turbulence on the mooring lines fatigue damage will differ from one wind farm to another according to the wind farm layout and the wind rose distribution.

Figure 6.17 shows the maximum mooring line tension in operation conditions for all wind directions for wind speeds between 8 m/s and 13 m/s for both the baseline and the relocating FWF compared to the standalone FOWTs. The Figure shows a slight increase in maximum tension for the FOWTs when the entire FWF is considered. However, the increase is untrue for all FOWTs and can be considered negligible.

6.3.3 Fatigue damage of the FOWT's tower inside the farm

The tower base fatigue damage for wind speeds between 8 m/s and 13 m/s is presented in Figure 6.18. The Figure shows the results of the tower fatigue damage for the BMS design and the customized MS design as standalone and inside the FWF. For both the BMS design and the customized MS design, the fatigue damage of the tower base inside the FWF is much greater than the fatigue of the FOWT when standalone. This means that the tower base fatigue damage is sensitive to the turbulence intensity for all wind speeds. The increased turbulence due to wakes affected the tower fatigue even at low wind speeds. This is different from the mooring

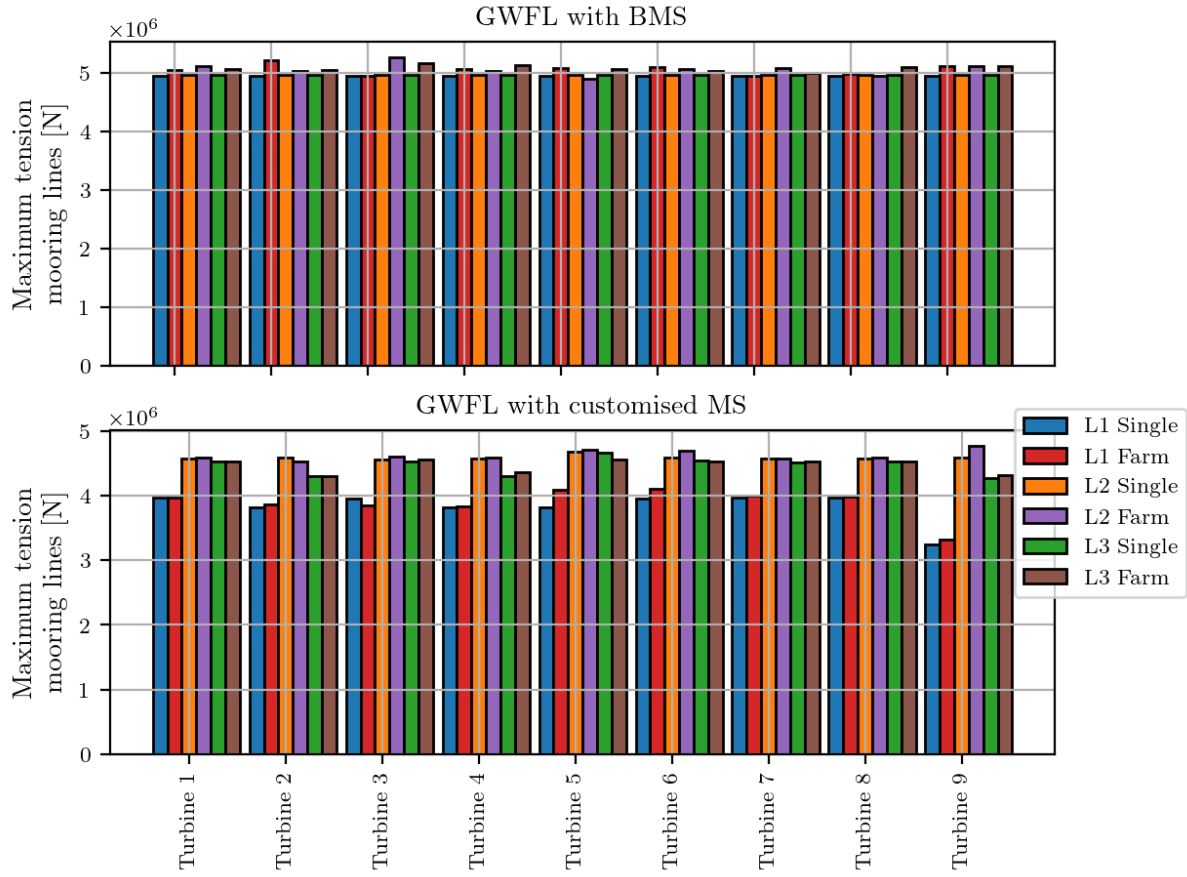


Figure 6.17: Maximum mooring lines tension for the BMS and the customized MS designs for a single FOWT and FOWTs in a FWF

lines, where the increase in turbulence at low wind speeds did not significantly increase fatigue damage.

For the BMS design, the fatigue damage is approximately three times higher for the FOWTs inside the FWF than for a single FOWT. For the customized MS design, the fatigue damage is approximately four times higher for the FOWTs inside the FWF than for a single FOWT. Therefore, tower fatigue damage is always greater when the FOWT is coupled to customized MS designs. This differs from the results of the standalone FOWTs in Figure 5.16, where the 25-year fatigue damage of the customized MS designs was always lower than the BMS design. The increase in tower base fatigue damage of the customized MS design compared to the BMS is because the customized MS design allows the FOWTs to relocate partially out of the wake, which means that the rotor wind speed for the customized MS design is higher. Hence, the damage also increases. This is clear in the results of Turbine 4 at wind speed 8 m/s or 12 m/s, where the tower fatigue damage is higher for the customized MS design. The results of Figure 6.10 show that the power of Turbine 4 at any wind speed starting at 8 m/s increased, which

indicates that the rotor average wind speed increased due to the FOWT's relocation.

The maximum axial stress load at the tower base for wind speeds between 8 m/s and 13 m/s is presented in Figure 6.19. The difference between the single FOWTs and the FOWTs in the FWF is negligible for both the BMS and the customized MS designs. Hence, the maximum loads acting on the FOWT in operation conditions can be checked without simulating the entire FWF. Wake effects do not affect the maximum loads acting on the FOWTs' tower base.

6.3.4 Fatigue damage of the rotor blades inside the farm

The differences between the lifetime DELs ($\Delta DEL_{lifetime}$) of the blade root fatigue loads of the standalone FOWT and the FOWTs inside the FWF are shown in Figure 6.20. The results show that the blade fatigue loads are less for all FOWTs in the FWF when coupled to the BMS design. When coupled to the BMS design, the decrease is less than 1% for all turbines; the highest decrease is at Turbine 6.

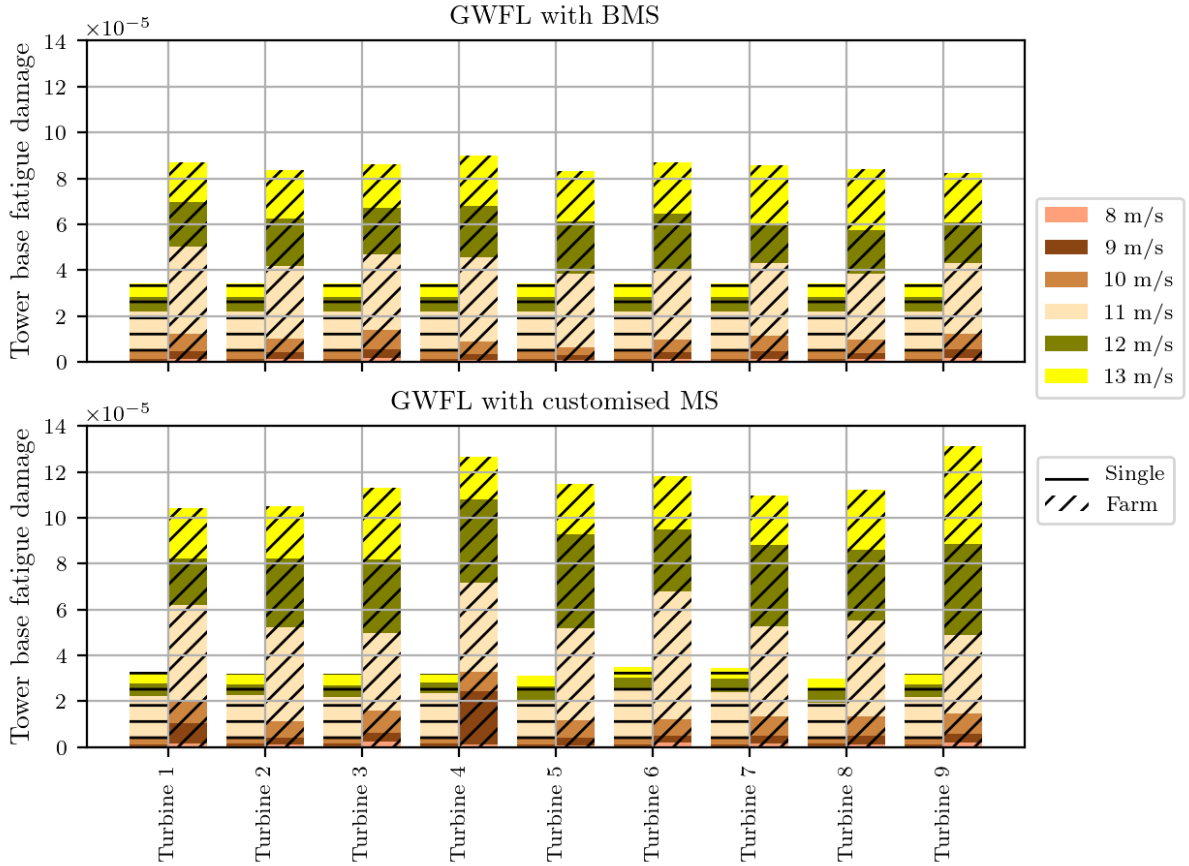


Figure 6.18: Tower base fatigue damage from wind speeds between 8 m/s and 11 m/s for the BMS design and the customized MS design when coupled to a single FOWT and inside the FWF

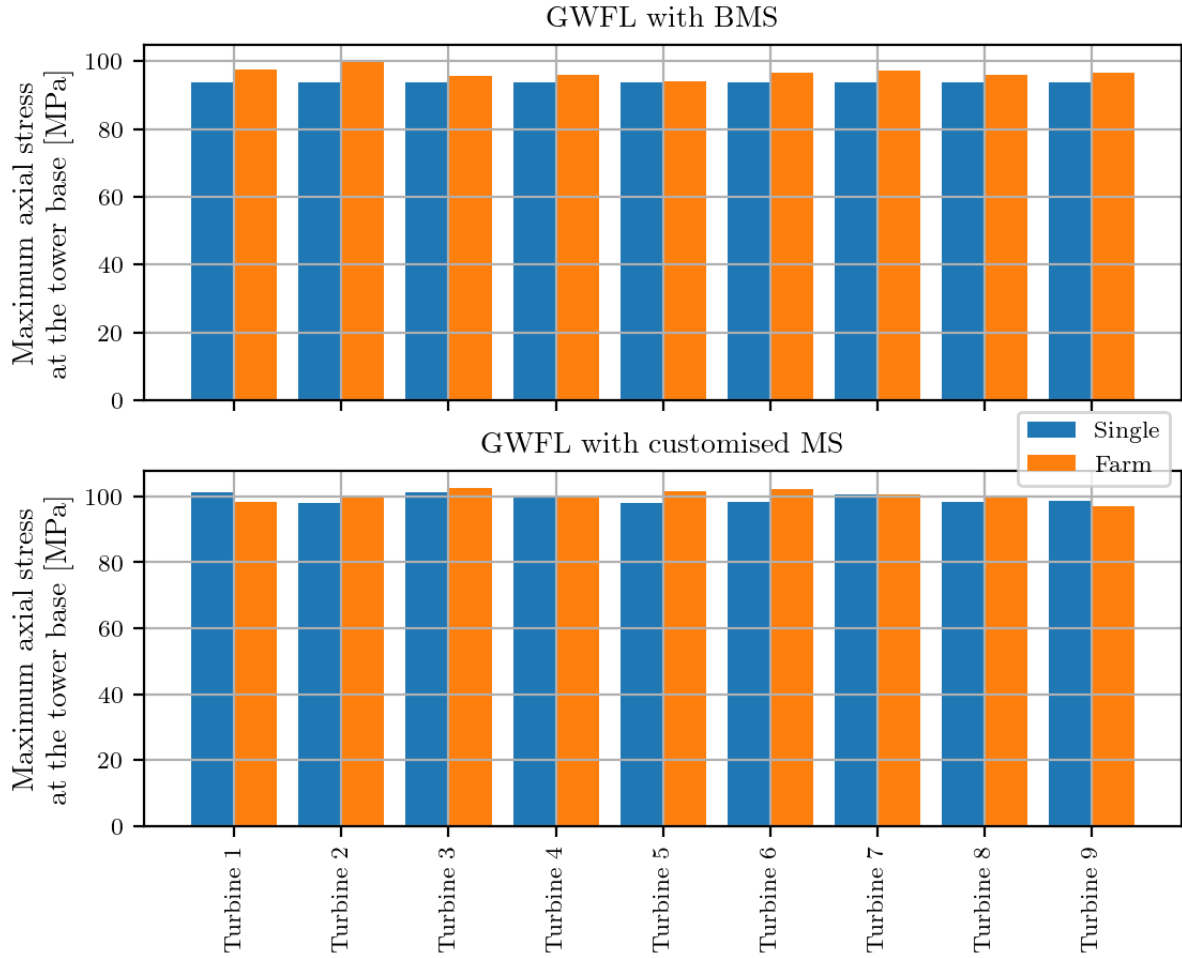


Figure 6.19: Maximum axial stress at the tower base for the BMS and the customized MS designs for a single FOWT and FOWTs in an FWF

When coupled to the customized MS design, the blade lifetime DEL decreases for all turbines in the FWF compared to the standalone turbines except for Turbine 4. Turbine 4 is the turbine with the largest relocation and the largest power gain due to the relocation. It, therefore, sees higher rotor wind speeds and higher turbulence intensity, leading to the increase of the fatigue loads of the blades. Turbine 6 has the highest decrease of the lifetime DEL, around 2%. The changes in the lifetime DEL of the blades for the turbines as a standalone and inside the FWF are small in all cases and can be considered negligible.

6.4 Conclusion

This chapter showed that the relocating FWF layout has a higher AEP than the baseline FWF layout using a DWM model. The AEP gain is 1.5%, which is equal to 47% of the AEP gain

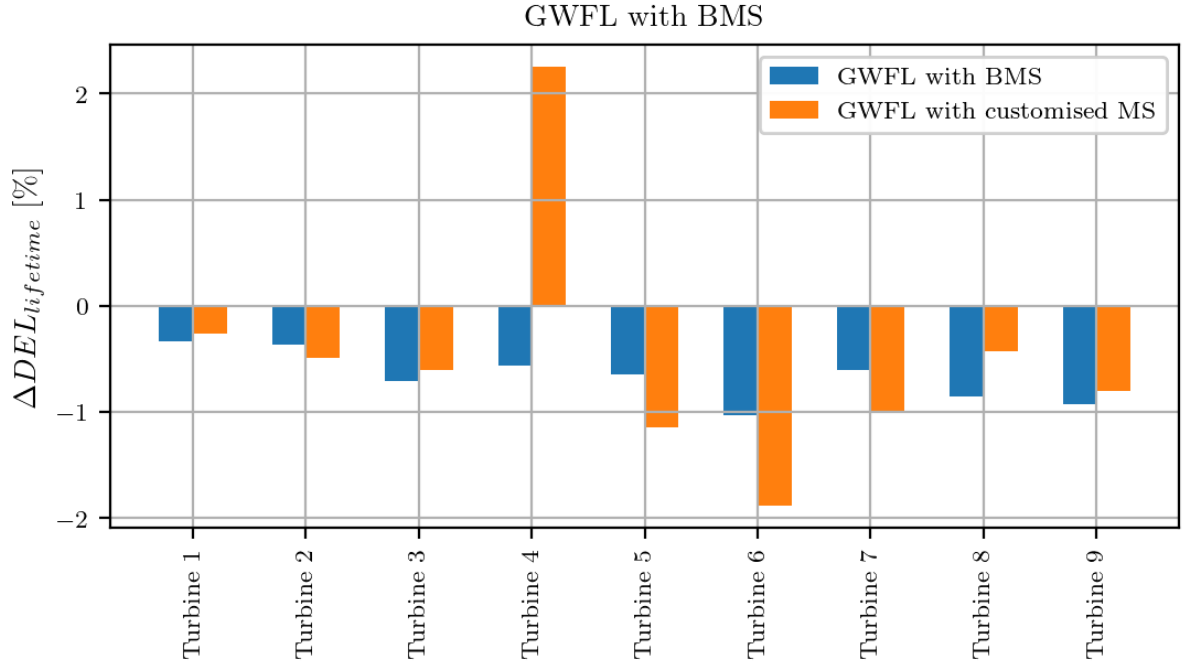


Figure 6.20: The difference in lifetime DEL $\Delta DEL_{lifetime}$ between the standalone FOWTs and inside the FWF for wind speeds between 8 m/s and 13 m/s

predicted using the steady-state wake model. These results confirm the potential of relocating the FWF to increase AEP gain while decreasing the cost of the MS design. The results also showed the difference in the wake evolution inside the FWF between the two models. The wake expansion is larger in the DWM model, and the velocity deficit is higher, especially for the upper half of the rotor, compared to the steady-state model. Additionally, the steady-state model does not capture the wake deflection in the vertical plane due to the pitch angle of the FOWT and the effect of the FOWT movement on the shape of the velocity deficit. These differences lead to differences in AEP prediction between the two tools. The analysis of the wake models emphasized the gap between the simplified steady-state wake models and the DWM and the need to modify the steady-state models for FOWTs.

The mooring line fatigue loads of the relocating FWF MS designs and the BMS were in the same range inside the FWF and when modeled as standalone. However, this depends significantly on the farm layout and the wind rose and will change from one wind farm to another. The tower base fatigue loads were higher for the FOWTs in the FWF than when standalone. The increase of fatigue damage on the tower base is higher for the relocating FWF layout than the baseline layout, as the relocating FWF layout FOWTs are loaded with higher rotor average wind speed than the baseline layout. The change in the blade root fatigue between the standalone FOWTs and the FOWTs in the FWF was minimal and can be neglected.

APPLICATION - HORNS REV 1 WIND FARM

7.1 Overview

In this chapter, I will apply the method I developed for relocating the FOWTs to increase the FWF's AEP on an existing wind farm design. Since no large-scale FWFs were installed when I did this work, I decided to use a fixed-bottom offshore wind farm and update it to be an FWF. As a reference wind farm layout, I chose the Horns Rev 1 wind farm in the North Sea. The goal is to add more constraints to the method and check its validity in a more realistic design. This chapter summarizes the research idea and reflects on the practicality of relocating the FWF layout design and the future work needed to increase the reliability of such designs.

The chapter is organized as follows: First, I introduce the Horns Rev layout and explain how I updated the Horns Rev 1 design to fit the current work. I will also introduce the environmental site conditions of the wind farm. Afterward, I will introduce how I applied the methodology on this large wind farm and the motivations behind the design choices made in this step. Then, I will introduce the MS designs for the FOWTs in the Horns Rev farm, and using the steady-state wake model FLORIS, I will show the AEP gain of the relocating FWF. Additionally, the costs of the MS designs will be calculated and presented. I will then test the dynamic performance of the entire FOWT when coupled to the new MS designs similar to the work done in Chapter 5. Finally, FAST Farm will be used to verify the performance of a section of the relocating FWF at rated wind speed and compare the results to the steady-state wake model results.

7.2 Horns Rev 1 farm definition

Horns Rev 1 wind farm is an offshore fixed bottom wind farm in the North Sea, off the coast of Denmark, consisting of 80 wind turbines each with a capacity of 2 MW and 80 m rotor diameter, i.e., the farm capacity is 160 MW. I chose this wind farm due to the lack of a constructed full-scale FWF that I can use as a reference design for applying the methodology and verifying the results, as well as the availability of data on the layout and environmental conditions at the Horns Rev 1 site. The Horns Rev 1 layout is introduced in Figure 7.1 along with the wind rose (Thomson and Zaaijer, 2022). The distance between two turbines in the x and y directions is $7D$. The layout consists of 8 rows, and each row is made of 10 turbines.

The first step was to update the turbine from 2 MW to the 15 MW IEA reference wind turbine, as using the 2 MW turbine would have made this work irrelevant to the research community and industry. Updating to the 15 MW turbine increases the wind farm capacity to 1.2 GW. As the wind turbine is updated, the absolute distances between the turbines in the x and y directions are increased to keep the $7D$ ratio the same as the baseline layout in Figure 7.1. The floating platform is the same submersible Activefloat platform I used throughout the work and introduced in Figure 2.4.

