

CRANFIELD UNIVERSITY

DAWN WARD

REDUCING TOWER FATIGUE THROUGH MODELLING AND
ANALYSIS OF A PITCH-TO-STALL, BACK TWIST BLADE, FOR
FLOATING OFFSHORE WIND TURBINES

CENTRE FOR RENEWABLE ENERGY SYSTEMS
EngD in Renewable Energy Marine Structures (REMS)

EngD
Academic Year: 2015 - 2020

Supervisor: Joy Sumner
Associate Supervisor: Maurizio Collu
April 2020

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ABSTRACT

The negative effects of anthropogenic climate change has led to an increase in electricity generated from renewable energy sources. Within this, offshore wind is currently one of the fastest growing markets, and industry is now looking towards the role that floating offshore wind turbines (FOWT) may play in the future. However, FOWT are often subjected to increased tower loads, up to 1.6 times those experienced by their fixed-to-seabed counterparts. Reducing these loads would help to decrease the costs of this fledgling technology, by diminishing the tower strengthening requirements.

In the present work, as a possible technological solution to reduce the above mentioned loads, a variable speed, variable pitch-to-stall (VSVP-S) control strategy, is proposed for wind turbines. The 5 MW turbine is applied to both a semi-submersible and a spar floating platform, as these floaters both suffer from increased tower fore-aft oscillations. The VSVP-S control configuration avoids negative damping by design, allowing higher controller gain settings and hence a more regulated power output, than a pitch-to-feather controlled floating scenario. The FOWTs are further altered to incorporate back twisted blades, to decrease the blade bending moment response. This was seen to decrease the tower fore-aft moment range, creating an increase in the turbine tower life expectancy, when compared to their respective feather base models.

To predict the overall tower axial fatigue life, the frequency of anticipated wind speeds are required. The likely occurrence of the different wind speed cases was accounted for through a weighted analysis. This took account of the distribution of probability of occurrence at three mean turbulent wind speeds: 8, 13 and 18 m/s. FOWT analysis highlighted trends in terms of back twist angle initiation point and magnitude were similar for both VSVP-S models (i.e. semi-submersible and a spar floating platforms). When a back twist angle to -6° at the tip was imposed, starting at 75% along the blade length, increases in the tower axial fatigue life of 10.2% for the semi-submersible and 18.8% for the spar were achieved, with the VSVP-S controlled turbines, compared to their feather controlled counterparts.

Keywords: Floating offshore wind turbine (FOWT); tower fore-aft moments; negative damping; blade flapwise moment; tower axial fatigue life; spar; semi-submersible

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LIST OF ABBREVIATIONS

AHSE	aero-hydro-servo-elastic
CAPEX	capital expenditure
CB	centre of buoyancy
CG	centre of gravity
C_p	coefficient of power
DOF	degree(s) of freedom
DTU	Technical University of Denmark
Eq	equation
FAST	Fatigue, Aerodynamics, Structures, and Turbulence
FORCE	For Reduced Cost of Energy
FOWT	floating offshore wind turbine
HAWT	horizontal axis wind turbines
IEC	International Electrotechnical Commission
IPC	individual pitch control
LC	load case
LCOE	levelised cost of energy
MARIN	Maritime Research Institute Netherlands
NREL	National Renewable Energy Laboratory
PI	proportional-integral
RMS	root mean square
SWL	sea water level
TFB	tower-top acceleration feedback
TLCD	tuned liquid column damper

TLP	tension-leg platform
TMD	tuned-mass damper
TRL	technology readiness levels
UNFCCC	United Nations Framework Convention on Climate Change
VAWT	vertical axis wind turbines
VPPC	variable power collective pitch control
VSVP-S	variable speed, variable pitch-to-stall