The water depth is set to 200 m, as this value fits with the expected FWF lease areas around Europe in the Mediterranean Sea and the west coast of Europe in the Atlantic Ocean. The BMS design was used for the baseline layout, and the layout with the BMS is introduced in Figure 7.2. A constant value of significant wave height of 2 m and a wave period of 6 s were used for the wave height and wave period, which coincides with the wave data for the Horns Rev 1 wind

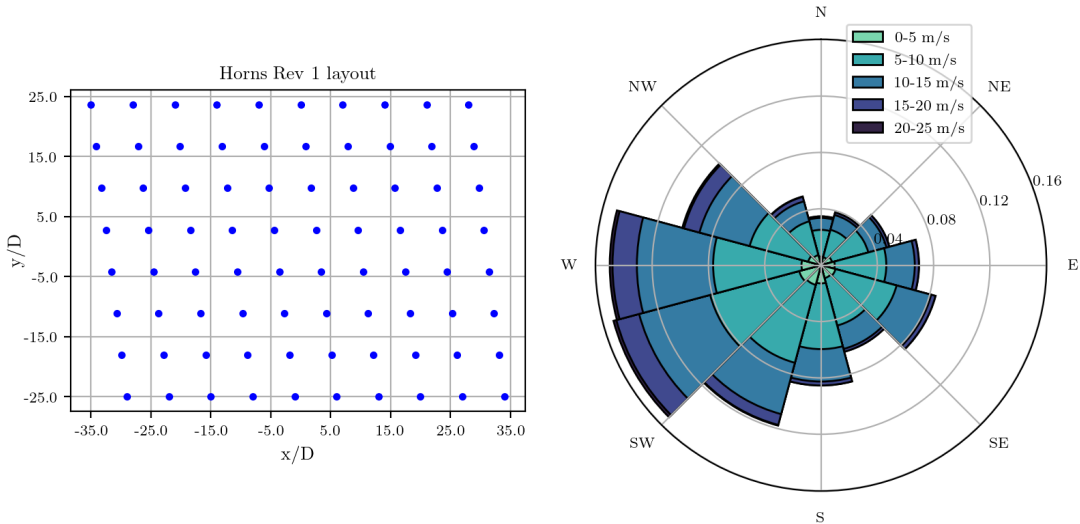


Figure 7.1: Horns Rev 1 layout and wind rose

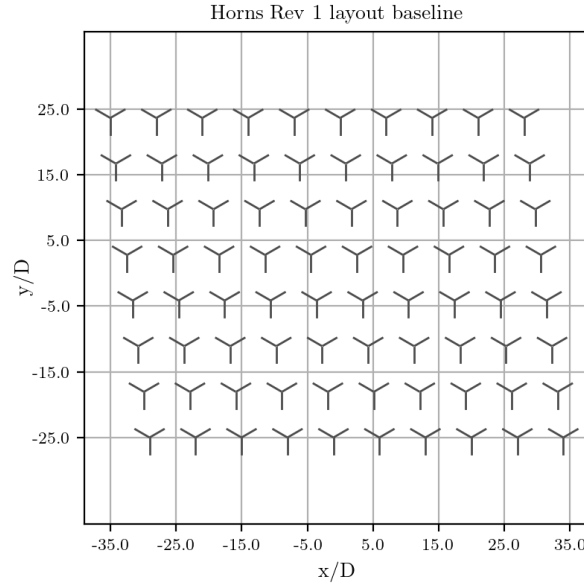


Figure 7.2: Horns Rev 1 layout with BMS design

farm. According to the report by Tech-wise A/S and Hansen (2002), the significant waves for the Horns Rev site range between 0.5 m and 3 m and are linear with the wind speed. The wave period ranges between 2 s and 6 s. Since the range of the significant wave height and wave period is narrow, I decided to use the above-mentioned fixed values for the wave parameters that are the same as the design values of the Activefloat platform used within the work. The wind and waves were always aligned in this work.

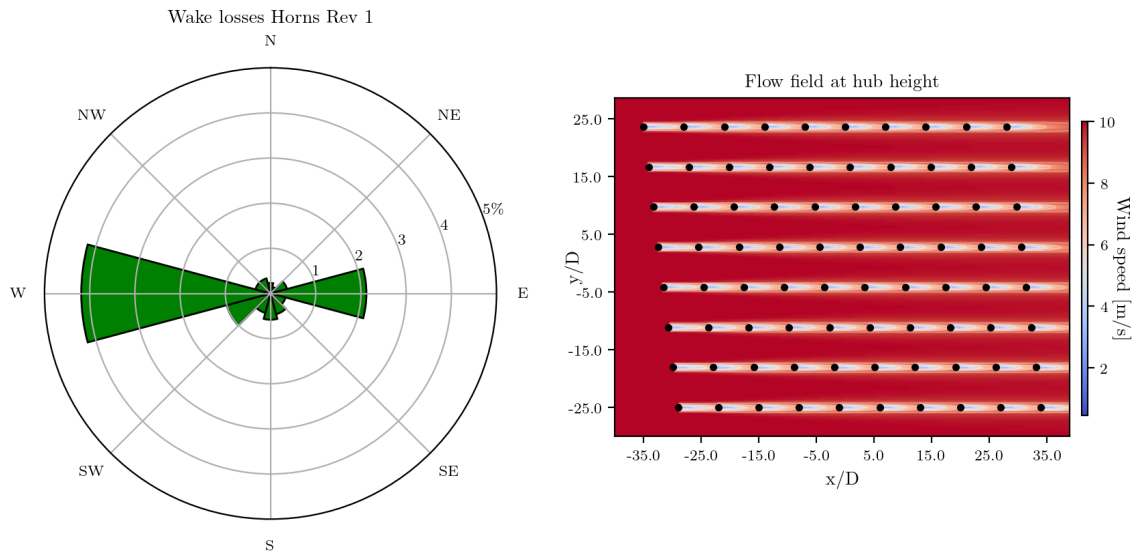


Figure 7.3: Wake losses distribution at each wind direction of Horns Rev 1, and the flow field at hub height for inflow wind speed of 10 m/s

Figure 7.3 shows the wake losses of the Horns Rev 1 layout when coupled to the BMS design. The total wake losses are 10.6%, and the main wake losses happen for the wind direction from west to east with wake losses of 4.2%, and for the wind direction from east to west, the wake losses are 2.1%. The losses for these two wind directions represent 59% of the total wake losses of the FWF. Because the wind direction from west to east is the second most probable, and the layout is not optimized for this wind direction. This is common as the wind farm layout optimization can be constrained by several factors, such as the wind farm's lease area relative to the number of turbines to be placed and the shape of the lease area. In these cases, the proposed method of relocating the FOWTs can add an extra DoF to mitigate these constraints and move the FOWTs out of the wake. Figure 7.3 shows the flow field at the hub height for an inflow wind speed of 10 m/s, which shows that all the downwind turbines are fully in the wake of the upwind turbines. This makes the Horns Rev 1 layout more interesting for applying the method I developed in this work, as relocating the FOWTs only for two wind directions will decrease the wake losses significantly.

7.3 Methodology

As the wake losses are dominated by the losses from only two wind directions, I decided to relocate the FOWTs inside the FWF only for these two wind directions while keeping the displacements as small as possible for the rest of the wind directions. Therefore, our method is adapted to fit this goal. However, before diving deep into the method adaptation, I decided to add more constraints to the MS design to increase the credibility of the proposed designs. First, to consider the ease of installation and the supply chain of the MS, I decided to decrease the total number of MS inside the farm. I decided to allow one or a maximum of two unique MS designs for the entire FWF, so I will apply my method twice, once allowing one unique MS design for the entire FWF and once allowing two unique MS designs. In the design case of one unique MS design, I will allow the FOWT to have different orientations of the same MS design.

The Horns Rev 1 layout in Figure 7.1 is used as a baseline layout. The second step (section 3.3) with the targeted layout was adapted to fit the goal of this chapter. The layout optimization process for each wind direction was not performed using a layout optimization algorithm. Since I only aim to relocate the wind turbines in two wind directions, I manually defined the crosswind displacement matrix $\mathbf{Cr}$ to decrease the computational costs as optimizing this large wind farm using a gradient-based optimizer is computationally expensive and unnecessary due to the simplicity of the optimization problem for these two wind directions. The crosswind displacements were set to 120 m ($0.5D$) for the two wind directions 0° and 180° , and the rest of the wind directions were not considered in $\mathbf{Cr}$. To define whether the FOWTs are shifted to the left or the right in the crosswind displacement matrix, the results from Chapter 6 about the wake

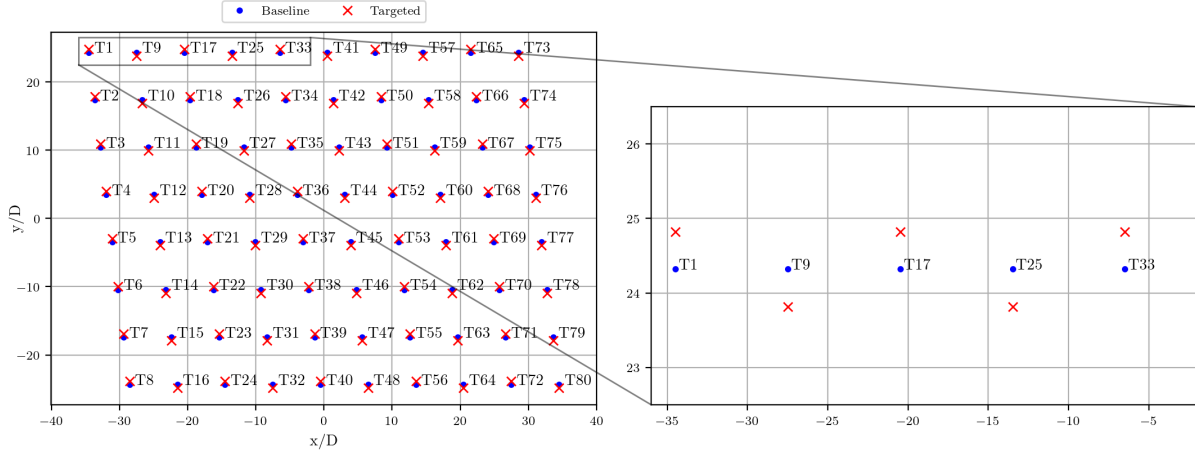


Figure 7.4: Horns Rev 1 baseline and targeted layouts

asymmetry were considered to account for the shift in the wake towards the positive y direction in FAST Farm. As an illustration, the target layout is shown in Figure 7.4 for wind direction of 0° . The Figure shows that the downwind turbine is shifted by negative 120 m while the upwind turbine is shifted by positive 120 m, which has proven to be more beneficial as illustrated in Chapter 6 as the center of the wake in FAST Farm is shifted towards the positive y direction. If the target layout is achieved, the wake losses decrease to 6.9%, equivalent to a decrease of 34.9% of the total wake losses. Additionally, the AEP produced by the FWF increases by 4.1% for the targeted layout.

To compensate for neglecting the effect of relocation for the other wind directions and focusing only on the two directions with the highest losses, I did not decrease the number of possible MS designs by choosing only one unique orientation for each MS design, but several orientations were considered (as illustrated in section 4.3). This means that several orientations will be applied in the brute force optimization step (the final step in the method developed), and the orientation leading to the highest energy gain will be considered. This is not computationally expensive in this application as only one or a maximum of two MS designs are considered for the entire FWF.

The mooring database used is the database with the yaw constraint between $\pm 3^\circ$ at wind speed of 10 m/s. This MS provides enough yaw stiffness, and the loads on the FOWTs are comparable to the BMS design, as illustrated in Chapter 5. The rest of the methodology is applied as introduced in Chapter 3 without further changes or modifications.

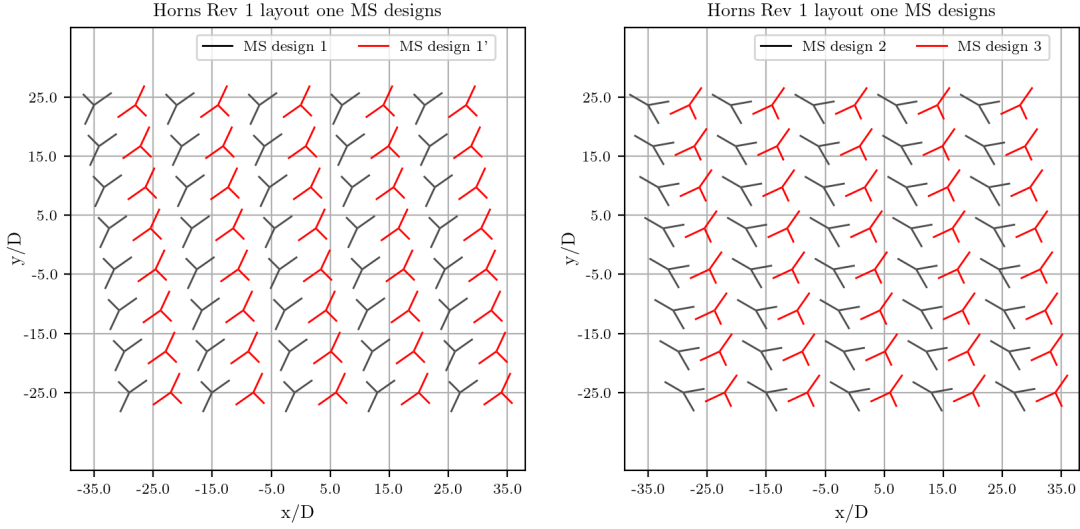


Figure 7.5: Horns Rev layout coupled to the customized MS designs. On the left, all the FOWTs are coupled to the same MS design, and on the right, two MS designs are coupled to the FOWTs

7.4 Relocating Horns Rev layouts

As explained earlier, the method is applied twice on the Horns Rev baseline layout. The first time, all turbines had the same MS design but allowed different orientations. The second time, I allowed a different mooring design for each Horns Rev wind farm column. The resulting MS designs and the two layouts are shown in Figure 7.5. To easily differentiate between my MS designs, I will refer to the MS design of the FWF with a single MS design as MS design 1 and the rotated version of it as MS design 1'. The two MS designs in the other FWF layout with two unique designs will be referred to as MS design 2 (in black in Figure 7.5) and MS design 3 (in red in Figure 7.5) respectively. The MS design parameters for the unified MS design for the entire FWF are shown in Table 7.1, while the design parameters for the two MS designs are shown in Table 7.2. The horizontal stiffness in the x-axis and y-axis for all MS designs for the Horns Rev 1 layout is shown in appendix C.

For the single MS design for the entire layout, the orientation of the second column is rotated by 180° in comparison to the second column. Then, the MS design of each row of the FWF layout alternates between MS design 1 and MS design 1'. This is because while choosing the MS designs to be considered, the method treats the two wind directions equally, and no priority is given to the wind direction with the higher energy gain. This is detailed in section 3.5.1. Since the two considered wind directions are 180° apart, the method acts as expected and rotates the MS designs by 180° . Having no priority for the different wind directions was a good approximation when a different MS design could be chosen for each FOWT in the FWF. However, when only one MS design is chosen, the more probable wind direction should be prioritized. This is something

Table 7.1: Single MS design for all FOWTs in the Horns Rev layout

	heading 1	d 1	AncR 1	L1	heading 2	d 2	AncR 2	L2	heading 3	d 3	AncR 3	L3
MS de-sign 1	245	0.18	840	884.22	35	0.15	840	884.22	135	0.12	600	680.46
MS de-sign 1'	65	0.18	840	884.22	215	0.15	840	884.22	315	0.12	600	680.46

Table 7.2: Two MS designs for all FOWTs in the Horns Rev layout

	heading 1	d 1	AncR 1	L1	heading 2	d 2	AncR 2	L2	heading 3	d 3	AncR 3	L3
MS de-sign 2	10	0.15	840	916.98	150	0.18	840	884.22	300	0.15	840	884.22
MS de-sign 3	295	0.12	600	680.46	55	0.18	840	884.22	205	0.15	840	884.22

Table 7.3: The energy gain and the cost of the MS designs for the Horns Rev layout

MS design	Single MS design		Two MS designs	
AEP gain (full wind rose) [%]		0.7		1.9
Cost gain [%]		13.3		6.0
Maximum mean excursion [m]		150		144 and 151

to be considered in future work, as the goal of this work is not the optimization process itself but the proof of concept; I kept the method used as is. Table 7.3 shows that the energy gain is negligible due to this assumption and only 0.7% while the targeted gain is 4.1%.

On the other hand, the results in Table 7.3 show that this simplification does not have an effect when each column in the FWF is allowed to have a different MS design. The AEP gain for this layout with the two MS designs is 1.9%, around 46% of the possible targeted AEP gain. The results shown in Table 7.3 for the AEP consider the feedback effect from the wake on the FOWT's position. In addition, the full windrose is considered.

Table 7.3 shows that the cost of the MSs decreases for both cases. Both MS designs are less stiff and lighter, decreasing material costs. The cost of a single MS design is 13.3% less compared to the BMS and 6% less when two MS designs are used. These are high percentages as this FWF is a large farm with 80 FOWTs; a decrease of 1% of the MS costs for the FWF is equivalent to 3.4 million US dollars. The maximum mean excursions for the layout with one unique MS design is 150 m, and for the case with the two unique MS designs is 144 m and 151 m for MS design 2 and MS design 3, respectively.

7.5 Relocating FOWTs load analysis

7.5.1 Overview

Similar to section 5.4, I analyze the loads on the FOWTs due to coupling them to the less stiff customized MS designs developed for the Horns Rev 1 layout. The fatigue and maximum loads in operation condition will be the focus of the load analysis as the results in Chapter 5 showed that the ultimate loads are not the driving loads for the MS designs for the FOWT used in this work. The 12 wind directions from the Horns Rev windrose with an increment of 30° are used for the wind directions. Wind speeds between 4 m/s and 25 m/s are covered with an increment of 1 m/s. The significant wave height and the wave period were fixed to 2 m and 6 s, respectively, which coincides with the measurements at the Horns Rev 1 site introduced in the report by Tech-wise A/S and Hansen (2002). The Mann box turbulence generator generated a 3600 s wind field with a turbulence intensity of 6%. The wind field resolution is 2 m in the x direction and 5 m in the y and z directions. The simulation time was 4200 s, with the first 600 s neglected in the post-processing to remove any transient effects. The section is arranged as follows: First, the loads on the MS design are introduced, then the loads in the tower base, and finally, the blade roots.

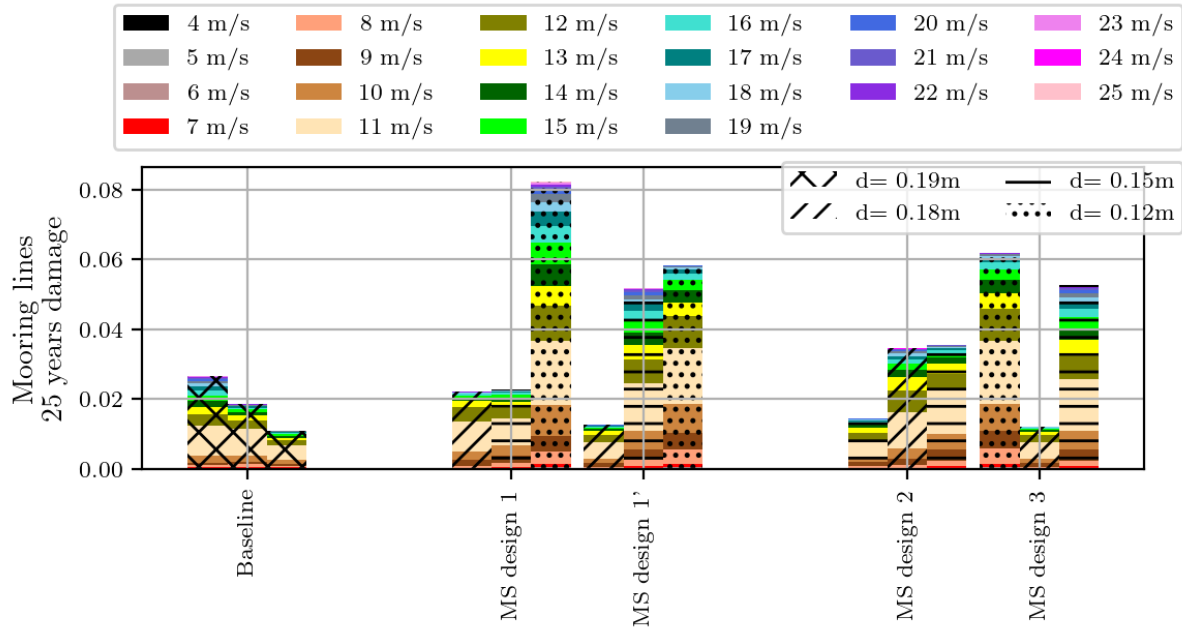


Figure 7.6: Horns Rev 1 BMS, and customized MS designs 25 years fatigue damage

7.5.2 Fatigue and maximum loads on the MS designs in operation conditions

Figure 7.6 shows the 25-year fatigue damage on the customized MS designs. Compared to the fatigue damage results of the nine turbine wind farms presented in Figure 5.10, the fatigue damage for the MS designs of the Horns Rev is higher for above-rated wind speeds. This is because the above-rated wind speeds are more probable for the Horns Rev wind rose than for the IEA task 37 wind rose. The higher probability of the occurrence of above-rated wind speeds leads to higher fatigue damage at these wind speeds. The 25-year fatigue damage results show that all the mooring lines are below the maximum allowable value of MS fatigue damage.

As expected, the mooring lines with the 0.12 m diameter suffer from greater damage, while the mooring lines with diameters of 0.18 m and 0.15 m are within the same range of fatigue damage as the baseline MS design with 0.19 m. The smaller diameters of the customized MS designs are the reason the costs of the soft MS designs are less than the baseline design. Although MS design 1 and MS design 1' are identical, the performance of the systems is affected by the difference in orientation. For MS design 1, the third mooring line, with the heading of 135° , is aligned with the fourth most probable wind direction, leading to an increase in the fatigue damage of the line, which is not the case for MS design 1'. Figure 7.7 shows the DEL distribution of each mooring line in MS design 1.

Figure 7.8 shows the DEL distribution of MS design 2 at wind speed of 11 m/s. The Figure shows that mooring line 2 has high DELs at the most probable wind directions. However, since

the diameter of the second mooring line is large, the 25-year fatigue damage is still low. This again emphasizes the importance of integrating the MS design as part of the FWF design early on in the planning phases to avoid any mooring lines having significant fatigue damage.

The maximum loads on each mooring line in operation conditions are presented in Figure 7.9. The maximum tension in all lines in the customized MS designs is always lower than in the BMS design. Contrary to fatigue damage, as the mooring line diameter increases, the maximum tension on the line also increases. The orientation of the MS design does not affect the maximum value of the line tension.

7.5.3 Fatigue and maximum loads on the tower base in operation conditions

The 25-year fatigue damage on the tower base in operation conditions is shown in Figure 7.10. The time series of the side-to-side and fore-aft moments and the axial vertical force at the tower base were extracted from the OpenFAST results and used for the stress calculation at the tower base using equation 2.12. The 25-year fatigue damage of the FOWT's tower when coupled to the MS design 1, MS design 1', and MS design 2 are all below the fatigue damage when the baseline MS design is coupled to the FOWT. Except for MS design 3, the wind speed with the highest contribution to the fatigue damage is the rated wind speed. The fatigue damage below-rated is almost negligible, and most of the fatigue damage occurs at above-rated wind speeds.

Despite having identical designs, the 25-year fatigue damages of MS designs 1 and 1' are not identical. The different MS orientations affect the tower loads slightly, and MS design 1 has higher fatigue damage than MS design 1'. This is due to the effect of the MS design on the yaw motion of the FOWT, which affects the fatigue loads at the tower base. Higher platform yaw causes higher tower base fatigue damage.

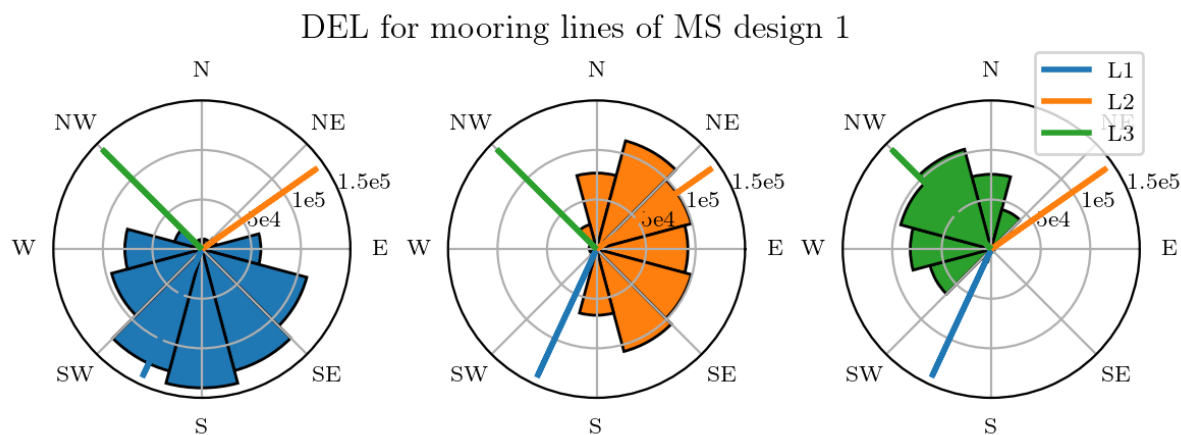


Figure 7.7: Horns Rev 1 MS design 1 DEL at 11 m/s

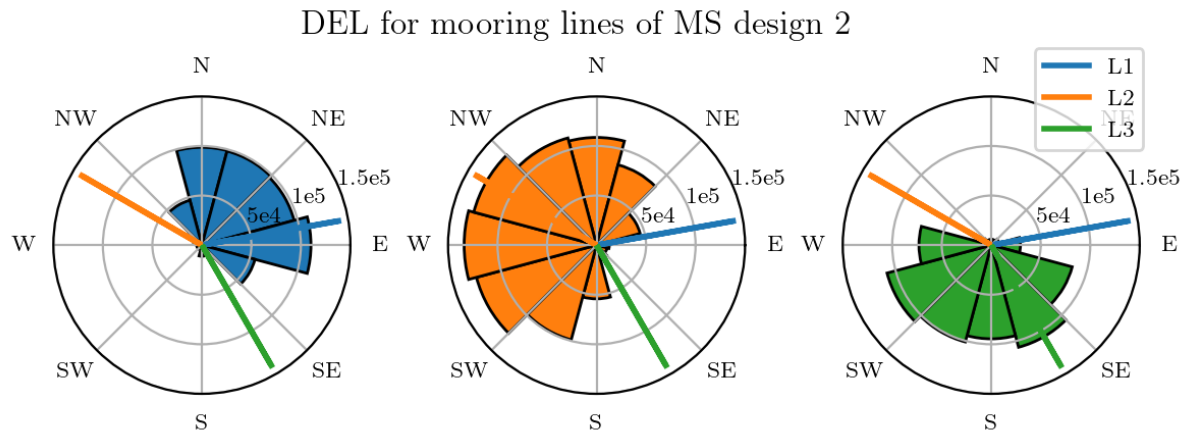


Figure 7.8: Horns Rev 1 MS design 2 DEL at 11 m/s

The Fatigue damage of the tower base when the FOWT is coupled to MS design 3 is higher for wind speed of 25 m/s despite being one of the least probable wind speeds in the wind rose. MS design 3 is identical to the MS design coupled to FOWT 9 in the Yaw 3 layout discussed in section 5.4.4. I have analyzed the yaw stiffness and the time series of the responses of this MS design extensively in Chapter 5. I also explained why the fatigue is higher only at higher wind speeds. For the Horns Rev layout, the fatigue damage of MS design 3 at 25 m/s is greater than that in section 5.4.4 for the same MS design. The reason is that the wind directions with the lowest MS stiffness, hence the greatest fatigue damage, are more probable for the Horns Rev 1 case. The wind directions with the lowest MS yaw stiffness are -120° , 30° , and 60° . The

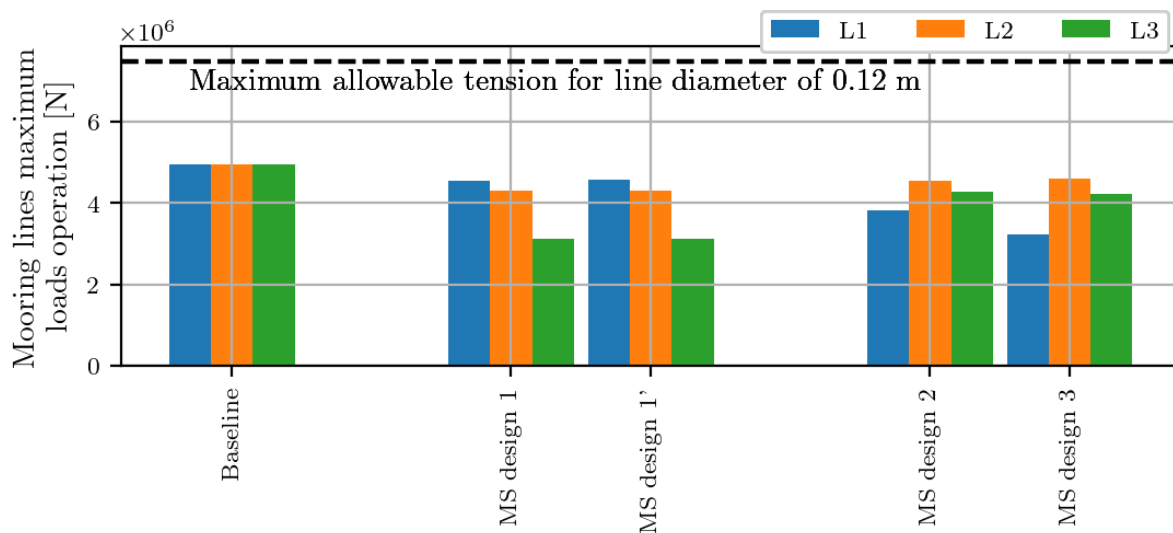


Figure 7.9: Horns Rev 1 maximum line tension in operation conditions for the BMS and the customized MS designs

direction of -120° is aligned with mooring line 2, while the wind directions 30° and 60° are when the wind is blowing between mooring line 3 and mooring line 2. Despite having a higher fatigue at wind speed of 25 m/s than other MS designs, the overall fatigue damage is far below the fatigue limit and slightly higher than the baseline MS design.

Figure 7.11 shows the maximum axial stress at the tower base. The results show that for all MS designs, the tower base is far below the tensile strength threshold when a safety factor of two is considered. MS design 3 has the highest axial stress with a value of 99 MPa. It is expected that MS design 3 will cause the highest axial stress at the tower due to the higher fluctuations at wind speed of 25 m/s, but the results show that the axial stress is far below the tensile strength limit. The baseline MS design leads to the lowest axial tower tower base load with a value of 93 MPa.

7.5.4 Fatigue loads on the blade root in operation conditions

The lifetime DEL of the blade root is introduced in Figure 7.12; the results are introduced as a comparison to the FOWT when coupled to the BMS. The lifetime DELs of all customized MS designs are higher than the baseline case by less than 1%, with the highest increase for MS design 1. Despite being identical designs, MS designs 1 and 1' have different blade root lifetime DEL,

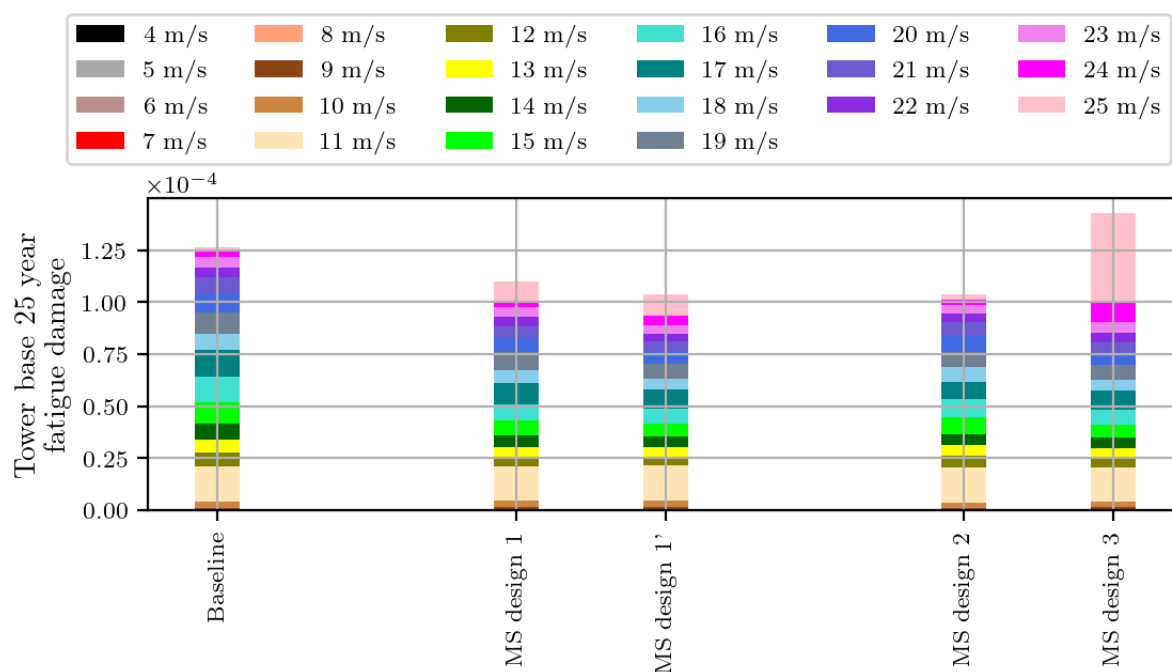


Figure 7.10: 25-year fatigue damage at the tower base for Horns Rev 1 layout when coupled to the BMS, one unique MS design, and two unique MS designs

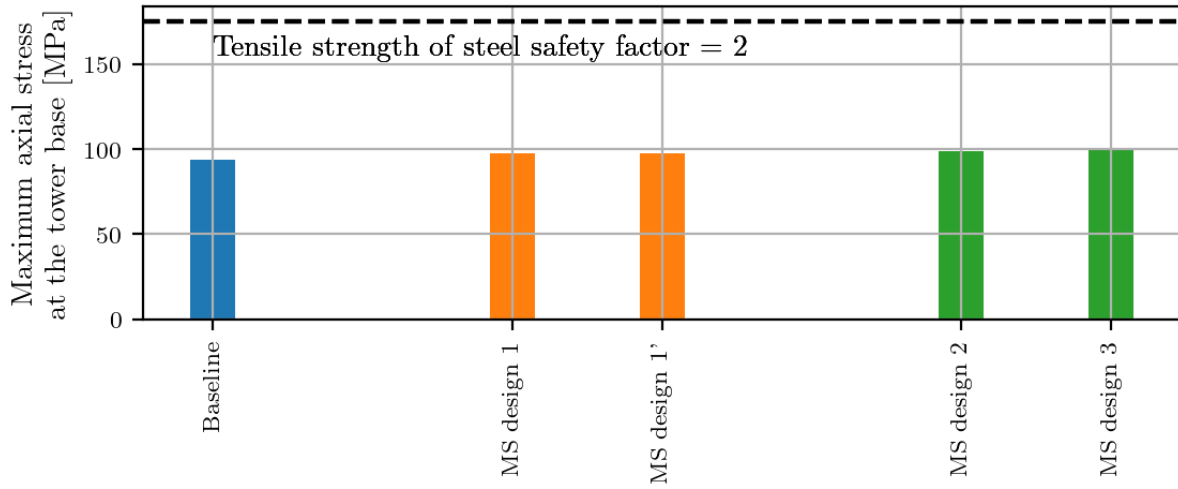


Figure 7.11: Maximum stress loads at the tower base for Horns Rev 1 layout when coupled to the BMS, one unique MS design, and two unique MS designs

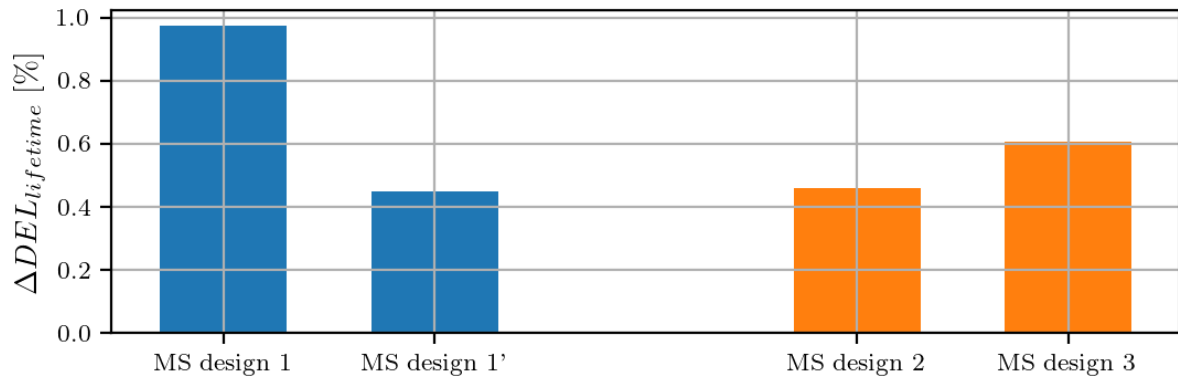


Figure 7.12: Blade root lifetime DEL for each MS design compared to the BMS. A positive value indicates that the new MS design has a higher lifetime DEL than the BMS

which shows that the orientation of the MS affects the FOWT loads and not only the mooring line loads. The blade root lifetime DEL increase is very small and almost negligible. However, it is important to remember the limitations of the BEM model implemented in OpenFAST in cases with higher yaw misalignment and how it affects the blade root bending moments.

7.6 Dynamic modeling of the Horns Rev 1 wind farm

7.6.1 Overview

To test the performance of the relocating MS design when a dynamic wake model is applied, I used the mid-fidelity DWM implemented in FAST Farm. The Horns Rev 1 layout consists of 80 turbines, which is computationally expensive. Therefore, I decided to simulate only two rows of the layout (20 turbines) and not the entire layout, as shown in Figure 7.13, representing 25% of the wind farm. Moreover, I also decided to focus on the wind direction with the highest energy gain, from west to east (wind direction 0°). The wind speed used in the FAST Farm simulation was 11 m/s. I modeled the simplified layout three times, once with the FOWTs coupled to the BMS, once with one unique MS design (MS design 1 and MS design 1'), and finally, with the FOWTs coupled to two unique MS designs (MS design 2 and MS design 3).

The time of each load case was set to 4800 s while the first 1200 was not considered while post-processing the results to ensure the wake is fully developed throughout the farm and decrease any transient effects on the results. The wind field of the farm was created using the Mann turbulence box generator (Liew, 2022), with the grid size of 5 m in the x-y-z directions. The turbulence intensity of the wind field was 6%, and the parameters of the turbulence box I used followed the IEC standard (IEC, 2019). The duration of the wind field created was 3600 s. The high-resolution grid size in FAST Farm was set to 5 m in x-y-z directions to match the resolution of the wind field. The low-resolution grid size was set to 35 m, 20 m, and 20 m in the x-y-z directions, respectively. The curl wake model was used with the same settings as Chapter 6,

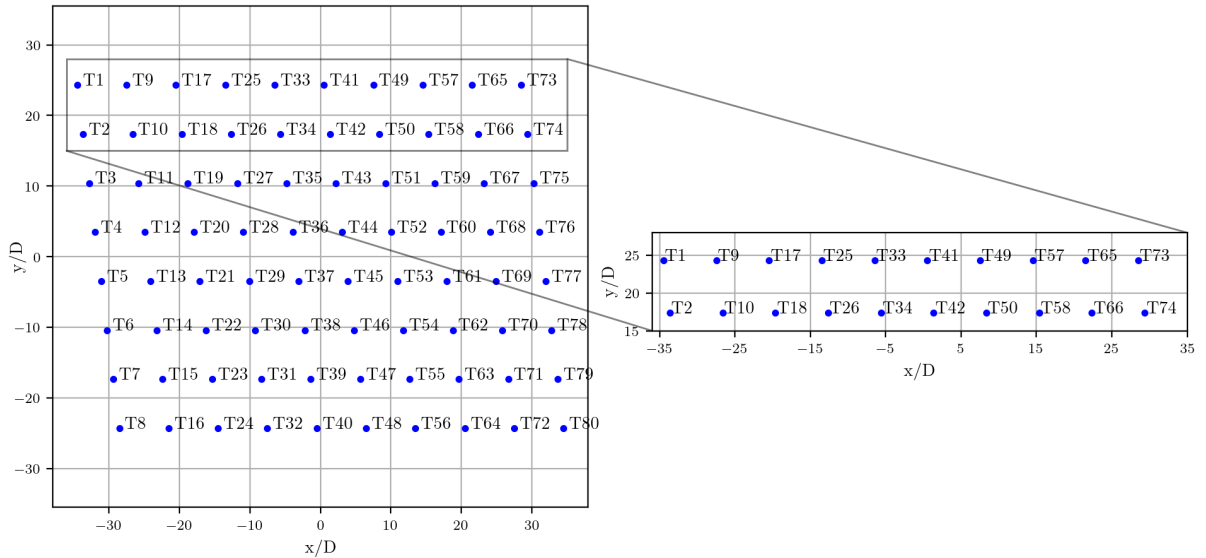


Figure 7.13: Section of the Horns Rev 1 layout verified in FAST Farm

with the wake meandering ($C_{Meander}$) parameter set to 2.1, and the cut-off corner frequency (f_c) set to 0.01 Hz. The significant wave height used is 2 m, the wave period used is 6 s, and no second-order wave effects were considered. The computation time using a single core for the FWF with the BMS was 5.7 days, while for the one unique MS design and two unique MS designs, the computation time was 6.7 days for both simulations. The simulation time for the relocating FWF is larger as the high-resolution box around the FOWTs needs to be larger to ensure the FOWTs do not get out of the high-resolution boundaries.

7.6.2 Energy gain and wake models comparison

In this section, I focus on the energy gain of FAST Farm in comparison to FLORIS for the wind direction of 0° and wind speed of 11 m/s. The energy gain discussed in this section is not the AEP but rather the increase in energy for this single wind speed and wind direction using equation 2.17 and applying a single wind direction. The wake losses (W_{loss}) are calculated using equation 2.16, assuming one wind speed and one wind direction is used for the energy calculation with and without wake losses. The results of the energy gain and wake losses in FAST Farm and FLORIS for the Horns Rev layout coupled to the BMS design, one unique MS design, and two unique MS designs are introduced in Table 7.4. The high energy gain and wake loss values result from considering only one wind speed and one wind direction. If the probability of occurrence for wind speeds and directions are considered, these values will be the real values. It is simple to get the values considering the full wind rose in FLORIS. However, to obtain the overall AEP of the wind farm in FAST Farm, all wind speed and wind directions need to be modeled, which is computationally expensive and out of the scope of the defined research questions.