LIST OF NOMENCLATURE

A_{55}	the added mass with respect to the pitch hydrodynamic radiation
B_R	the damping with respect to the pitch hydrodynamic radiation
B_{55}	the linearized damping with respect to the pitch hydrodynamic viscous drag
C_{lines}	the linearized hydrostatic restoring of the mooring lines in pitch
C_{55}	the pitch hydrostatic restoring
$C_{55, MOOR}$	the total stiffness in pitch
C_x	the damping coefficient
F_B	the buoyancy force
F_{env}	the sum of all the environmental forces
g	gravity
H_s	the significant wave height
$I_{DRIVETRAIN}$	the driveshaft inertia
I_{GEN}	the generator inertia
I_{ROTOR}	the rotor inertia
I_x	the second moment of area of the initial waterplane
I_{55}	the pitch inertia with respect to the combined turbine and platform masses
K_x	the stiffness coefficient
L_{HH}	the hub height
m	mass
m	Wöhler material exponents
M_l	the inclining moment (in the x-z plane)

$M_{R,G}$	the restoring moment due to gravity and buoyancy
$M_{R,MOOR}$	the restoring moment due to the mooring system
$M_{R,WP}$	the restoring moment due to the water plane
M_x	effective mass coefficient
N	the number of cycles
N_{GEAR}	the gearbox ratio
S	the stress amplitude
T_p	the spectral peak period
Z_B	the distance from centre of buoyancy to the coordinate centre along the z-axis
$Z_{CP (env)}$	the distance from centre of pressure of F_{env} to the coordinate centre along the z-axis
Z_G	the distance from the centre of gravity to the coordinate centre along the z-axis where the coordinate system is taken to have an origin at mean sea level and in the centre of floatation
Z_{MLA}	the distance from centre of mooring line action to the coordinate centre along the z-axis
Ω	the rotational speed
ξ_ϕ	the damping ratio related to the rotor speed error control system
$w_{\phi n}$	the natural frequency of the control system
$dP/d\phi$	the sensitivity of the aerodynamic power to the blade pitch angle
dT/dv	the change in thrust with change in wind speed
σ	density
θ	the angle of change in submersion for the DOF under analysis
ζ_x	the platform pitch damping ratio

1 INTRODUCTION

1.1 Context

Renewable energy from natural sources has been harvested by humans for over 2000 years, since the Byzantium's first utilized a simple waterwheel to irrigate their fields (Ward 2002). Over time renewable energy devices expanded to utilize the mechanical motion created by the waterwheel's turning, firstly to grind grain, then to perform other industrial activities such as paper and cloth production, wood mills and laundry.

The first use of wind energy was on the waters to power sailing ships, and although there has been some evidence of vertical axis wind turbines (VAWTs) being in use in 1700 BC in the Orient (Gasch & Twele 2002), it was not until the 10th century that horizontal axis wind turbines (HAWTs), in the form of post mills, became established. These performed the same tasks that waterwheels had been fulfilling for a long time, but opened up locations to industry that were not reliant on a good, flowing water source. Power to provide irrigation has also utilised localized renewable energy sources, with nowhere more prominent than the Netherlands who used wind to control the sea level. It has been estimated that over 10,000 wind turbines were operated for this, and other industrial activities, during their peak period of use between the 1300 and 1800s (Cleveland 2009).

For the last 100 years, all forms of renewable energy have been harnessed to enable electricity generation. For water power, this has included run-of-the-river systems, reservoirs, tidal and wave generation. Energy from the sun has been directly converted to electricity generation using either solar photovoltaics that convert photons from sunlight or concentrated solar power systems that collect the thermal heat of the sun in large farms, often utilizing parabolic troughs. Waste and purposefully grown crops are used in anaerobic and aerobic biomass converters. For wind, the rise from mechanical energy harvesting to the modern, large multi-megawatt electricity generating wind turbine has been relatively slow; held back by lack of vision, economics and the ease of generating electricity from

both coal and oil. In fact it wasn't until the oil crisis in the early 1970s that research into the use of wind power to create electricity for the grid really got underway. This lead towards the current trend for large megawatt wind turbines grouped together to create extensive wind farms both on land and out at sea (Gasch & Twele 2002).

The necessity to produce more electricity from renewable sources has also been driven by a number of other factors in the last few decades. These have included: an increased rise in energy requirements as consumerism and populations rise; uncertainty due to dwindling natural 'carbon rich' resources in financially accessible formations (James and Ros 2015); security of the energy supply in a world where oil resources are often found to be at the root of wars and atrocities; a desire for more environmental 'green' solutions; prevention of irreversible climate change; the need to avoid further habitat extinction and damage to the planet's eco-system; and local and international governmental requirements.

In the present day, the requirement to increase the renewable portion of the energy supply worldwide is becoming more imperative each day. Across the globe, environmental events are increasing in their frequency and scale, making the anthropogenic contribution to climate change indisputable (Knutson et al 2018). Unfortunately, this disproportionately effects the world's poorest people, which has likely contributed to the lack of adequate, speedy action on the part of some of the world's economic leaders, although it is worth noting that there are also individuals in positions of extreme power who still deny anthropogenic climate change, such as the current president of the United States of America. If power generation continues as it has until today, then it is predicted that by 2030 the planet will experience a 1.5 °C human-orchestrated global warming increase, due to the level of greenhouse gases in the atmosphere (Masson-Delmotte et al 2019). It has been predicted that this would cause widespread issues with food supply, water security, flooding, rises in sea level, droughts and storm conditions, which will overshadow the devastating impact from global warming that has already been seen in recent years (Masson-Delmotte et al 2019).

There have been many attempts to implement fixed targets to reduce energy production emissions, including global commitments as well as individual country led incentives. The UK is committed to reducing emissions of greenhouse gas, relative to 1990 levels, by a minimum of 80% by 2050 (The UK government 2008). The Contracts for Difference scheme, to support low-carbon energy generation such as by new offshore wind farms, is another example of a UK-led incentive (Contract for Difference 2019). Within the European Union's (EU) 'policy framework for climate and energy in the period from 2020 to 2030', mandatory targets are set for 32% of the energy consumed within the EU, to be provided from renewable energy sources by 2030 as a minimum (European Commission 2014).

On a larger scale, the Paris Agreement calls on all participating countries within the United Nations Framework Convention on Climate Change (UNFCCC) to reduce their emissions from energy production to achieve the overall aims set out within Article 2, which includes the proviso that global temperatures should be prevented from increasing by more than 2 °C in comparison to pre-industrial temperatures (United Nations 2015). The Paris Agreement was much celebrated as a great success in the fight to reduce anthropogenic climate change worldwide, however, it should also be noted that the Paris Agreement will not become binding until the end of 2020 and then only if 55 countries accounting for at least 55% of global emissions have joined the agreement (United Nations 2015). As the pledges to reduce emissions are all voluntary, the Paris Agreement has not had much positive impact to date (Cléménçon 2016; Watson et al 2019), and there is also the question of whether the Article 2 aims can now be achieved at all with the planned withdrawal of the US from the UNFCCC, and hence the Paris Agreement. This is problematic because the US is the world's 2nd largest emitter of all greenhouse gases globally. There are no clear guidelines of what the protocol will be if the 55% requirements have not been achieved by the end of 2020.

Despite the failings of the Paris Agreement, other climate policies have encouraged the development of energy from renewable resources, such that

within Europe 11.6% of energy demand was provided solely from wind energy in 2018 (WindEurope 2019). Whilst some countries have embraced onshore wind turbines, sometimes against the desires of the local inhabitants, others have had to contend with local objections as part of the planning process (Burningham et al 2006). Within the UK a small handful of outspoken locals, opposed to a site due to perceived detrimental effects on birds or visual impact, have often managed to prevent a viable farm from being developed, or have delayed the process by many years, increasing costs for developers drastically and making funding agreements harder to achieve (Burningham et al 2006). Therefore, the move from land-based turbines towards offshore wind farms has created a more definable planning and financing process, allowed larger turbines and farms to be developed, and has also gained more public support. The wind resource is also better at sea, as it is generally stronger due to less surface roughness at sea and more consistent than it is on land, including high sites (Robertson and Jonkman 2011).

The installed capacity of offshore wind turbines increased globally by 24% in 2018, achieving a total global capacity of 23 GW (Ohlenforst et al 2019). Currently, floating offshore wind turbines (FOWTs) only play a small part, with the world's first floating farm (with a capacity of 30 MW) coming online in 2017. However, due to limited sites with shallow bed and low seabed slope, the offshore wind industry is looking towards floating solutions for the future, with predictions of an additional 5 GW of installed energy coming from floating wind by 2030. This would amount to 5% of the offshore wind market (Fried et al, 2017).