Table 7.4: Wake losses and energy gain in FLORIS and FAST Farm at wind speed of 11 m/s and wind direction = 0°

		Baseline	One unique MS	Two unique MS
FLORIS	W_{loss}	-44%	-40%	-35%
	Energy gain	-	7%	32%
FAST Farm	W_{loss}	-49%	-48%	-41%
	Energy gain	-	3%	17%

The results of Table 7.4 show that the wake losses in FAST Farm are always higher for all cases. When all FOWTs inside the FWF are coupled to one unique MS design, FLORIS predicts 7% energy gain, while FAST Farm predicts 3%. Hence, the energy gain in FAST Farm is 43% of the energy gain predicted by FLORIS. On the other hand, when the FOWTs are coupled to two MS designs, FLORIS predicts 32% while FAST Farm predicts an energy gain of 17%, which is 53% of the energy gain predicted by FLORIS. Assuming that the ratio between the total AEP

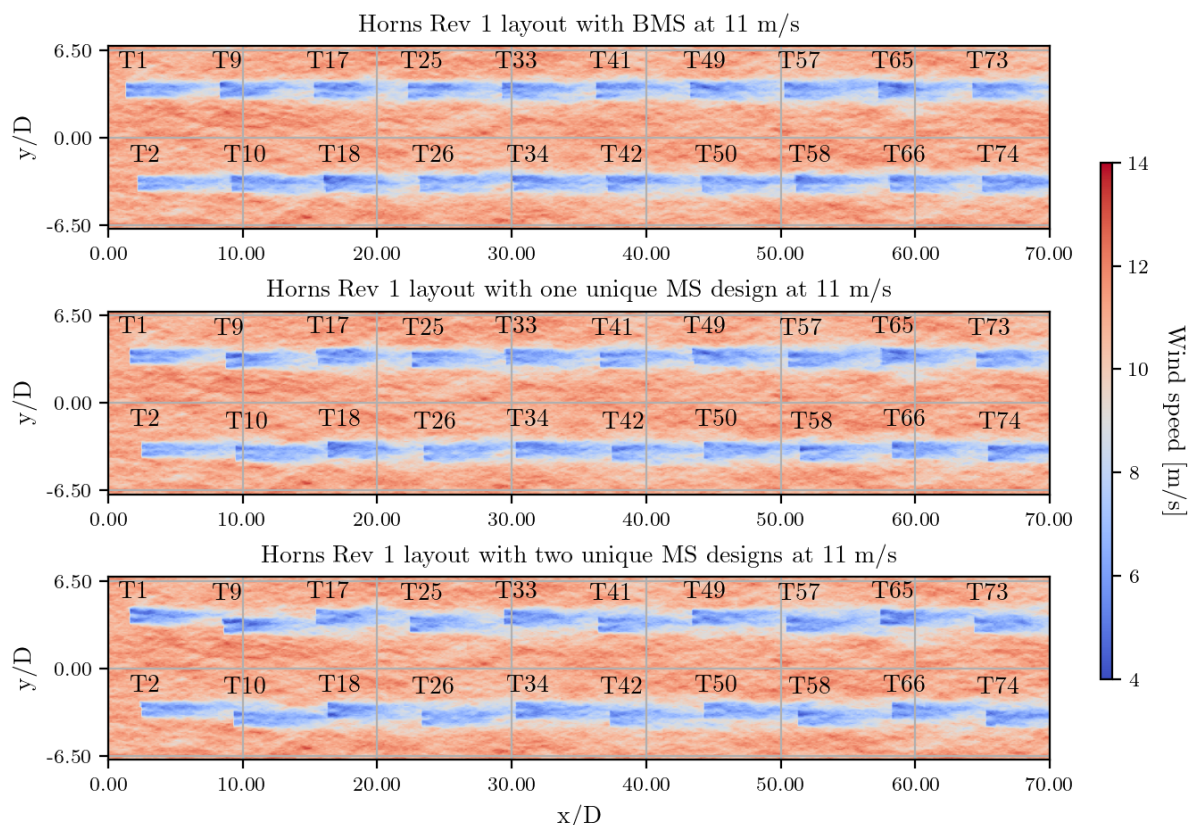


Figure 7.14: Horns Rev 1 wind field visualization at hub height

gain will be the same between FAST Farm and FLORIS, then the overall AEP gain with one unique MS design is negligible with a value of 0.3%. Following the same assumption, the total AEP gain of the layout with two unique MS designs will be 1%. Throughout the rest of this section, I will analyze the wake models in each tool and show the reason for the difference in wake losses and energy gain in FAST Farm and FLORIS.

Figure 7.14 shows a visualization of the flow field inside the farm at the hub height for the three cases. The layout, coupled with the BMS, shows that all turbines are fully in the wake. The layout with FOWTs coupled to one single MS design shows that turbines slightly relocate in the first two columns of the farm (turbines 1 and 2 and 9 and 10). However, the relocation becomes less visible on this large-scale plot for FOWTs further downwind. Finally, the layout with two unique MS designs is the layout where the relocation is visible for all FOWTs, even the last FOWTs in each row.

The change in rotor average wind speed due to relocating the turbine is analyzed in Figure 7.15. A positive value indicates that the rotor average wind speed is higher than the non-relocating FWF and vice versa. The values of the change of the rotor average wind speeds are alternating through each row because the MS design attached to each turbine alternates,

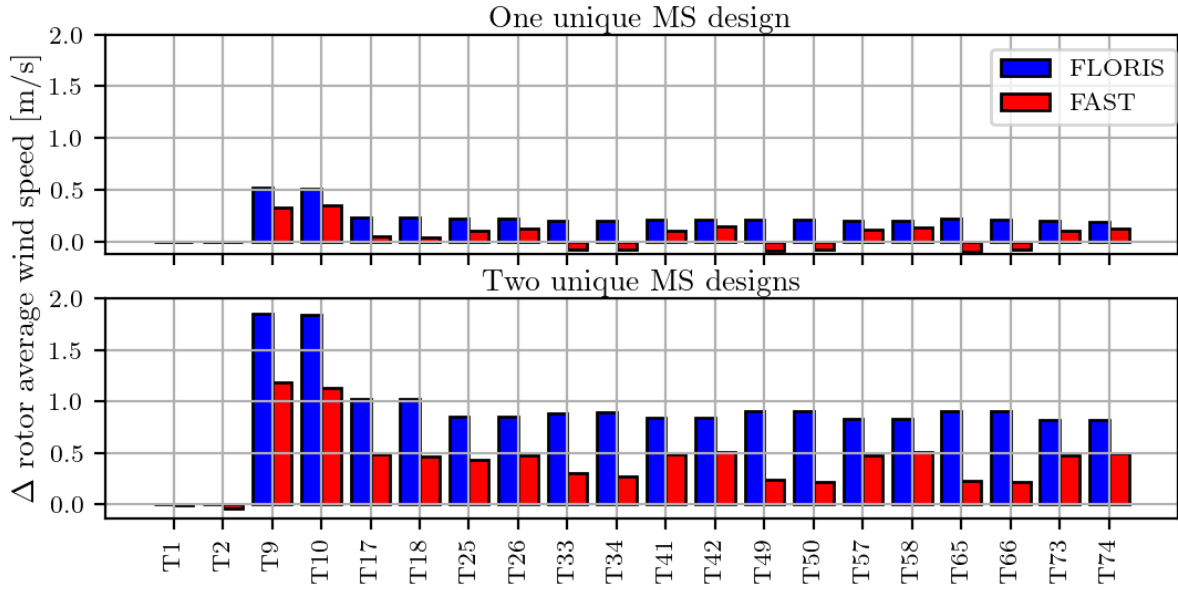


Figure 7.15: The change in rotor average wind speed due to relocating the FOWTs in FLORIS and FAST Farm

leading to a different displacement. For the FWF layout coupled to a single unique MS design, the total increase of the rotor average wind speed due to relocation is negligible, which is the reason for the small energy gain in this case. On the other hand, the increase of the rotor average wind speed of the FWF when coupled to two unique MS designs is significant, which is why the increase of energy gain in this case is large. The change in the rotor average wind speed in FLORIS is larger for all cases; this is the reason for the higher energy gain predicted in FLORIS. It is normal for the FLORIS average rotor speed to be higher than the FAST Farm average rotor speed, as FAST Farm accounts for the rotor tilting, but this should not affect the change in the rotor average wind speed as it is not an absolute value.

The average power production for each FOWT in the farm with an inflow wind speed of 11 m/s for the baseline case and the customized cases is presented in Figures 7.16, and 7.17. The power produced by all downwind turbines in the Horns Rev layout, coupled with the two unique MS designs, is significantly higher than the baseline design. The results also show that the increase in average power in the layout with the single MS design is negligible. The power production of the layout with the customized MS design is alternating as the MS design also alternates, which is predicted from the findings from Figure 7.15. Since the two rows are identical, the average power produced by the turbines in the same column is equal.

Figure 7.16, and 7.17 also shows that starting the sixth turbine in each row (T41, T42), the change in the power produced by the turbines constantly alternates. This is because the wake is saturated after the fifth turbine in each row. Hence, the velocity deficit does not decrease

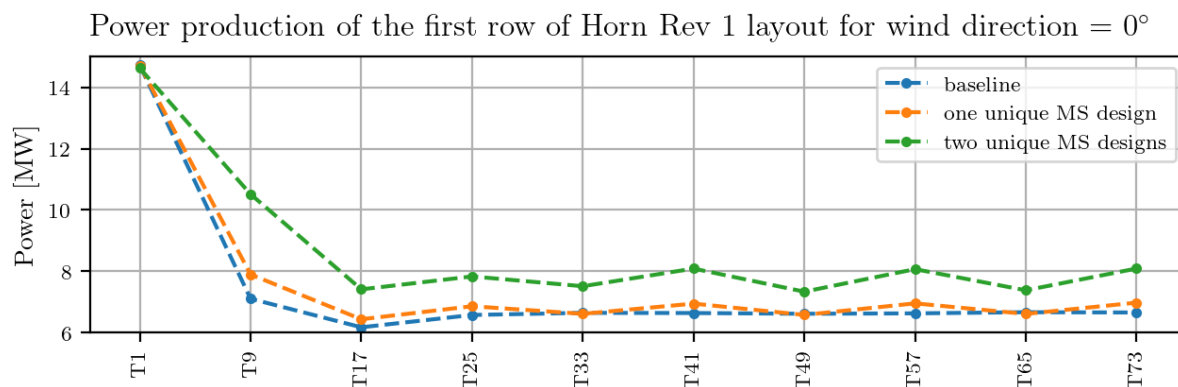


Figure 7.16: The power produced by the FOWTs in the first row of the Horns Rev 1 layout

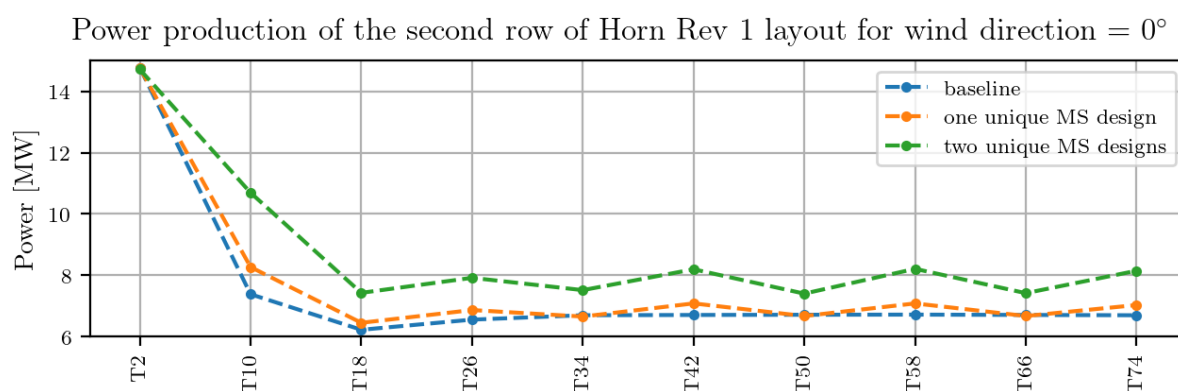


Figure 7.17: The power produced by the FOWTs in the second row of the Horns Rev 1 layout

further, starting at the sixth turbine in the row. For the layout with the BMS, the wake saturation happens one row earlier, coinciding with the findings of Frandsen et al. (1996). The power produced by FOWTs in the layout coupled to BMS becomes constant, starting the fifth turbine in each row (T33, T34). This shows that relocating the FOWT causes the turbulence saturation to be reached further down the FWF.

The velocity deficit behind the FOWT in the second row is analyzed in Figure 7.18 for the layout design with one unique MS design and in Figure 7.19 for the layout with two unique MS designs. Similar to the approach followed in Chapter 6, the wind flow at the rotor height (visualized in Figure 7.14) was saved every 9 s. The last 3600 s were used to calculate the velocity deficit. The Figures show the velocity deficit behind each FOWT in the row when coupled to the BMS and the customized MS design at three different downwind locations: $4D$, $5D$, and $6D$. Generally, the results are similar to the findings in Chapter 6. I will divide the findings into overall conclusions and conclusions specific to each layout with a different MS design.

For all cases, FLORIS predicts higher wake losses at a downwind distance of $4D$, but the wake recovery afterward in FLORIS is faster as the velocity deficit in FLORIS at $6D$ is smaller. Only

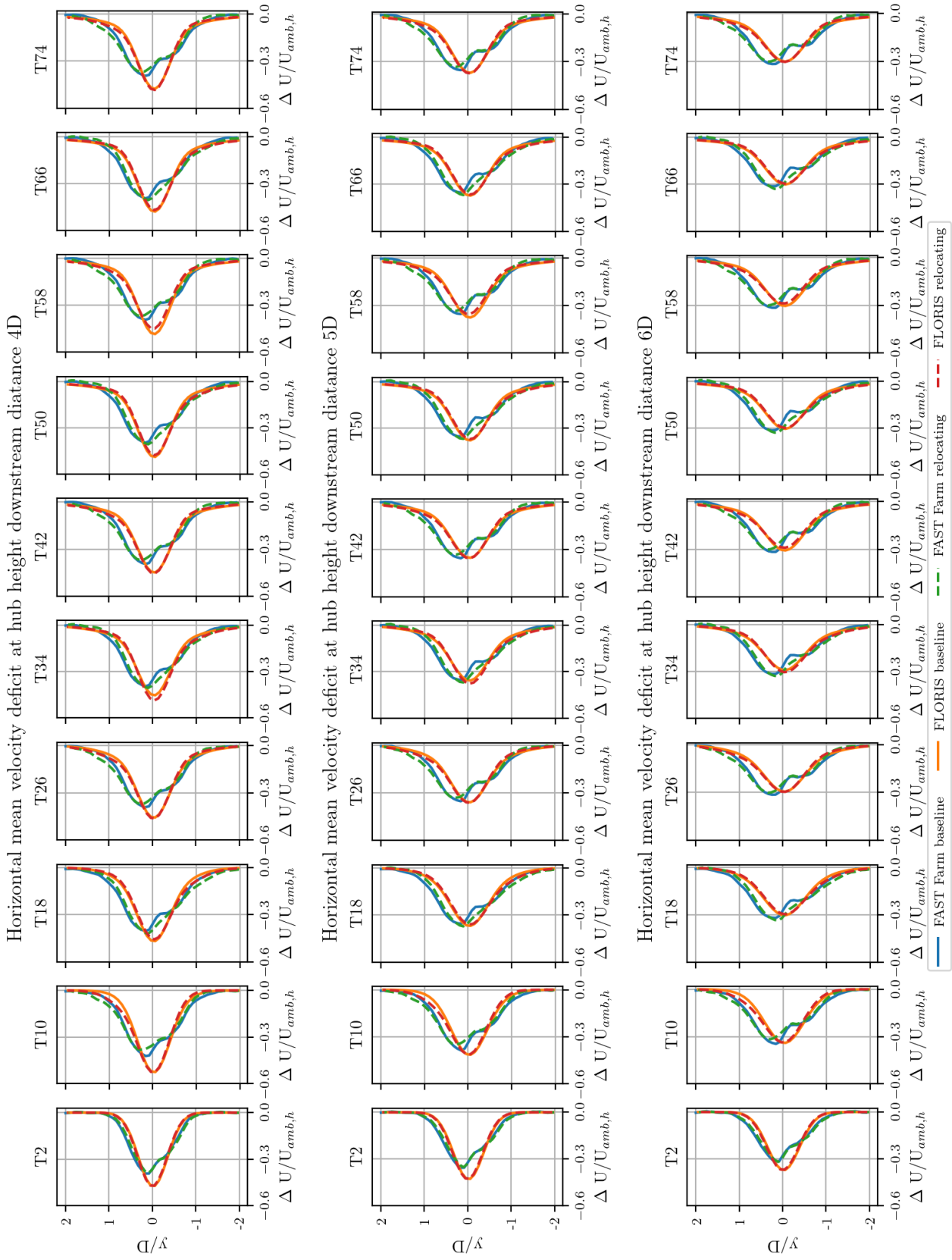
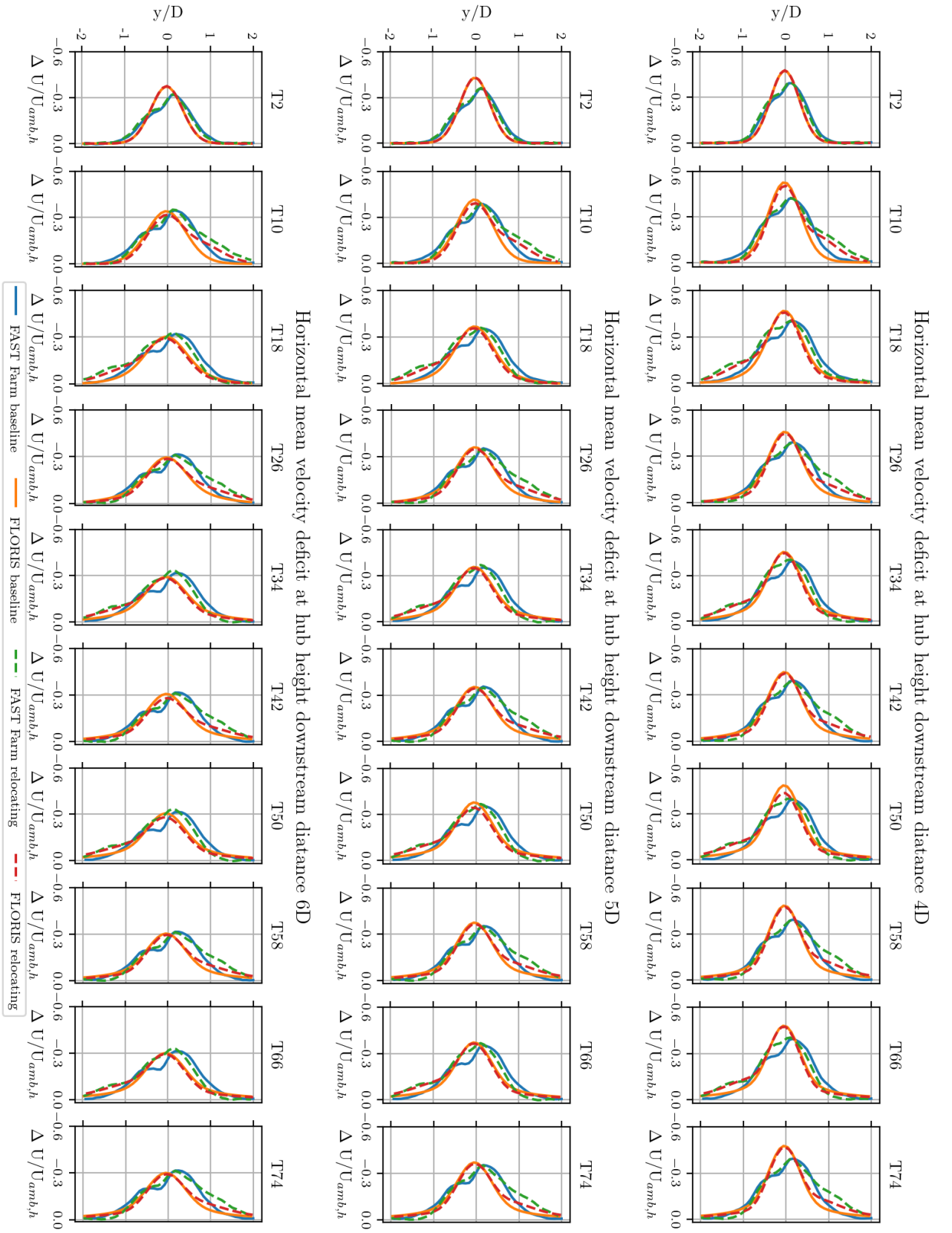


Figure 7.18: Horizontal velocity deficit for the layout with one unique MS design



behind the turbine in the free flow are the wake losses in FLORIS higher than in FAST Farm, but as the wake moves downwind, the wake losses in FAST Farm become higher. This explains why the wake losses in FAST Farm are higher. The velocity deficits are higher, so the average rotor speeds are lower. The wake center in FLORIS is always in the center behind the rotor, while the wake center in FAST Farm always shifts in the positive y direction. Since this effect was also seen in Chapter 6, this is a property of the wake associated with the wind turbine. In the work of Carmo et al. (2024), the results of the 5MW reference turbine show that the wake center is also shifted to the positive side of the rotor, which suggests that it is due to the curl wake model in FAST Farm. The wake is wider in FAST Farm than in FLORIS, especially in the positive y direction of half of the rotor, while the difference between the two models is smaller for the other half of the rotor.