1.2 Problem statement

Moving to floating wind farms requires a better understanding of potential failure mechanisms, e.g. tower fatigue. In the first instance, this understanding is generated through modelling. For economic reasons, the HAWTs specifics used for prototype, model experimentation, and simulation purposes on FOWTs are generally those that were originally designed for use on onshore locations. Although these HAWT models are modified for the offshore environment,

including increasing the tower strength to withstand the additional loads due to the waves (Jonkman and Buhl 2007), they are generally designed to be installed on a foundation fixed into the seabed. The same is true of most components and controllers for the turbine. However turbine loads, specifically the induced tower base bending moments, are often increased for FOWTs. This can be by a factor as high as 1.6 times more than those seen in a fixed land-based turbine, depending upon the floating structure type and individual designs (Robertson & Jonkman 2011). These increased tower moments would cause a reduction in the expected life of the turbine.

Currently all HAWTs that pitch-to-feather to control the rotor speed, whether fixed on dry land, the seabed, or floating offshore, experience a phenomenon generally referred to as 'negative damping', where the tower fore-aft motions can increase due to the rotor thrust decreasing as the wind speed increases above rated (the wind speed at which the turbine achieves the maximum 'rated' power output). This cyclical increase in loads due to the tower fore-aft movement can be avoided by ensuring that the chosen blade pitch controller bandwidth avoids the first resonance modes of the tower. However, for FOWTs, the frequency of the motions in surge, sway, roll and pitch are one or more orders of magnitude lower than those seen with a fixed foundation, therefore the blade pitch controller bandwidth must be set at a lower frequency to avoid the first resonance modes of the turbine tower, and thus avoid negative damping (Fleming et al 2019). The generated power output is however negatively affected by the lower frequency setting, which results in FOWTs delivering a lower performance compared to fixed turbines. This occurs as the rotor speed regulation does not maintain a smooth response to wind speed changes that occur above the rated wind speed, when the lower frequency setting is applied (Larsen & Hanson 2007). Unless undesirable motions of the FOWT's tower (specifically the tower base fore-aft bending moment) can be significantly reduced, to create a more stable platform, then the strength of the tower must be increased which will increase costs and weight (Henderson & Patel 2003; Lackner 2009).

This research is therefore concerned with reducing the excessive motions and loads associated with FOWTs, whilst improving the regulation of the energy generated. This will be through the utilization of a turbine pitching-to-stall strategy, instead of a pitching-to-feather strategy, to control the rotor speed, which avoids the negative damping issues by design.

1.2.1 Aim

The main aim of this research is to investigate the potential of a variable speed, variable pitch-to-stall (VSVP-S) control FOWT that incorporates a back twisted blade, to increase the tower axial fatigue life. An optimum set of criteria, in terms of the back twist magnitude at the tip, and the back twist initiation point along the blade radius, will also be identified. Hence, a design will be proposed that provides good mitigation of the increased undesirable loads experienced, without undue power loss, thus making floating wind solutions more economically viable.

1.2.2 Objectives

1. Select a suitable floating platform type and configuration that is subject to higher tower loads and that could benefit from reduced tower fore-aft responses.
2. Evaluate and compare the state-of-the-art methodologies utilised for the simulation, analysis and control of loads as they propagate on a wind turbine tower fixed to a floating platform.
3. Select a reference site with appropriate environmental conditions, and hence define the load case for the aerodynamic and hydrodynamic models.
4. Select appropriate aerodynamic, hydrodynamic, structural dynamic and control models for the analysis of the selected FOWT system, and validate them by comparison with model data from a variety of other projects.
5. Develop a VSVP-S control model, and implement it into the aero-hydro-servo-elastic (AHSE) model.

6. Identify, define and create blade models to reduce tower fore-aft responses and perform simulations to derive the dynamic responses of the FOWT under the different environmental and operational conditions specified.
7. Analyse the findings in terms of the effects of back twist angle, initiation point and also the constant pitch angle for the below rated wind speeds.
8. Identify the most appropriate active-stall blade profile modifications for fatigue reduction at the tower base.
9. Determine if the wind turbine with blade modifications would provide benefit to another floating platform type.

1.3 Thesis plan

This research is presented as a 'Thesis by Paper', comprising of seven chapters, including an extended literature review and three journal articles. Each research section builds upon the previous findings as illustrated in Figure 1-1.

Each of the three papers has been reformatted to match the overall thesis style, including the renumbering of sections, figures and tables to match their section placement.

Abbreviations used within each paper have however been retained, regardless of an earlier appearance within the thesis, to facilitate the stand-alone reading of each individual journal article. The objectives met by each of the studies are presented in Table 1-1, and the outline of each section of the thesis are as follows:

In section 1, the context behind FOWTs is presented, including both the historic pathway to the modern wind turbines of today and the political incentives in place to support their further growth. This section also addresses the problem statement, aims and objectives, and presents the thesis outline.

Section 2 contains an extended literature review that provides background information on FOWT types, dynamic responses to the offshore environmental loads, and the increased loads a wind turbine can experience when coupled to a floating platform. Different methods to mitigate undesirable turbine tower loads

are examined along with the simulation techniques utilized to examine their effectiveness. A summary of the key literature findings are presented and the knowledge gaps this research will address are also identified.