For the baseline Horns Rev 1 layout with the BMS, the results confirm that the wake is fully developed starting the fifth turbine downwind, and the wake profile deficit no longer changes for all the following turbines. The results show that the velocity deficit is always asymmetric, with a drop in the deficit on the negative half of the rotor. This is due to the large inflow skew angle of the turbines when coupled to the BMS. Since all the FOWTs are coupled to the same MS design, all the FOWTs have the same velocity deficit shape. The inflow skew angle in FAST Farm is affected by the yaw angle, pitch angle, and tower top deflections. These effects create a larger skew angle for the BMS design, leading to wake asymmetry. This asymmetry is large for the small pitch, yaw angles, and the tower top motions. This shows the importance of comparing the wake model implemented in FAST Farm to a higher fidelity model to verify its performance.

In Figures 7.18 and 7.19, the velocity deficit alternates between the wind farm columns because the different MS designs cause different crosswind displacements, so the velocity deficit is different. The alternating velocity deficit here proves that relocating the FOWTs affects the velocity deficit. The asymmetry of the wake in FAST Farm also alternates with the MS design, showing that the MS design can affect the asymmetry of the wake around the wake center. The MS design affects the FOWT yaw angle, which affects the wake symmetry.

The shape of the tail of the velocity deficit is also clearly affected by the FOWTs' relocation, and the effect is more visible for the layout with two unique MS designs in Figure 7.19. Due to the relocation, Turbine 10 is no longer aligned with Turbine 2, as it is in the negative crosswind direction. This means that the wake of Turbine 2 is more visible on the positive side of the rotor of Turbine 10, while the negative side is out of the wake. This is visible in the velocity deficit plots for FAST Farm and FLORIS, where the velocity deficit on the positive side downwind from Turbine 10 is larger than the negative side as it is affected by the wake coming from Turbine 2. For Turbine 18, the effect is reversed, and the deficit on the negative side of the rotor is higher as the turbine is shifted in the positive crosswind direction.

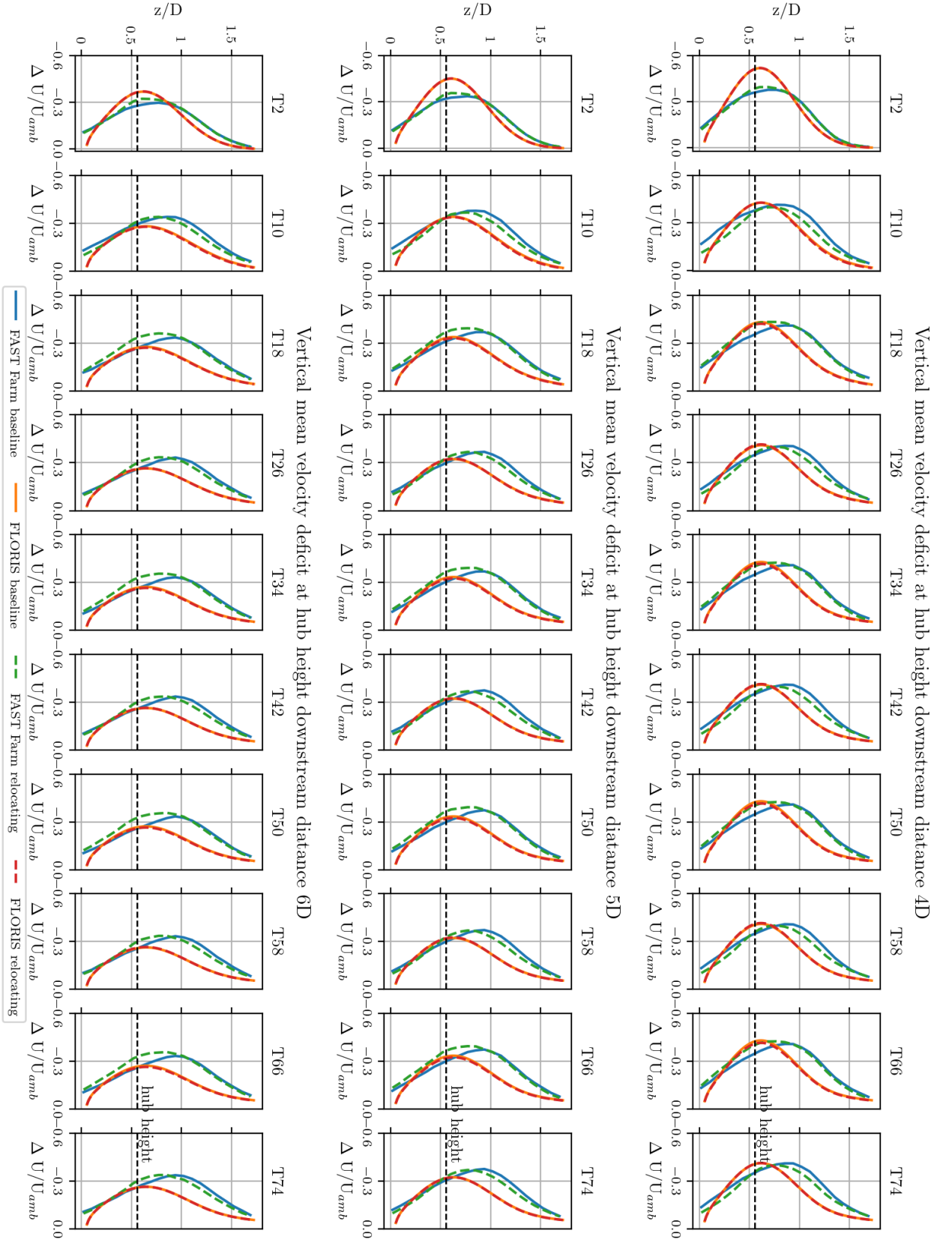


Figure 7.20: Vertical velocity deficit for the second row for the layout with one unique MS design

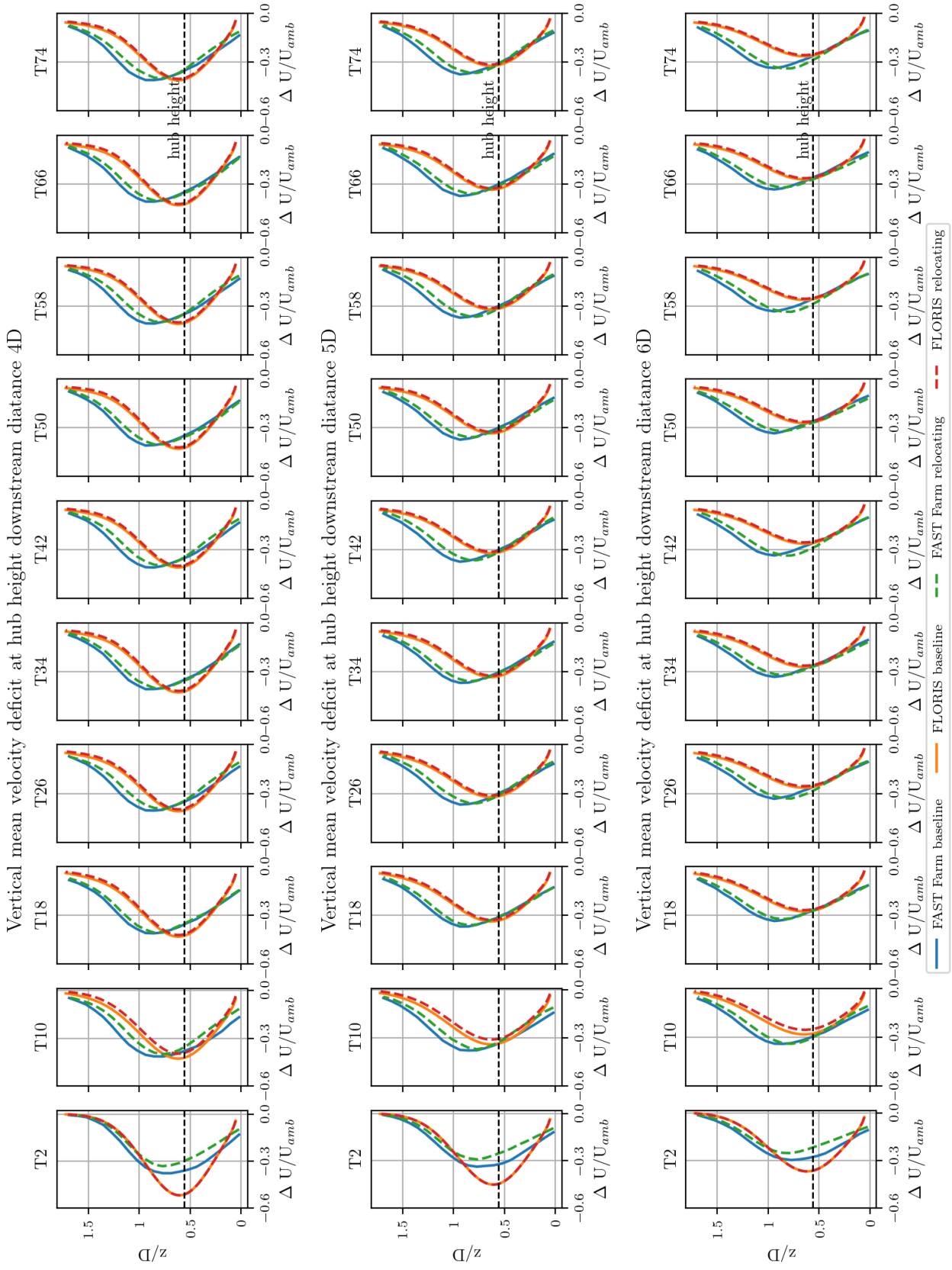


Figure 7.21: Vertical velocity deficit for the second row for the layout with two unique MS designs

The wind flow in the vertical plane passing through Turbine 2 was saved every 9 s, and the last 3600 s were used to calculate the velocity deficit profile. The wake profile saved did not move with the FOWT. Hence, it only passes accurately through the center of all turbines in the second row of the layout for the BMS. For the relocating design with one unique MS design and two unique MS designs, the vertical plane does not pass through the center of the turbines. The average vertical velocity deficit profiles for all three cases in FAST Farm and FLORIS are shown in Figures 7.20, and 7.21. The profiles are drawn at three different downwind distances behind each turbine of $4D$, $5D$, and $6D$.

Also, for the vertical velocity deficit, the wake recovery for FLORIS is faster than that of FAST Farm. As the Figures show, despite the higher velocity deficit in FLORIS at $4D$ downwind, FLORIS wake recovery is faster, and at a downwind distance of $6D$, only the turbine in the free flow (Turbine 2) has a higher velocity deficit than FAST Farm. The wake center for FLORIS is at the hub height, while in FAST Farm, the wake center is higher. This is expected as the mean pitch angle of the FOWT shifts the wake upwards. This is only captured in FAST Farm and not in FLORIS. The biggest difference between FAST Farm and FLORIS is that the velocity deficit for the upper half of the rotor is much higher in FAST Farm than in FLORIS. This and the slower wake recovery in FAST Farm explain why the wake losses predicted in FAST Farm are higher.

Finally, the wake center of the relocating MS designs in both Figures is lower than when the FOWTs are coupled to the BMS. This can be because the vertical wake plane does not cut perfectly through the center of the relocating Turbines or because of the change due to the effect of the FOWT's crosswind movement on the wake development downwind. Since the velocity deficit profile behind the first turbine in the free flow does not match, it indicates that it is more likely because the vertical wake profile does not perfectly cut through the center of the turbine. The velocity deficit profile also alternates between each column in the relocating design for the FAST Farm results as the MS design alternates. However, the vertical velocity deficit profiles of the layout with the BMS and the customized MS designs in FLORIS are identical to those with one unique MS design. The velocity deficit is slightly lower for the layout with the two unique MS designs compared to the layout with the BMS in FLORIS.

7.7 Conclusion

In this chapter, I applied the method for relocating the FOWT to increase AEP on the Horns Rev 1 layout. I added a constraint that the layout can have only one or a maximum of two unique MS designs. I also considered relocating the FOWTs only for two and not all wind directions. These assumptions make the designs useful for more practical cases where relocating the FOWTs will be beneficial.

The results show that the method needs modification when one unique MS design is used, and the AEP gain in this case was negligible. However, the one unique MS design cost was 13% lower than the BMS. The method did not perform well in these cases because all wind directions at which FOWT relocation was intended were treated equally. However, one direction had a much higher probability of occurrence than the other. In cases with one MS design, the wind direction with a higher probability should be prioritized. On the other hand, the results with two unique MS designs were very promising, predicting an AEP gain of around 1% when a dynamic wake model was used. The cost of the MS also decreased by 6%. This highlights the potential of considering FOWT relocations as a design parameter in the FWF layout planning phase to increase the FWF AEP.

The loads on the mooring lines, tower base, and blade roots of both cases were checked. The loads were always within the same range as the loads of the BMS. Then, the difference between the AEP predicted with the dynamic wake and steady-state models was discussed, and the main reasons for the difference were shown. The effect of the relocation on the velocity deficit and turbulence saturation was also shown.

With the results of this chapter, all the research goals of this work were achieved and thoroughly discussed. The chapter represents a perfect wrap-up for all the results shown in the thesis and highlights the work needed in the future to increase the TRL of the design ideas presented. The future work and the overview of the results are discussed in the final chapter.

CONCLUSION

“*No research is ever truly completed; it is simply set aside,
awaiting the next curious mind to continue its journey.*”

8.1 Summary of research

The aim of this study is to determine if the MS of the FOWT can be designed to benefit from the FOWT’s ability to relocate. Since FOWTs are not fixed to the seabed but are moored to it using mooring lines, this allows them to move around their unloaded position. The magnitude of FOWT displacement for each wind speed and direction is governed by its MS design. Therefore, a passively self-adjusting FWF layout is possible through customizing the MS design, and the concept shows a high potential to decrease the wake losses of an FWF.

This research began with this simple idea. To the best of my knowledge, this approach has not been explored before in any research work. I started with small, simple steps, gradually increasing the idea’s TRL level and building it brick by brick from the bottom up. The thesis is structured similarly, following critical thinking approaches at each step along the way. The first chapter introduces the research question and the motivation behind this research. In Chapter 2, I introduced the current state-of-the-art FWF modeling and design and the tools and methods used in my work. I introduced the method I developed to design passively self-adjusting FWF layouts using simple quasi-static steady-state tools in Chapter 3. I followed the methodology chapter by checking how different inputs and user decisions affect the tool’s performance in Chapter 4. Then, I started checking the performance of the designed MSs and FWF layouts

using mid-fidelity time domain tools. Chapter 5 checked the fatigue and ultimate loads on the FOWT when coupled to multiple MS designs with different yaw stiffnesses. The AEP gain achieved by the passively self-adjusting FWF layouts is verified in Chapter 6 also using mid-fidelity dynamic wake models. Finally, in Chapter 7, Horns Rev 1 wind farm is used to apply the methods developed throughout the work, highlighting the potential of relocating the FOWT on the FWF's AEP on a real case scenario with more constraints.

The rest of this chapter is organized as follows: I introduce the key contributions of this work. Then, I will discuss the limitations and the assumptions made during the analysis. Finally, I discuss how one can build on this work in the future for future research.

8.2 Key contributions

This section presents the key contributions achieved through this work. The contributions are divided into three sections according to their relevance to the three research questions answered by this research.

8.2.1 Can passive relocation of FOWTs inside an FWF reduce wake losses and the MS costs?

Passively relocating the FOWT increases the AEP of the wind farm. The increase is highly affected by the FWF layout and the windrose of the FWF site. An FWF that is already optimized has lower wake losses; hence, the AEP gain that can be achieved by relocating the FOWT is limited. However, most wind farm layouts are grid-shaped and suffer high wake losses between 10% – 15%. For gridded layouts, passively relocating the FOWT presents an opportunity to mitigate these wake losses, as illustrated in Chapters 4 and 7. The AEP gain occurs only at below-rated wind speeds, so if the wind rose is highly shifted towards above-rated wind speeds, the AEP gain due to relocating decreases. The self-adjusting FWF layouts were designed using the open-source tool FloatingWAYS (Mahfouz, 2024).

Additionally, the fidelity of the wake model affected the absolute value of AEP gain, which can be achieved by passively relocating the FOWT. I used steady-state wake models to design the self-adjusting FWF layout and the MS design coupled to each FOWT. Then, I used mid-fidelity dynamic wake models to verify the results. The verification showed that the dynamic models predict lower AEP gain than the steady-state wake models, where the dynamic wake models predict between 46% to 53% of the AEP gain in the steady-state wake model. The reasons for these differences can be summarized in the following points:

- The wake recovery in the steady-state wake model at downwind distances higher than $5D$ was faster than the dynamic model.
- The wake in the steady-state wake model was symmetric on both sides of the rotor, but for the dynamic wake model, the wake was shifted to the positive side of the rotor. This made relocation in one direction more beneficial than the other.
- Vertical wake deflection due to steady-state platform pitch was not captured in the steady-state wake model.
- The velocity deficit on the upper half of the rotor was higher in the dynamic wake model than in steady-state ones.

Despite these differences between the wake models, the AEP gain distribution over wind speeds and wind directions was as predicted, and the differences do not affect the credibility of the results but open the door for future research. Using the dynamic wake models, a passively self-adjusting FWF layout of nine turbines achieved an AEP gain of 1.5%, and an AEP gain of 1% was achieved for the Horns Rev 1 layout.

The AEP gain increases as the crosswind displacement increases, as a larger area of the downwind rotor becomes out of the wake. Therefore, as the area of the rotor diameter decreases, the FOWT's relocation will become more beneficial. In this work, I used the IEA 15MW reference wind turbines with rotor diameters of 240 m. The AEP gain will be more beneficial for the 12 MW or 10 MW turbines as they have smaller rotor diameters; I chose to use the largest available turbine when I started my research to be more conservative.

Although the MS cost was not an optimization objective in the self-adjusting FWF design process but only a constraint on accepting the MS designs, the MS costs of all the self-adjusting FWF layouts decreased. This is expected as allowing the FOWT to relocate means that MS is less stiff. The MS designs used in this work all consist of three catenary-shaped mooring lines made of steel; a less stiff catenary mooring line is also less heavy. As the mass decreases, the material decreases; hence, the mooring line's cost decreases. The costs of the anchors are a function of the mooring line's MBL, so a line with a smaller diameter will have a lower MBL and a cheaper anchor. This can differ for taut or for mooring lines made out of different materials, which again opens the door for future research and investigation. The decrease in MS costs for the gridded design used in the detailed dynamic analysis was 4%; for the Horns Rev 1 self-adjusting layout, the decrease in MS cost was 6%.

8.2.2 How do the MS design parameters affect the watch circle?

The watch circle is the area within which the FOWT roams; the shape and size of the watch circle are governed by the MS design. Therefore, the different design parameters affect the ability of the FOWT to relocate and how much of the relocation is in the crosswind or aligned with the wind direction. In Chapter 3, section 3.4.4, I analyzed how the different parameters affect the MS watch circle. The findings can be summarized in the following points:

- The shape of the watch circle depends on the mooring line headings. Any MS with the same heading will have the same watch circle shape. The size of the watch circle can be tuned by altering the other MS design parameters.
- Increasing the mooring line length or decreasing the diameter increases the magnitude of the displacements and vice versa. However, the effect of the line length on the relocation is more significant than the effect of the line diameter. The anchoring radius has a negligible effect on the relocation.
- The amplitudes of the displacement increase for the wind directions blowing between two mooring lines by increasing the angle between the two lines' headings and vice versa.
- The displacement aligned with the wind direction is highest when the wind blows exactly in the middle between two mooring lines' headings.
- The crosswind displacement is negligible if the angle between two mooring line headings is less than 90° for all wind directions between the two lines.
- For the span of wind directions between two mooring lines, the crosswind displacement has two peaks close to each line and reaches zero when the wind direction is exactly in the middle of the two lines.

Understanding the effect of the MS design parameters simplified my method for selecting the appropriate MS design for each FOWT within the FWF. This insight also opens the door for future work on developing a machine-learning model based on surrogate models to design MSs that self-adjust FWF layouts without creating the MS database.

8.2.3 What are the consequences of relocating FOWTs on the fatigue and ultimate loads experienced by the FOWT?

The self-adjusting FWF layout's MS is less stiff than conventional MS designs, allowing larger displacement in the x and y directions. However, these are not the only DoFs the MS is responsible for providing stiffness for, as the MS is also responsible for providing yaw stiffness for the FOWT. A softer MS design also leads to higher yaw displacement, which affects the load

on the different components of the FOWT. To understand the effect of the lower MS stiffness on the FOWT loads, I analyzed the fatigue and extreme loads on the FOWT's mooring lines, tower base, and blade roots in Chapter 5. To understand how the MS stiffness affects the results, I used three layouts with different MS stiffness ranges: 9 times lower than the state-of-the-art MS design, 5 times lower than the state-of-the-art MS design, and 4 times lower than the state-of-the-art MS design.

The effect of the MS yaw stiffness on the FOWT's response was only noticeable for wind speeds higher than 20 m/s; for lower wind speeds, the loads on the FOWT were within the same range as the loads on the FOWT when coupled to a state-of-the-art MS design. At above-rated wind speeds, as the blade pitch angle decreases, the aerodynamic yaw moment increases, leading to an increase in the platform yaw of the FOWT. As the yaw angle increases, the pitch and roll angles increase, leading to higher fatigue and maximum loads at the tower base. The maximum loads at the tower base were higher than the acceptable structure loads on the tower for the MS designs with the lowest MS stiffness, which led to tower structural failure. The minimum yaw stiffness required to avoid any increase in the MS fatigue or maximum values was 67 MN/rad. The blade root loads also increased in cases with small MS stiffness, but the increase was negligible compared to the increase in the tower base loads. However, these results have a high level of uncertainty as the analysis was performed using OpenFAST, which uses a small angle approximation for the FOWT's platform motion. For the MS with low stiffness, the yaw angle is higher than the range within which small angle approximations are acceptable.

The effects of the small yaw stiffness can be mitigated using an IPC controller similar to the approaches used for single-point MSs, which do not provide yaw stiffness. However, this has not been discussed in the current work. Moreover, the higher yaw misalignment only happens at mean wind speeds above 23 m/s for the MS designs with yaw stiffness 5 times lower than the state-of-the-art MS design. These wind speeds are rare, and it is highly probable that it is not economical to operate the turbine at such wind speeds or that the turbine will reach the cut-off speeds already as the maximum of the wind speeds when the mean is 23 m/s is above the cut-off value due to the turbulence of the wind field. Finally, the blade and tower loads do not increase with the MS designs that are 4 times lower than the state-of-the-art MS design for all wind speeds and wind directions.

The fatigue and maximum loads on the mooring lines were affected not directly by the lower yaw stiffness but by other parameters. The effect can be summarized as follows:

- As the mooring line diameter decreases, the fatigue damage of the mooring lines increases. This is because a smaller line diameter leads to a smaller MBL, which increases the mooring line fatigue damage.

- The fatigue damage of less stiff MS with a smaller mooring line diameter was within the same range as that of a stiff MS with a larger diameter.
- The highest MS fatigue damage occurs at the rated wind speed, where the MS stiffness is highest.
- The maximum tension force of the soft MS design is always lower than the state-of-the-art stiff MS design for all cases.
- The mooring line DEL is affected by the MS orientation and mooring line headings:
 - The highest DEL of a mooring line occurs when a line is upwind. Hence, no mooring lines should be placed upwind for the most probable wind direction.
 - If the headings between all three lines are equal, the DELs are symmetric for all three lines. The span of wind directions at which the DELs are high for each mooring line is 120° .
 - The span of wind directions at which the DELs of a mooring line are high decreases if the headings between the mooring line and its neighboring line decrease and vice versa.
 - If a mooring line has a larger heading difference with one neighboring line than the other, the highest DEL shifts away from being aligned with the mooring line. Instead, it moves closer to the neighboring line with the larger heading difference.

The results show that relocating the FOWT is possible without increasing the loads on the FOWT's component or compromising its reliability. For the stiff MS designs, which do not increase the loads of the FOWT, the AEP gain was 1.5% for the grid layout and 1% for the Horns Rev 1 layout.

8.3 Limitations and future research

In this section, I will review all my assumptions and limitations during this work and touch on a couple of research ideas that can be tackled in future work.

8.3.1 Assumptions and limitations

The research topic's novelty provided ample space to investigate and learn. Still, it also required making some assumptions for simplicity or due to the limitations of the tools I used. I start with the assumptions I made to simplify the research process:

- I chose to use the IEA 15MW reference wind turbine with a semisubmersible platform. The turbine rotor was selected because this was the largest available turbine when I started this work and will give the most conservative results of AEP gain due to relocation. Smaller turbines will show higher gain values as their rotor diameter is smaller. I had the choice of using a semisubmersible or a spar floating platform, so I chose the semisubmersible one because it is easier to design its MS. A crowfoot mooring configuration is required for a spar platform to provide the yaw stiffness.
- When designing the passively self-relocating FWF layout, while choosing the MS design, I neglected the wake effects on the FOWTs displacements. I assumed all FOWTs in the FWF would have the same average rotor wind speed as the mean inflow wind speed. This would have affected the optimization process and enhanced the results but would have made it computationally expensive. Therefore, in Chapter 3, I followed the simple and computationally efficient option. I consider the effect of the wake on the relocation of the FOWT later on in Chapter 6 while calculating the full AEP of the FWF, which showed that this assumption has a limited effect on the predicted AEP gain values.
- I assumed constant seabed depth throughout the FWF lease area; this is unrealistic as the depth would vary in the FWF lease area. However, the MS designs can be updated to have the same watch circles by tuning the MS design parameters.
- I assumed the soil type would be the same over the FWF lease areas. The type of soil will change the type of anchor used. I assumed the DEA would always be suitable for use throughout the FWF.
- I assumed the mooring lines were made of steel chains and did not investigate different materials that can be used in the 200 m water depth sites, such as sheathed steel wire.
- I assumed the mooring line fairleads could be attached anywhere over the Activefloat platform and not only at the tip of the three pontoons. This assumption was necessary to test different mooring line heading combinations.
- I designed asymmetric MSs where each line can have a different length, diameter, and anchoring radius without considering the effect of asymmetry on procurement, logistics, and installation.
- I did not consider the limitations on the FOWT imposed by the power cable design limits.

Other assumptions were made due to the limitations of the available tools used in the analysis. The main two limitations were the small angle approximation used for the platform rotational motions within OpenFAST, which increased the uncertainty of the results of any MS design with a platform yaw angle larger than 15° . The other uncertainty comes from the lack of validation of the dynamic wake model against higher fidelity tools. I used the curl wake model in FAST Farm with the tuned parameters of the NREL 5MW reference wind turbine from the work of Carmo et al. (2024). The work of Rivera-Arreba et al. (2024) checks the effects of yawing and pitching the rotor of the 15 MW without fully accounting for the platform motions; the work shows different tuning parameters for the polar wake model in FAST Farm, which I did not use as I was not aware of this research until I concluded my work.

8.3.2 Recommendation for future research

As my research approached its conclusion and the research questions were being answered, it became clear that this work only scratched the surface of the novel ideas presented. This is particularly true for the concept of relocating FOWTs and, more broadly, for FWF design and optimization. I will summarize some of these open questions and research opportunities in the following points.

1. Dynamic cable design for relocating FOWTs

No work has been done to investigate the excursion limits due to the cable design limitations. The current excursion limits are adopted from the oil and gas industry, where limited platform motion was allowed. Additionally, no open-access cable designs are available for research purposes. The existing work for cable design for FWF presented in Hietanen et al. (2024) uses static simple equations to account for the cable routing and losses in the FWF. The work of Abrahamsen et al. (2024) presents a first attempt to assess and understand the fatigue damage of the dynamic cable. However, none of the existing work sets a concrete limit on the excursions of the FOWT relative to the cable fatigue and ultimate loads. Answering this open question will allow FWF designers to decide how much the FOWT can relocate and how to use this relocation to decrease the farm wake losses.

2. FWF layout design tool integrating the FOWTs' relocation and the mooring lines design

This work created an open-source method to increase the FWF's AEP by allowing the FOWTs to relocate. I achieved this by integrating the MS design as a design parameter within the method. However, the method presented here lacks the effect of the sea bed bathymetry on MS design and lacks any information on cable routing. Other FWF design

and optimization tools presented by Hietanen et al. (2024) and Hall et al. (2024) consider many of these parameters but neglect the ability of the FOWT to relocate. A tool that integrates the MS design and the ability to relocate while considering cable routing and bathymetry is lacking.

Additionally, I used a database for the MS design. When an MS did not meet the cost or excursion constraint I defined, the replacement MS design came from the MS database. This means that only designs existing in the database are considered. Instead of using the database, optimizing the MS design using an optimization tool would cover the entire design space better than the database. The results I presented in Chapter 3 show the connection between the different design parameters and the watch circle shape and size. The database created in this work can feed a surrogate model to create a machine-learning tool to design the MS. The input to the tool would be the required watch circle, and the output would be the MS design that fits the input watch circle as closely as possible.

3. Machine learning techniques for MS designs which withstand fatigue loads

The results in Chapter 5 demonstrate how different MS design parameters, such as mooring line diameter, line headings, and MS orientation, affect fatigue damage and DELs of the mooring lines. The consistent relationship between each parameter and its effect on fatigue across all analyzed MSs suggests that a machine-learning model could be developed to predict the fatigue of MS designs based on these parameters. The inputs to the model would include the MS design and the wind rose. Furthermore, the model could be extended to predict how the loads on the mooring lines would change when the FOWTs are placed in an FWF compared to standalone configurations. In this case, the FWF layout would also be an input to the model.

4. The effect of relocation on AEP for taut MS in deep waters

Throughout this work, I focused on catenary MS designs with a water depth of 200 m. Catenary mooring lines have a non-linear force-displacement curve, allowing the stiffness to change with varying wind speeds and directions. The restoring force in catenary lines depends on the weight of the hanging length of the line. However, catenary mooring lines become uneconomical for deeper waters and taut mooring lines are used.

Taut mooring lines operate differently, with a more linear force-displacement curve, indicating constant stiffness. Hence, further investigation is needed to understand the limitations of designing a less stiff taut MS, the resulting loads on the mooring lines, and the different FOWT components, and how this affects the AEP gain due to relocating the FOWTs. Once this is explored, deeper sites could potentially benefit more from relocating the FOWTs, as the excursion limits increase with water depth.

5. Improving low and mid-fidelity wake models

The difference between the wake of the low and mid-fidelity tools used is analyzed in Chapters 6, and 7. The difference between the two wake models is large and it increases the level of uncertainty while designing a FWF. This is because the low-fidelity models do not capture the mean displacements of the FOWT. There are new developments to FLORIS that add a correction factor to the power curve to capture the effect of the platform pitching on the power. However, this still does not account for the vertical wake deflection. The work of Riva et al. (2024) was recently published and accounts for the FOWT's mean displacement on the wake development and propagation in PyWake, this can decrease the uncertainty in the AEP calculation in future work.

Despite the mid-fidelity wake model matching well in most cases with higher fidelity models, the work of Carmo et al. (2024) and Rivera-Arreba et al. (2024) show that there is still room for further development of the model to increase its reliability. For example, the polar model needed to be tuned separately for vertical and horizontal wake deflections due to pitching or yawing the FOWT. Additionally, the model cannot capture the wake's pulsation due to the fluctuation of the surge motion of the platform, which affects the DELs calculation.

6. FOWT's passive relocation coupled with wake steering using yaw control

Wake steering using yaw control increases the crosswind motion of the FOWT, as the yaw misalignment increases the crosswind aerodynamic yaw motion. A larger crosswind motion can decrease the benefit of the wake steering techniques using yaw misalignment. This idea is touched upon in the works of Lozon et al. (2024), but only using static tools with a steady wake model. I believe that wake steering with yaw misalignment and passively relocating the FOWT can go hand in hand, so a detailed analysis is required. This detailed analysis should include a fully functioning yaw controller that can account for the dynamic yaw motion of the platform and set the nacelle yaw accordingly.

7. Operation strategies of FWF

In this work, I did not change the controller for the different MS designs; a simple baseline wind turbine controller was used in all cases. Additionally, no specific operation planning technique was adapted for the wind farm. The FOWTs were assumed to be running full-time, and the wind rose was used to define the probability of occurrence of wind speeds and directions. Wind fields with a mean between 4 m/s and 25 m/s were simulated, although, in reality, the FOWTs will be shut down before the mean wind speed reaches 25 m/s. The results show that the above-rated wind speeds increase the loads on the FOWT tower as the MS design becomes more flexible, which limited my work to stiffer MS designs, thereby decreasing the potential AEP gain due to relocation.

For higher wind speeds with higher loads, two ideas for the FWF operation strategies can be investigated:

- Applying IPC controllers at higher wind speeds: Implementing IPC controllers at higher wind speeds could mitigate the low MS yaw stiffness, similar to methods used for single point MS designs (Sandua-Fernández et al., 2023) and (Namik and Stol, 2010).
- Adaptive operation strategy: An adaptive condition-based operation strategy, as introduced by Requate et al. (2023), can enhance the profit of the FWF by aligning its operations with the prevailing environmental conditions. In this approach, if the damage inflicted by a load case is high and the price of electricity is low, the turbine would either operate in a derated mode or be shut down, and vice versa. At higher wind speeds (above 20 m/s), all wind farms in the region typically operate at full power, reducing the electricity price. Therefore, shutting down turbines at such wind speeds could be more beneficial.

Adopting a long-term operation strategy could enable the use of less stiff MS designs, leveraging their larger relocations to increase the AEP of the farm.

8.4 Final Reflections

As discussed in Chapter 1, FOW needs to grow 2000-fold over the next 28 years to achieve global energy transition goals. Increasing the efficiency of FWFs plays a crucial role in meeting these goals, which motivated the work presented in this dissertation. This study explored a novel idea to benefit from passively relocating the FOWTs within the FWF to decrease wake losses. Additionally, the increase in FWF AEP should not be accompanied by increased MS costs or higher FOWT fatigue and ultimate loads.

The study achieved its goals by designing passively self-adjusting FWF layouts. A passively self-adjusting FWF layout of nine FOWTs resulted in an AEP gain of 1.5% and a reduction in MS costs by 4%. The Horns Rev 1 site was also used to demonstrate the method, showing an increase in AEP by 1% and a decrease in MS costs by 6%. These results highlight the proposed method's potential to contribute significantly to the efficiency and cost-effectiveness of FWFs. The self-adjusting FWF layouts were created using the newly developed open-source tool FloatingWAYS (Mahfouz, 2024), which can be used as a cornerstone for future developments.

I look forward to further developments of this idea and future collaboration on all the open research questions presented earlier. I understand that finding a research idea for a PhD is not always straightforward, and I hope that someone will benefit from these future recommendations

to build on the results achieved in this work. By advancing the development of ideas to increase the FWFs' efficiency and sharing knowledge broadly, one can help the FOW community progress and achieve the planned goals by 2050.



METHODOLOGY APPENDIX

A.1 Targeted layout at each wind direction

The Figures in this section show the targeted layout for each wind direction for the design discussed in Chapter 3.

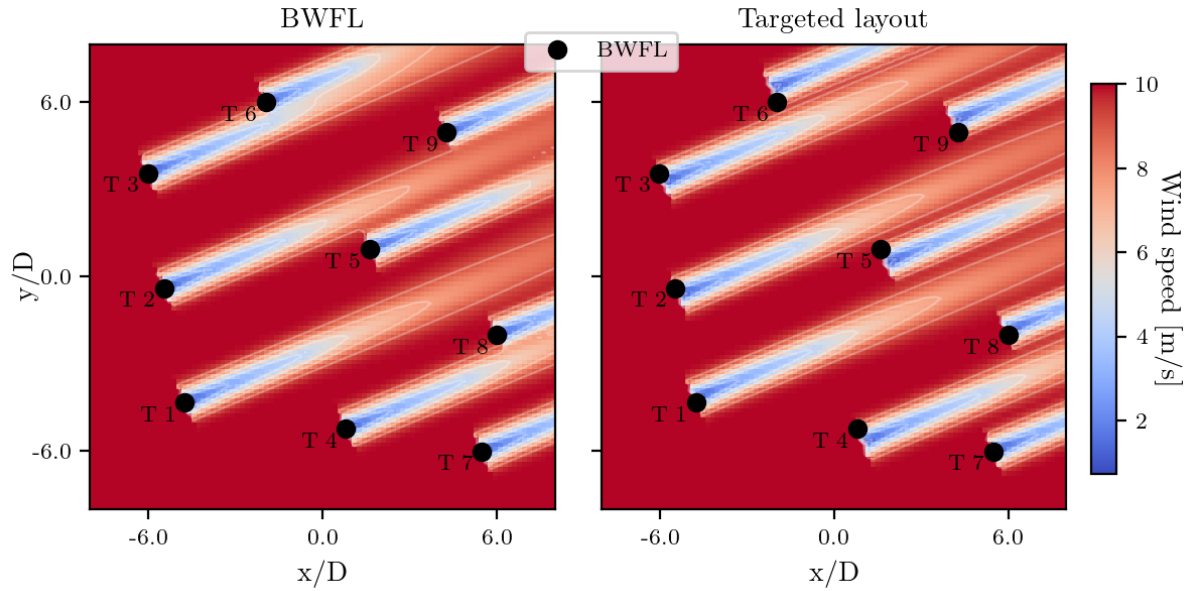


Figure A.1: BWFL and targeted layout for wind direction of 22.5° . The black dots represent the BWFL.

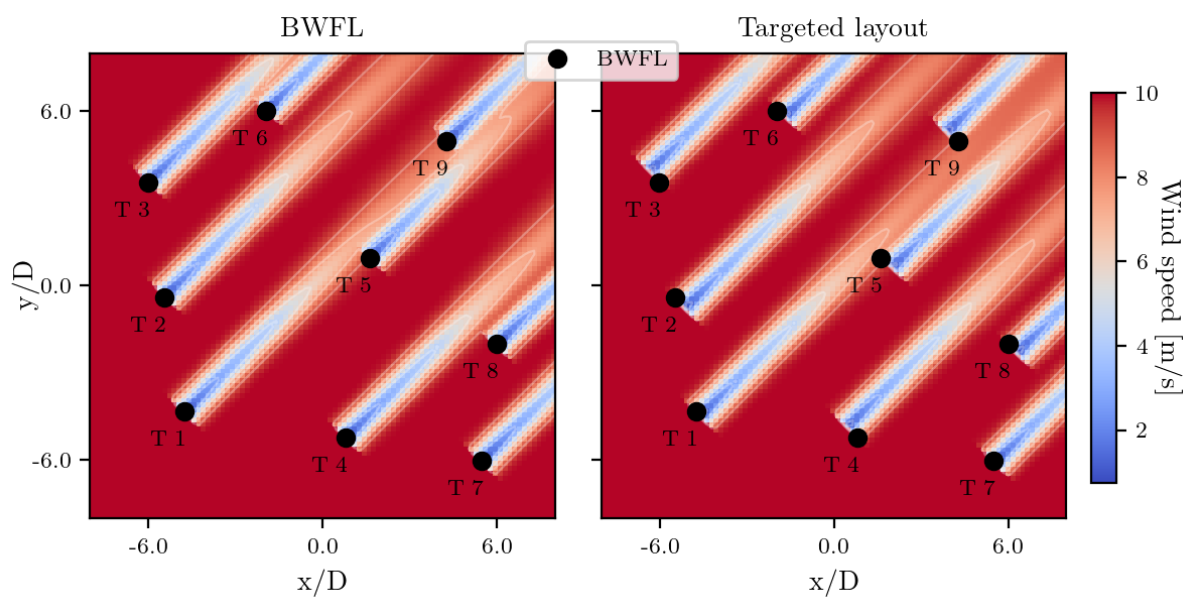


Figure A.2: BWFL and targeted layout for wind direction of 45° . The black dots represent the BWFL.

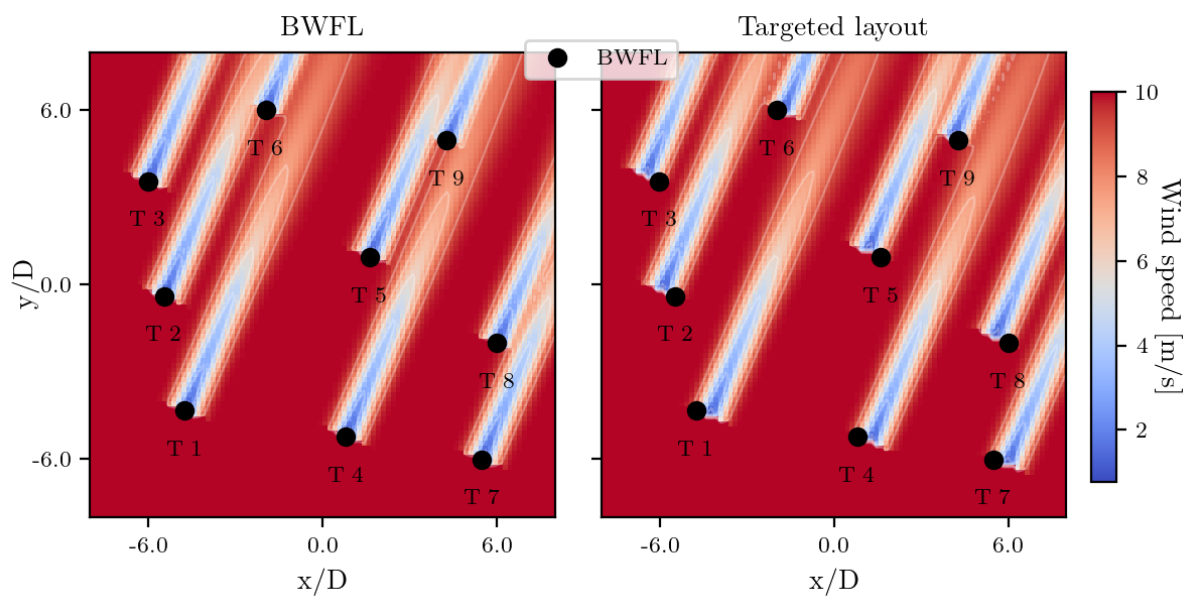


Figure A.3: BWFL and targeted layout for wind direction of 67.5° . The black dots represent the BWFL.