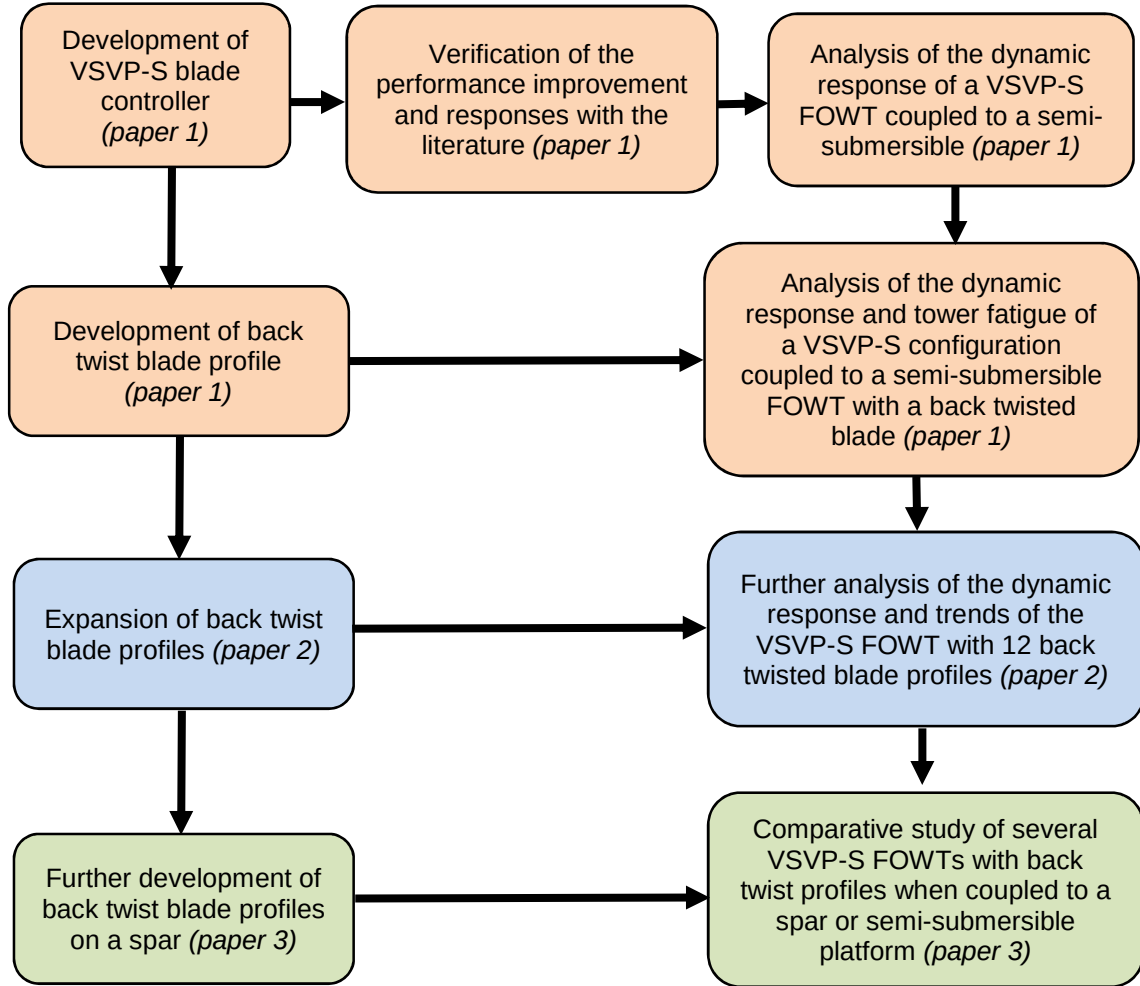


Figure 1-1. Tower axial fatigue life extension analysis method for variable speed, variable pitch-to-stall controlled FOWTs with back twisted blade profiles.

Section 3 presents the first paper: ‘Reducing Tower Fatigue through Blade Back Twist and Active Pitch-to-Stall Control Strategy for a Semi-Submersible Floating Offshore Wind Turbine’. This addresses the negative damping challenge present for FOWTs, and how, with the present solutions, tackling this issue can lead to a reduction in the quality of the generated power. It therefore presents a VSVP-S controller that can mitigate the effects by design. Possible reductions to the tower fatigue, through a back twisted blade profile for a turbine coupled to a semi-submersible floating platform, are also examined through a preliminary study.

Additional information related to the research presented in section 3 can be found within Appendix A.

Table 1-1. Addressing individual objectives

Objective	Main Section Title	Specific Section N°
1	Extended Literature Review	2.1, 2.3 & 2.6
	Paper 1	3.2
2	Extended Literature Review	2.2 & 2.4
3	Paper 1	3.3.1
4	Extended Literature Review	2.4
	Verification and Comparison of Results	6.1
5	Paper 1	3.3.1
6	Extended Literature Review	2.3.5
	Papers 1	3
	Appendices	A, B & C
7	Paper 2	4
8	Paper 2	4
9	Paper 3	5

Within section 4 the paper entitled: ‘Analysis of the effect of a series of back twist blade configurations for an active pitch-to-stall floating offshore wind turbine’ is presented. This builds on the study presented in section 3, expanding to examine 12 different back twist configurations. The trends seen due to the back twist angle magnitude and twist initiation point are identified and discussed. An ideal blade profile for tower axial fatigue life extension of the FOWT couple to the semi-

submersible is presented. Additional information related to the research presented in section 4 can be found within Appendix B.

Section 5 contains the paper: 'Back Twisted, Active Pitch-to-Stall Blade for Floating Offshore Wind Turbine Tower Damping'. This study examines if the benefits of a back twisted blade, developed for the semi-submersible platform, are transferable to other floating platform types, and takes the six most promising blade profiles, seen within the study presented in section 4, and applies them to a turbine coupled to a spar type floating platform. Additional information related to the research presented in section 5 can be found within Appendix C.

Section 6 covers the verification and comparison of the semi-submersible model and FAST programming capabilities and the performance benefits due to VSVP-S control.

Section 7 contains a general discussion on the interconnecting outcomes of the three studies, including their additional supplementary material presented within the relevant Appendices. The discussion also takes account of the relevant findings within the literature.

In section 8 the conclusions are presented, and suggested recommendations for further investigation are also proposed.

1.3.1 Intellectual contribution to knowledge.

To the author's knowledge, there have been no advancements in large commercial, actively pitching-to-stall regulated turbines, in the last two decades. The last such turbine commercially produced was the fixed, land-based Bonus 2 MW wind turbine, which ceased production in 1996. Only two simulation-based studies, for FOWTs, have explored the potential of large 5 MW (and above) full variable speed, variable pitch-to-stall blades, to control the rotor speed at wind speeds above rated, but these limited findings have been encouraging on the whole.