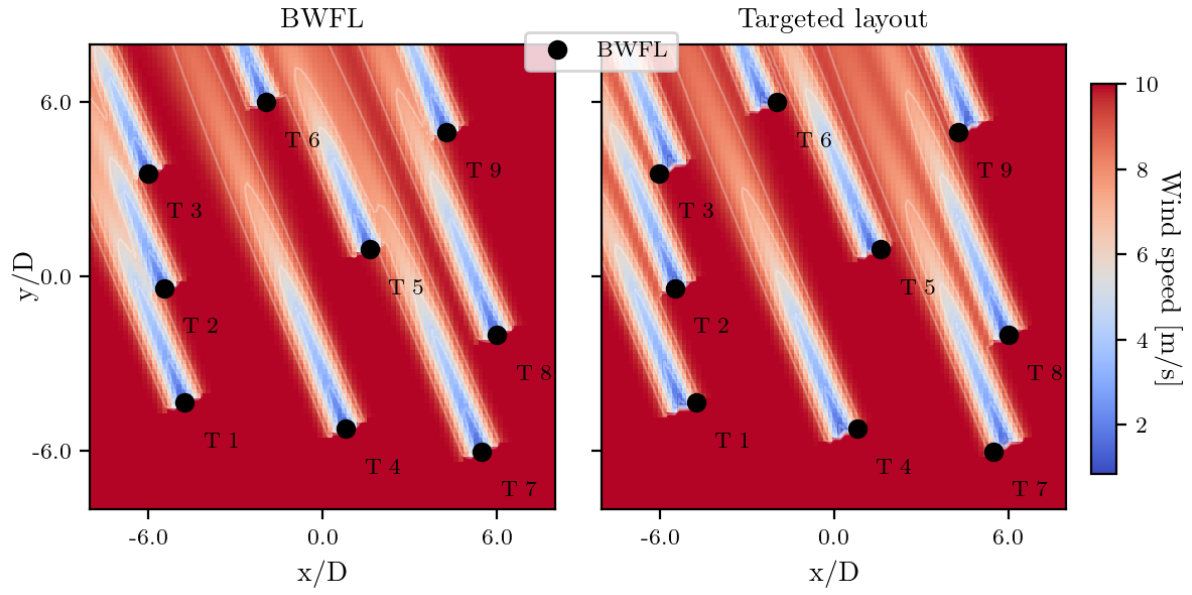


Figure A.4: BWFL and targeted layout for wind direction of 112.5° . The black dots represent the BWFL.

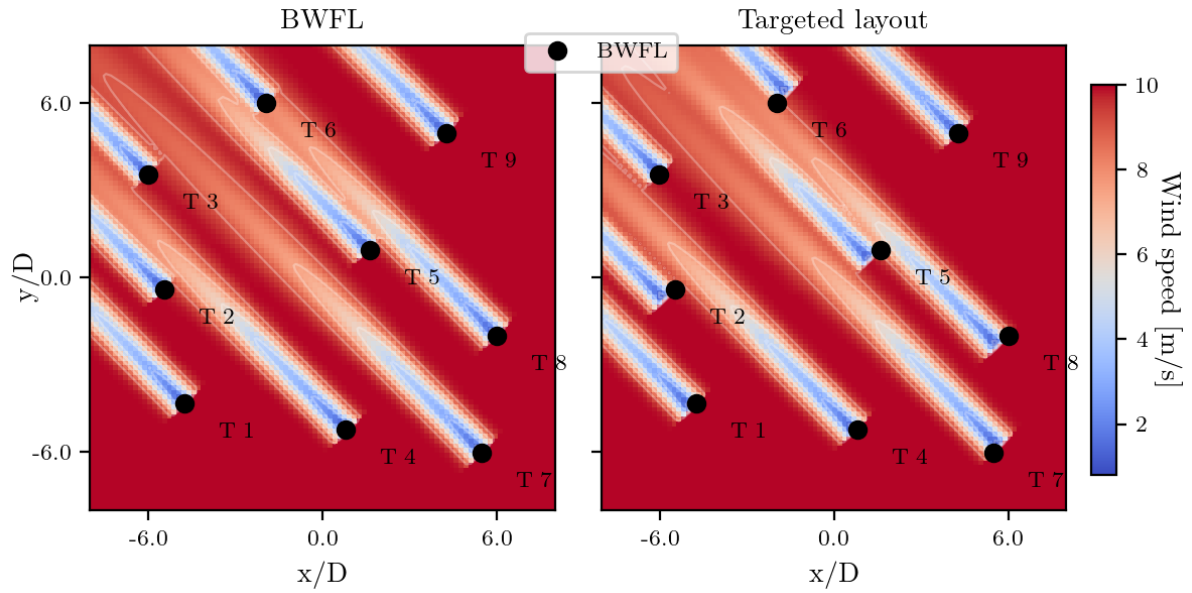


Figure A.5: BWFL and targeted layout for wind direction of 135° . The black dots represent the BWFL.

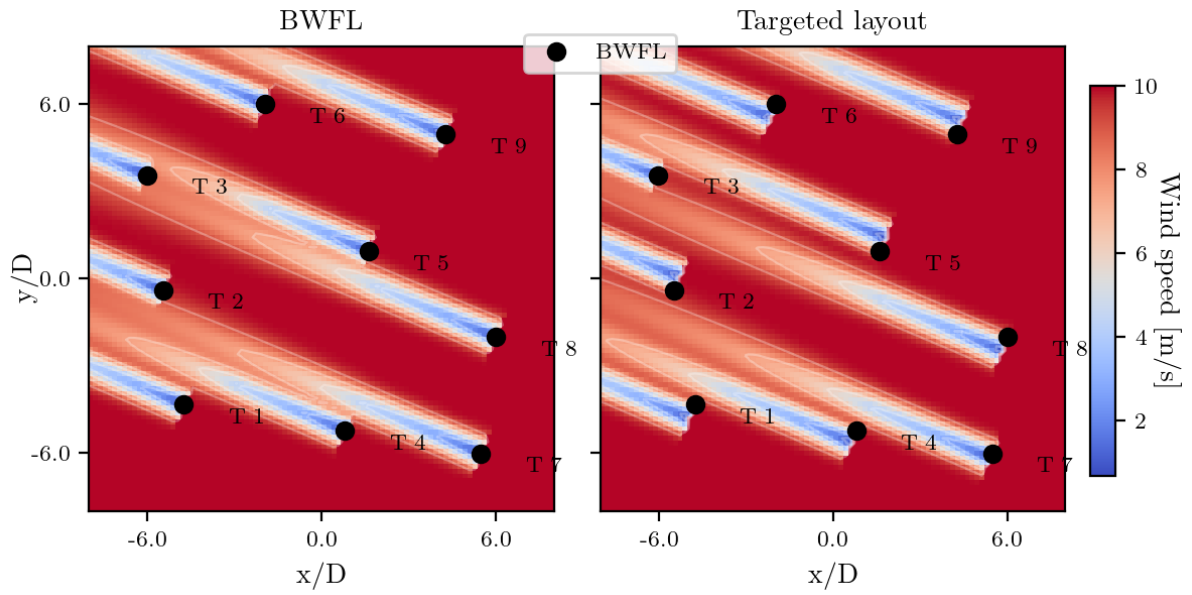


Figure A.6: BWFL and targeted layout for wind direction of 157.5° . The black dots represent the BWFL.

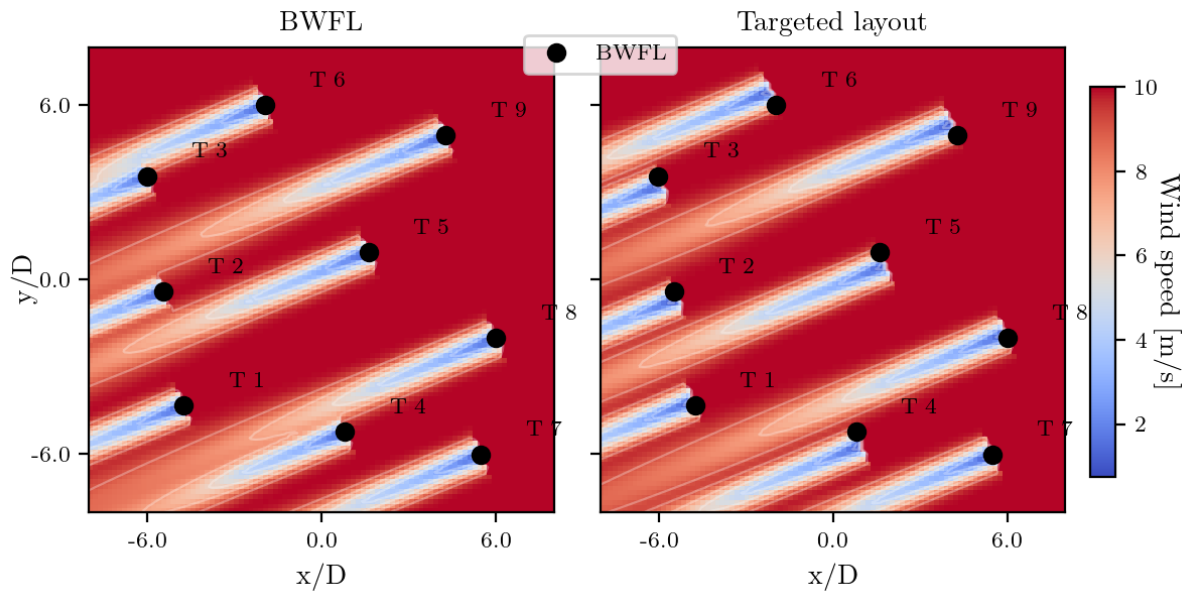


Figure A.7: BWFL and targeted layout for wind direction of 202.5° . The black dots represent the BWFL.

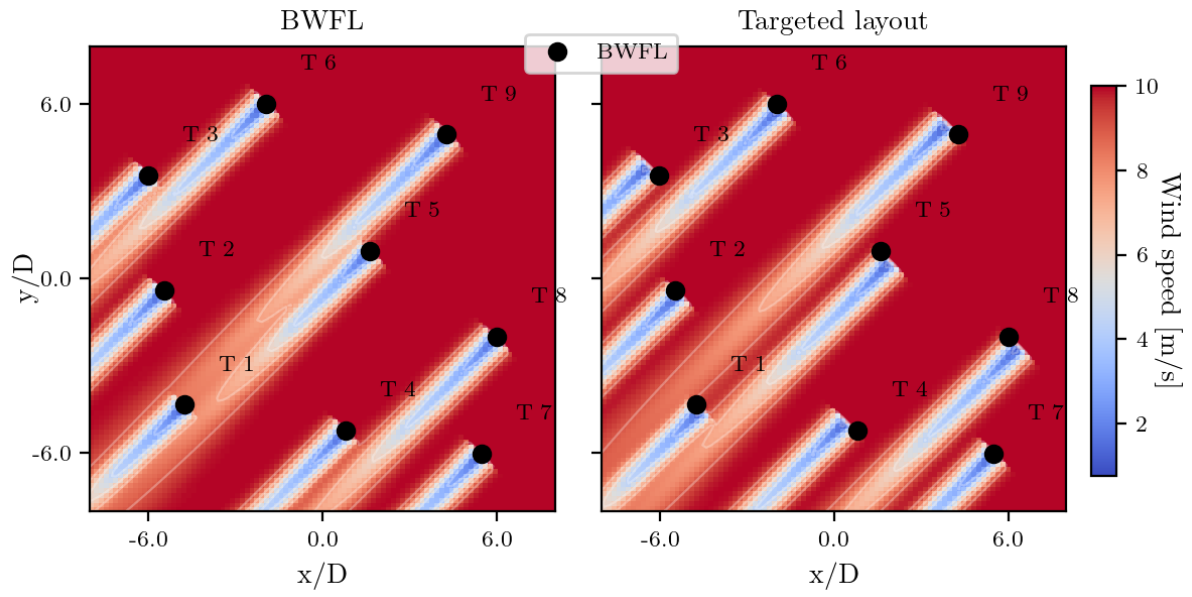


Figure A.8: BWFL and targeted layout for wind direction of 225° . The black dots represent the BWFL.

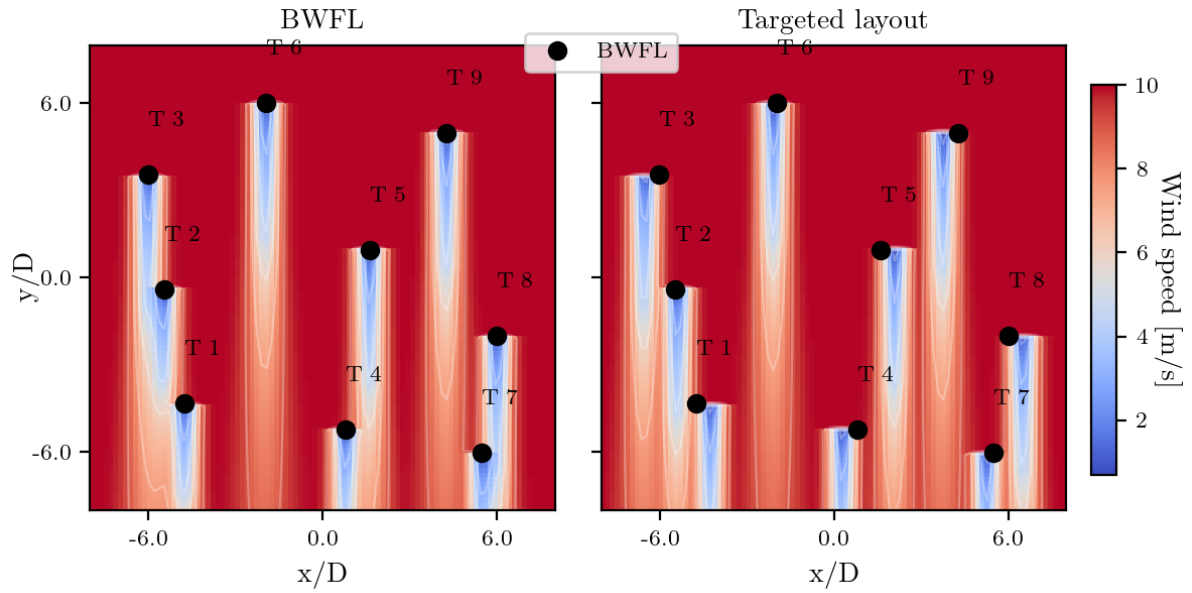


Figure A.9: BWFL and targeted layout for wind direction of 270° . The black dots represent the BWFL.

A.2 Change in aerodynamic forces due to FOWT's rotational motions

Figures A.10, A.11, and A.12 show how the aerodynamic force vector changes as the FOWT rotates around the x-axis, y-axis, and z-axis, respectively.