Therefore, at a broad level, this research provides useful data for the next big change in turbine environment; from fixed offshore turbines to floating structures. This will advance understanding of possible tower fore-aft moment range reduction through the increased blade drag and rotor thrust generated by a rotor model, designed for stall control, resulting in tower axial fatigue life extension.

A part of the intellectual contribution from this research is the detailed and comprehensive modelling of the coupled dynamics of a FOWT actively pitching-to-stall, and the critical assessment of the main advantages and disadvantages of this rotor-speed control strategy for a FOWT (Ward et al 2019).

From the matured understanding gained through the assessment of a pitch-to-stall FOWT, an innovative study of the effects on tower axial fatigue and hence lifetime increase of a VSVP-S FOWT was undertaken. This enabled trends arising due to variations in the initiation point and magnitude of a back twist to be identified when the FOWT was coupled to a semi-submersible floating platform (Ward et al 2020a).

This understanding was then further extended to determine if the VSVP-S wind turbine, with blade modifications, could also provide benefit (in terms of tower fatigue reductions), when the turbine is coupled to other floating platform types. Hence the FOWT was coupled to a spar type floating platform, which also enabled comparisons to be made between the turbine responses due to platform type (Ward et al 2020b). This will, therefore, provide further potential solutions to make pitch-to-stall a techno-economically viable solution for FOWTs.

1.3.2 Potential impact of the research

Within industry, the use of turbines pitching-to-feather is well established, and the priority has been to adapt these designs to the new environmental conditions found offshore, rather than conduct research that involves major component changes such as to the blades and rotor as required for active stall.

However, for a turbine mounted on a spar type floating platform, tower fore-aft fatigue loads can be 2.5 times those seen by the same turbine supported by a

fixed-to-seabed platform, whilst semi-submersible are subjected to increases of up to 1.8 times. If these loads cannot be reduced, the towers will need to be strengthened, which will result in increased costs and weight.

This, therefore, is the ideal time for research into the possibilities of reducing loads through active pitch-to-stall blade control, as making changes to the blades and controls may be more attractive to industry than having to strengthen the tower.

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2 EXTENDED LITERATURE REVIEW

Floating platforms have been used to support offshore operations within the oil & gas sector for many years, however, their scale is well beyond the requirements needed to support a single wind turbine (IRENA 2016). Also, the oil & gas sector has a very high revenue relative to offshore wind, and many of the platforms are under habitation at all times, meaning that their design constraints and requirements differ from those of the wind industry greatly (Butterfield et al 2005). Due to these factors, floating platforms for use within the wind industry have required designers to look at the issues anew, with cost and weight being paramount constraints for the fledgling industry (IRENA 2016).

This extended literature review therefore starts, in section 2.1, by defining how the responses of a specific platform are used to categorise the different floating platform concept types, such as a barge, spar or tension leg platform (TLP), and how those responses act upon the coupled wind turbine. This then leads on to a review of the prominent floating platform concepts suitable for individual HAWTs. Section 2.2 looks at the specific load increases that are seen on a turbine tower when it is coupled to a floating platform rather than fixed rigidly to the seabed or land. The added complexities, in terms of negative damping due to lower frequencies of motion for floating platforms, are also explored. Section 2.3 then examines different methods to mitigate these increased tower loads. This is followed by section 2.4, which looks at simulation methods to analyse FOWT responses. A summary of the key literature that is most relevant to this research thesis can be found in section 2.5, and is followed by section 2.6 which identifies the knowledge gaps addressed.