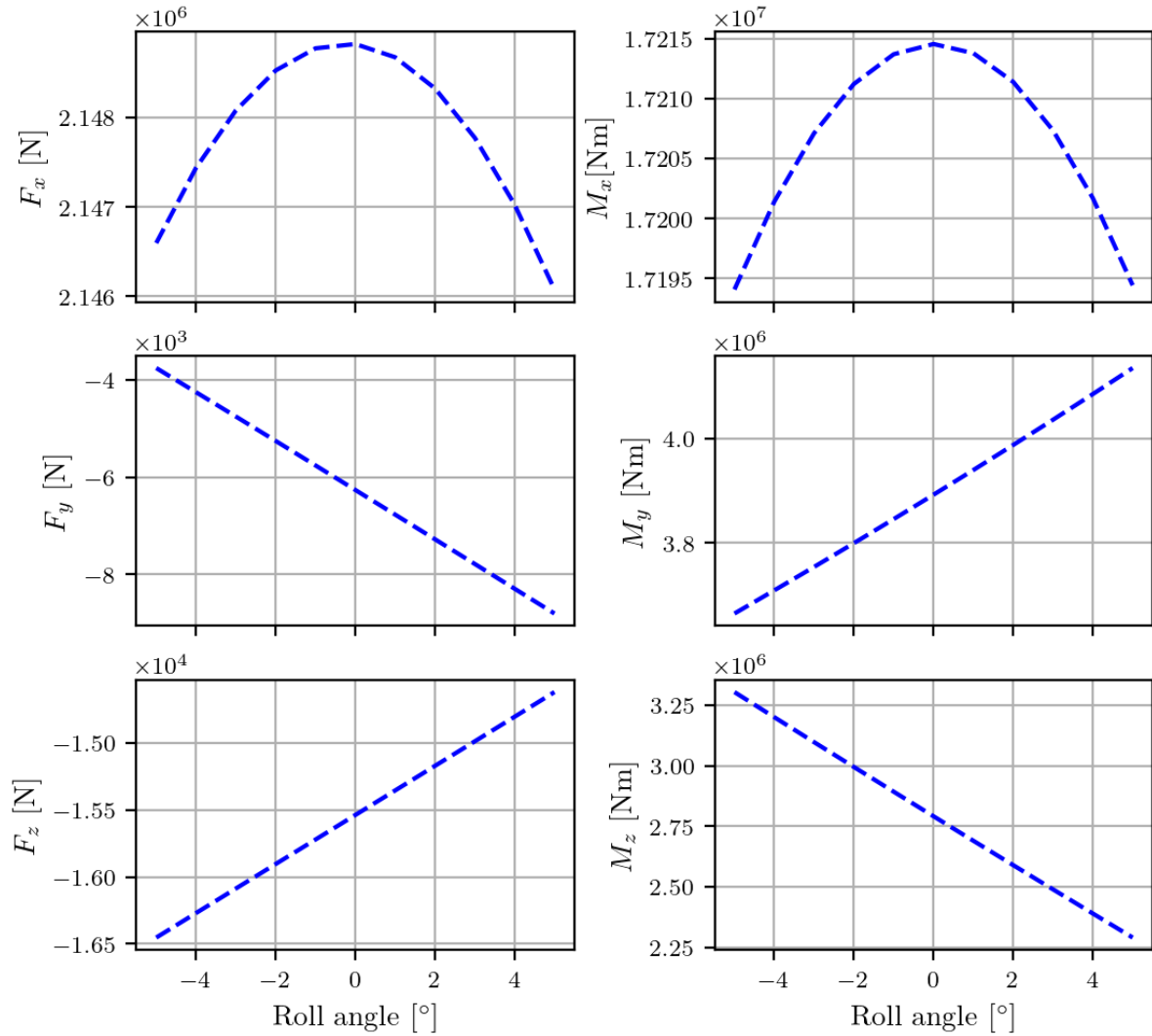


Figure A.10: Effect of platform roll motion on aerodynamic forces and moments

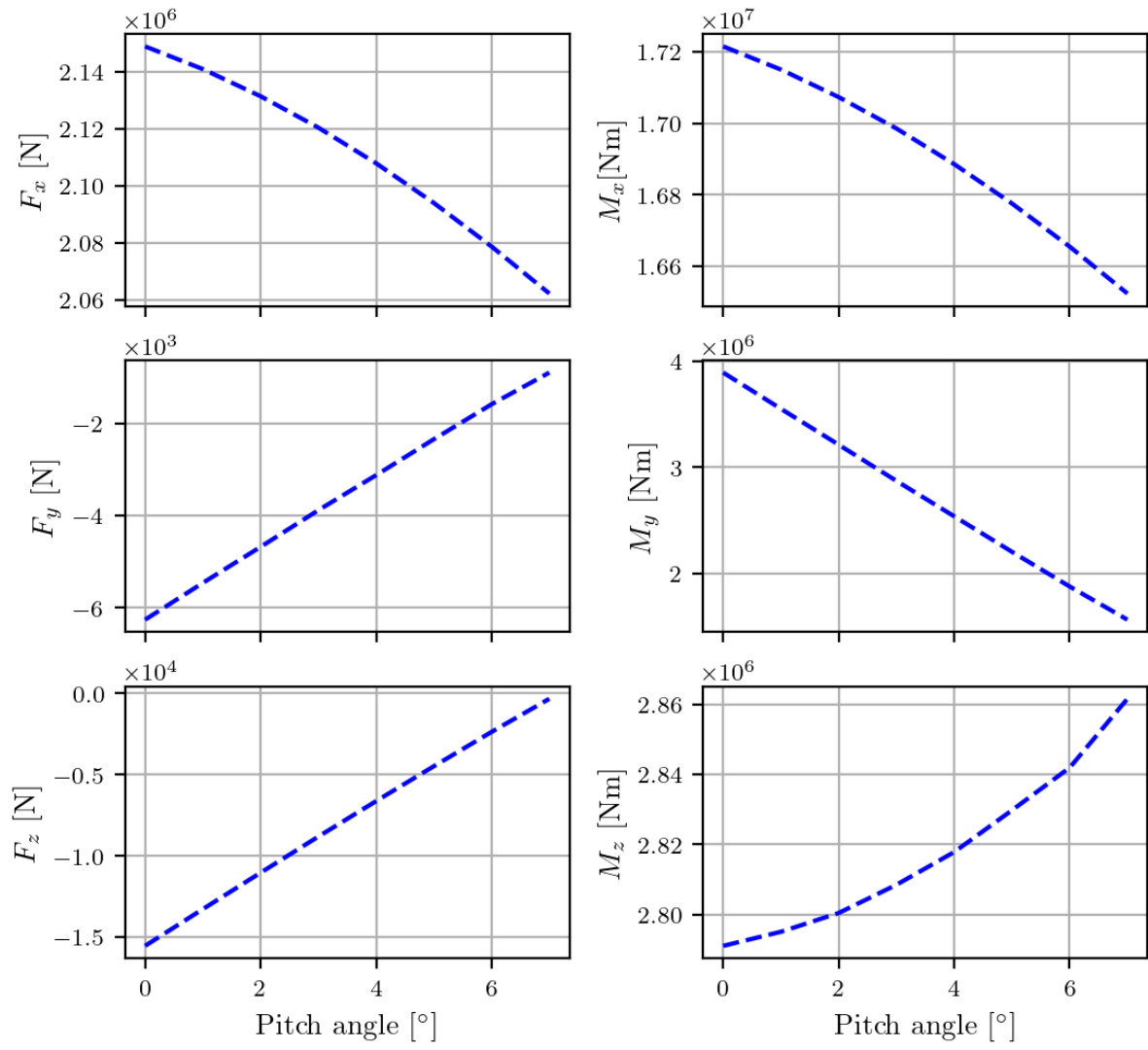


Figure A.11: Effect of platform pitch motion on aerodynamic forces and moments

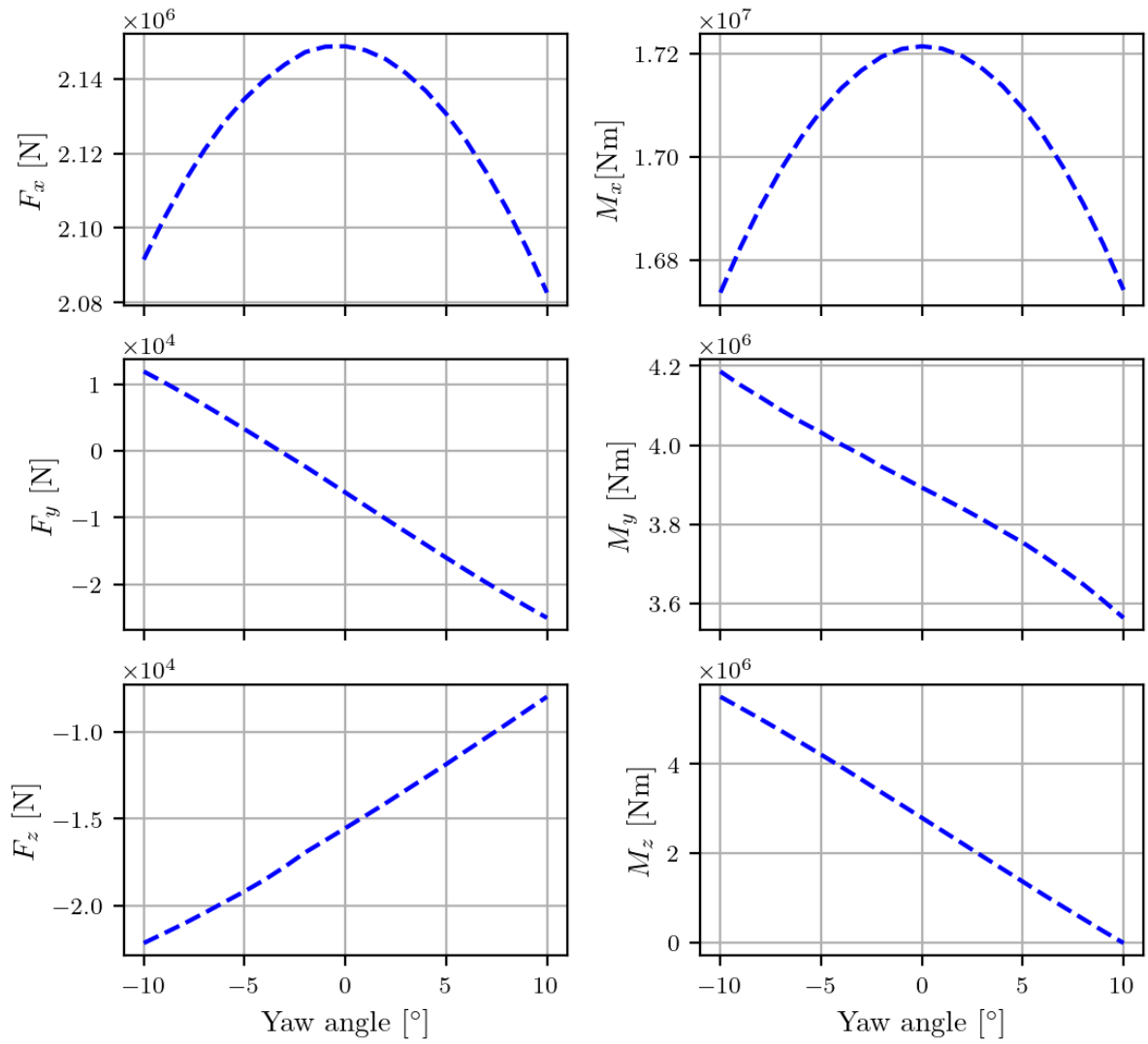


Figure A.12: Effect of platform yaw motion on aerodynamic forces and moments

A.3 The number of iterations needed for converging

Figure A.13 shows the mean of the maximum difference between each iteration step for all of the MS designs in the 5% sample. The maximum difference for each design is calculated for all wind directions. This is repeated for all designs and then the mean of all the maximum values is calculated. The Figure also shows the boundaries of the maximum differences.

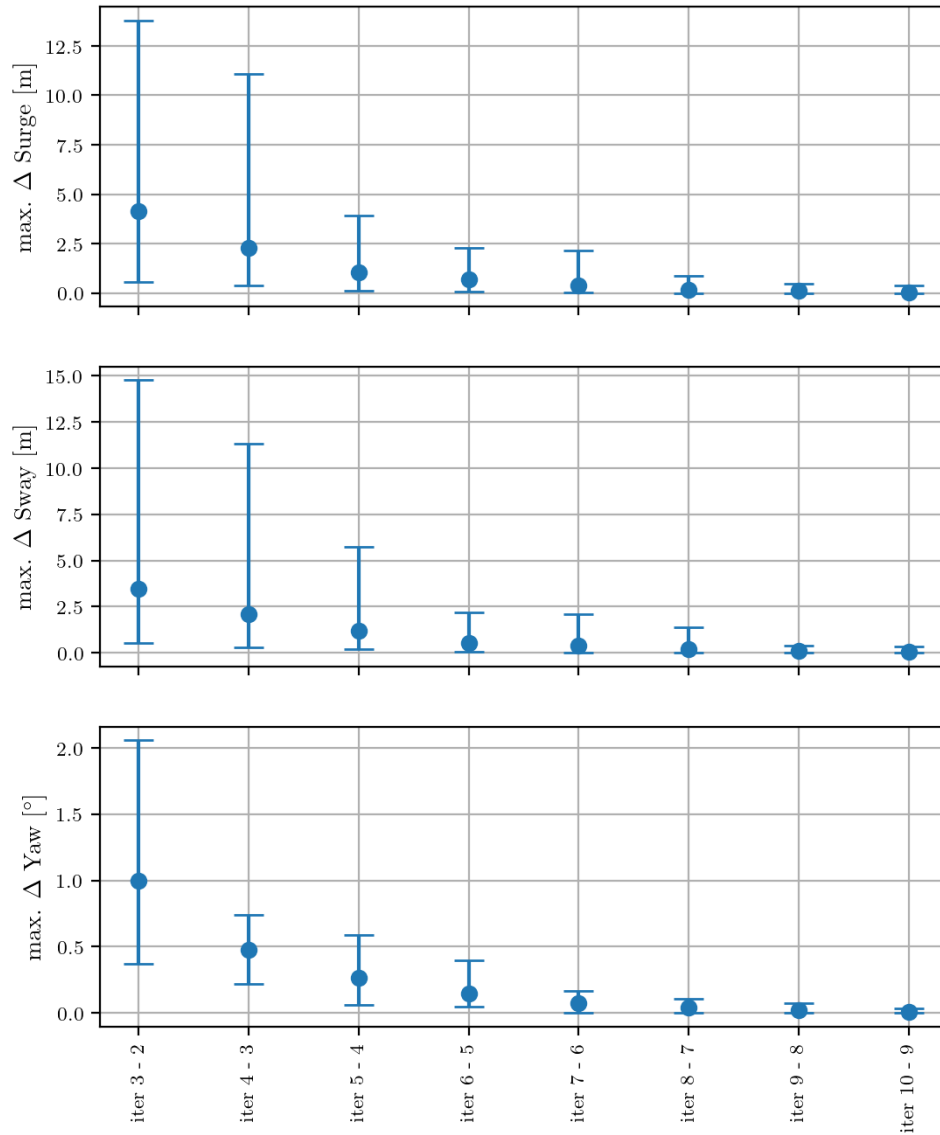


Figure A.13: Convergence per iteration in surge, sway and yaw DoFs respectively

MS DESIGN PARAMETERS

Table B.1: Customised MS designs for the BWFL with yaw angle range of $\pm 5^\circ$

	heading 1 [°]	d 1 [m]	AncR 1 [m]	L1 [m]	heading 2 [°]	d 2 [m]	AncR 2 [m]	L2 [m]	heading 3 [°]	d 3 [m]	AncR 3 [m]	L3 [m]
Turb 1	160	0.12	840	949.74	280	0.15	840	949.74	40	0.18	840	916.98
Turb 2	280	0.15	600	711.48	40	0.12	600	649.44	160	0.18	840	884.22
Turb 3	340	0.12	840	949.74	100	0.15	840	949.74	220	0.18	840	916.98
Turb 4	250	0.12	600	649.44	10	0.18	840	916.98	140	0.18	840	884.22
Turb 5	25	0.12	840	949.74	145	0.15	840	916.98	275	0.12	840	916.98
Turb 6	40	0.18	840	916.98	160	0.12	600	711.48	280	0.12	840	916.98
Turb 7	90	0.12	840	949.74	230	0.12	840	916.98	340	0.18	840	916.98
Turb 8	25	0.18	840	884.22	175	0.12	840	916.98	325	0.12	600	649.44
Turb 9	180	0.12	840	949.74	320	0.15	840	916.98	70	0.18	840	916.98

Table B.2: Customised MS designs for the BWFL with yaw angle range of $\pm 4^\circ$

	heading 1 [°]	d 1 [m]	AnchR 1 [m]	L1 [m]	heading 2 [°]	d 2 [m]	AnchR 2 [m]	L2 [m]	heading 3 [°]	d 3 [m]	AnchR 3 [m]	L3 [m]
Turb 1	145	0.12	840	949.74	285	0.18	840	884.22	35	0.15	840	916.98
Turb 2	185	0.18	600	680.46	305	0.18	600	649.44	95	0.12	840	884.22
Turb 3	100	0.15	840	916.98	220	0.12	840	916.98	340	0.15	840	916.98
Turb 4	110	0.12	840	884.22	270	0.15	600	649.44	10	0.18	840	884.22
Turb 5	140	0.15	840	916.98	280	0.12	840	916.98	30	0.18	600	680.46
Turb 6	280	0.12	840	916.98	40	0.12	600	711.48	160	0.18	840	884.22
Turb 7	220	0.12	840	916.98	340	0.12	600	711.48	100	0.18	840	884.22
Turb 8	75	0.12	840	916.98	195	0.12	600	711.48	315	0.18	840	884.22
Turb 9	185	0.15	840	884.22	315	0.15	840	916.98	85	0.12	600	680.46

Table B.3: Customised MS designs for the BWFL with yaw angle range of $\pm 3^\circ$

	heading 1 [°]	d 1 [m]	AncR 1 [m]	L1 [m]	heading 2 [°]	d 2 [m]	AncR 2 [m]	L2 [m]	heading 3 [°]	d 3 [m]	AncR 3 [m]	L3 [m]
Turb 1	160	0.18	600	680.46	280	0.18	840	884.22	50	0.12	840	916.98
Turb 2	300	0.18	600	649.44	80	0.18	840	884.22	190	0.15	840	916.98
Turb 3	350	0.18	840	916.98	110	0.18	840	916.98	230	0.18	840	916.98
Turb 4	245	0.12	600	680.46	5	0.15	840	884.22	125	0.15	840	884.22
Turb 5	25	0.18	600	680.46	145	0.18	840	884.22	275	0.12	840	916.98
Turb 6	275	0.18	840	916.98	35	0.18	840	916.98	155	0.18	840	916.98
Turb 7	70	0.18	840	884.22	200	0.15	840	916.98	340	0.15	840	884.22
Turb 8	50	0.18	840	884.22	190	0.12	840	884.22	330	0.12	600	649.44
Turb 9	190	0.18	840	884.22	330	0.18	840	884.22	80	0.12	600	680.46

Table B.4: Customised MS designs for the GWFL with yaw angle range of $\pm 5^\circ$

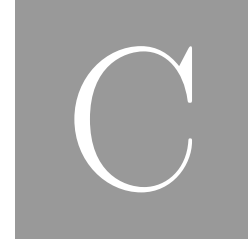
	heading 1 [°]	d 1 [m]	AnchR 1 [m]	L1 [m]	heading 2 [°]	d 2 [m]	AnchR 2 [m]	L2 [m]	heading 3 [°]	d 3 [m]	AnchR 3 [m]	L3 [m]
Turb 1	15	0.18	840	916.98	165	0.12	840	884.22	315	0.12	840	884.22
Turb 2	5	0.18	840	949.74	145	0.18	840	916.98	295	0.15	600	680.46
Turb 3	80	0.12	840	949.74	230	0.18	840	884.22	20	0.18	840	884.22
Turb 4	80	0.18	840	949.74	230	0.18	840	884.22	20	0.12	840	916.98
Turb 5	50	0.18	840	884.22	200	0.15	840	884.22	350	0.15	600	680.46
Turb 6	20	0.12	840	949.74	150	0.12	840	949.74	290	0.18	840	884.22
Turb 7	170	0.18	840	949.74	310	0.18	840	916.98	100	0.15	600	680.46
Turb 8	180	0.18	840	949.74	330	0.18	840	884.22	120	0.12	600	680.46
Turb 9	255	0.18	840	916.98	45	0.12	840	916.98	195	0.18	840	884.22

Table B.5: Customised MS designs for the GWFL with yaw angle range of $\pm 4^\circ$

	heading 1 [°]	d 1 [m]	AncR 1 [m]	L1 [m]	heading 2 [°]	d 2 [m]	AncR 2 [m]	L2 [m]	heading 3 [°]	d 3 [m]	AncR 3 [m]	L3 [m]
Turb 1	15	0.12	840	916.98	165	0.15	840	884.22	315	0.15	840	884.22
Turb 2	75	0.18	840	884.22	225	0.15	840	916.98	15	0.15	600	649.44
Turb 3	255	0.18	840	884.22	45	0.15	840	916.98	195	0.15	600	649.44
Turb 4	70	0.18	840	884.22	220	0.15	840	916.98	10	0.15	600	649.44
Turb 5	145	0.18	840	884.22	295	0.15	840	916.98	85	0.15	600	649.44
Turb 6	355	0.12	840	916.98	145	0.15	840	884.22	295	0.18	840	884.22
Turb 7	180	0.12	840	916.98	330	0.15	840	884.22	120	0.18	840	884.22
Turb 8	45	0.12	840	916.98	195	0.15	840	884.22	345	0.15	840	884.22
Turb 9	250	0.12	840	916.98	40	0.15	840	884.22	190	0.18	840	884.22

Table B.6: Customised MS designs for the GWFL with yaw angle range of $\pm 3^\circ$

	heading 1 [°]	d 1 [m]	AnchR 1 [m]	L1 [m]	heading 2 [°]	d 2 [m]	AnchR 2 [m]	L2 [m]	heading 3 [°]	d 3 [m]	AnchR 3 [m]	L3 [m]
Turb 1	355	0.12	840	884.22	145	0.18	840	884.22	295	0.18	600	649.44
Turb 2	85	0.15	840	916.98	225	0.18	840	884.22	15	0.15	840	884.22
Turb 3	265	0.12	840	884.22	55	0.18	840	884.22	205	0.18	600	649.44
Turb 4	285	0.15	840	916.98	65	0.18	840	884.22	215	0.15	840	884.22
Turb 5	10	0.15	840	916.98	150	0.18	840	884.22	300	0.18	840	884.22
Turb 6	130	0.12	840	884.22	280	0.18	840	884.22	70	0.18	600	649.44
Turb 7	155	0.12	840	884.22	305	0.18	840	884.22	95	0.18	600	649.44
Turb 8	40	0.12	840	884.22	190	0.18	840	884.22	340	0.18	600	649.44
Turb 9	30	0.12	600	680.46	150	0.18	840	884.22	300	0.15	840	884.22



HORNS REV 1 WIND FARM - MS

STIFFNESS

The appendix shows the stiffnesses of MS design 1, MS design 1', MS design 2, and MS design 3.

C.1 Horizontal stiffness of MS design 1 and 1'

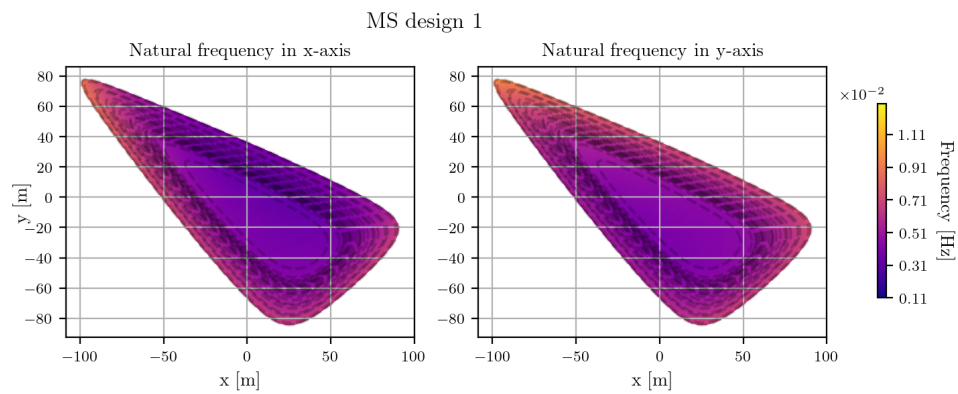


Figure C.1: MS design 1 stiffness in the x and y directions

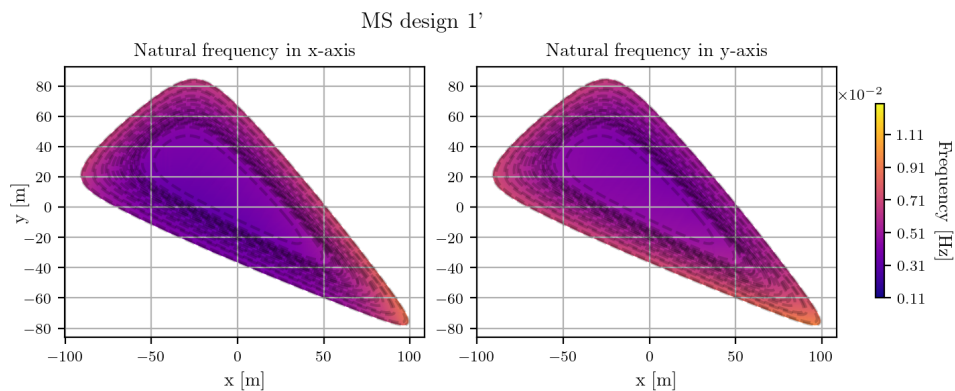


Figure C.2: MS design 1' stiffness in the x and y directions

C.2 Horizontal stiffness of MS design 2 and 3

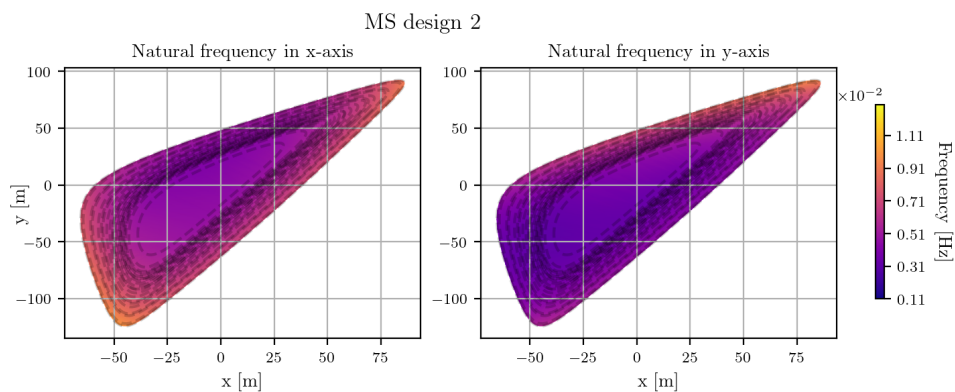


Figure C.3: MS design 2 stiffness in the x and y directions

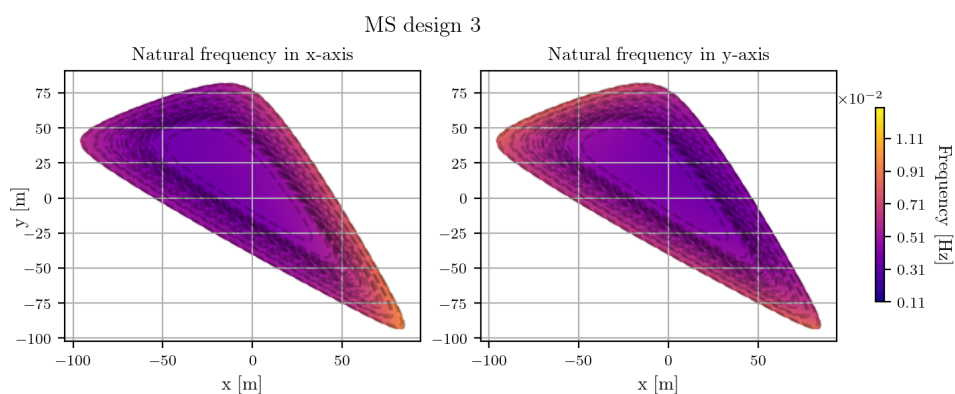


Figure C.4: MS design 3 stiffness in the x and y directions

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