2.1 Floating platform concepts

Floating platforms for wind turbines can broadly be categorised into three types, depending upon whether the structure's restoring moment is mainly due to the waterplane area, the mooring system, or the platform's gravity and buoyancy (Borg and Collu 2014). The restoring moment of a platform can be derived adopting a simplified single degree of freedom (DOF) approach, such as the

The diagram illustrates a rectangular plate tilted at an angle θ relative to a horizontal dashed line. The plate is divided into two regions: a light gray region labeled "volume no longer submerged" and a darker gray region labeled "additional submerged volume". A coordinate system is defined with a vertical dashed axis Z' and a horizontal axis X' . The plate's surface is defined by axes Z and X . Key points and forces are marked:

- CP(env)**: Center of pressure of the environment, located at the top of the plate, with a red arrow F_{env} pointing horizontally to the right.
- B**: A point on the plate with a red arrow F_B pointing vertically upwards.
- O = F**: A point on the plate where the buoyant force acts, with a blue arrow $F = F_{env}$ pointing horizontally to the left.
- G**: The center of gravity, located below the plate, with a red arrow mg pointing vertically downwards.
- MLA**: Metacentric Length of Arm, indicated by a blue curved arrow between the vertical line through **G** and the vertical line through **O**.
- $M_{R,moor}$** : A blue curved arrow representing a moment at the point **O**.

 A differential element $dx dy$ is shown on the submerged surface. Geometric parameters include the horizontal distance $x/\cos(\theta)$ from the vertical Z' axis to the element, and the vertical distance $x \sin(\theta)/\cos(\theta)$ from the horizontal X' axis to the element. The angle θ is shown between the horizontal dashed line and the plate's surface.

$$M_{R,WP} = \sigma \cdot g \cdot I_x \cdot \frac{\sin \theta}{\cos \theta} \quad [\text{Eq 2-1}]$$

17

$$M_{R,G} = F_B \cdot Z_B \cdot \sin\theta - m \cdot g \cdot Z_G \cdot \sin\theta \quad [\text{Eq 2-3}]$$

where $M_{R,WP}$ is the restoring moment due to the water plane area ($\text{N}\cdot\text{m}$), $M_{R,MOOR}$ is the restoring moment due to the mooring system ($\text{N}\cdot\text{m}$), $M_{R,G}$ is the restoring moment due to gravity and buoyancy ($\text{N}\cdot\text{m}$), σ is the seawater density (kg/m^3), g is the gravitational acceleration constant (m/s^2), I_x is the second moment of the waterplane area in initial conditions (m^4), θ is the pitch inclination angle change for the DOF under analysis ($^\circ$), $C_{55,MOOR}$ is the stiffness in pitch due to the mooring system ($\text{N}\cdot\text{m}$), F_B is the buoyancy force (N), Z_B is the vertical coordinate of the centre of buoyancy (CB) (m), m is the mass (kg), and Z_G is the vertical coordinate of the centre of gravity (CG), where the coordinate system is taken as at mean sea level at the centre of floatation (m).

The inclining moment in pitch can be defined by Equation 2-4 (Borg & Collu 2014).

$$M_I = F_{\text{env}} \cdot (Z_{\text{CP}(\text{env})} - Z_{\text{MLA}}) \cdot \cos\theta \quad [\text{Eq 2-4}]$$

where M_I is the inclining moment (in the x-z plane) ($\text{N}\cdot\text{m}$), F_{env} is the sum of all the environmental forces (N), $Z_{\text{CP}(\text{env})}$ is the vertical coordinate of the centre of pressure of F_{env} (m), and Z_{MLA} is the vertical coordinate of the mooring line action (m).

When analysing the loads created on a turbine due to it being situated on a floating structure, it is usual to define the rigid-body dynamics as combinations of the six DOFs shown in Figure 2-2. These are defined as the three linear (or translation) motions, surge (forward/backward), sway (side/side) and heave (up/down), and the three rotational (or angular motions), roll (side/side moment), pitch (forward/backward moment), and yaw (vertical moment) (Olav et al 2015).

These DOF are usually represented as one to six respectively (Wayman et al 2006). The most detrimental loads seen by a FOWT therefore come from the different motions induced depending on the structure's main restoring moment, individual design and the environmental conditions experienced. However, the overall requirement remains the same; cost effective methods to control and mitigate the unwanted motions that can lead to undesired loads, without disproportionately decreasing the overall performance of the controller and hence energy production and revenue. Thus, load mitigation can prevent damage that would cause excessive stress and fatigue, and allows the turbine to continue to operate and generate energy in situations where it would otherwise have to be shut down.

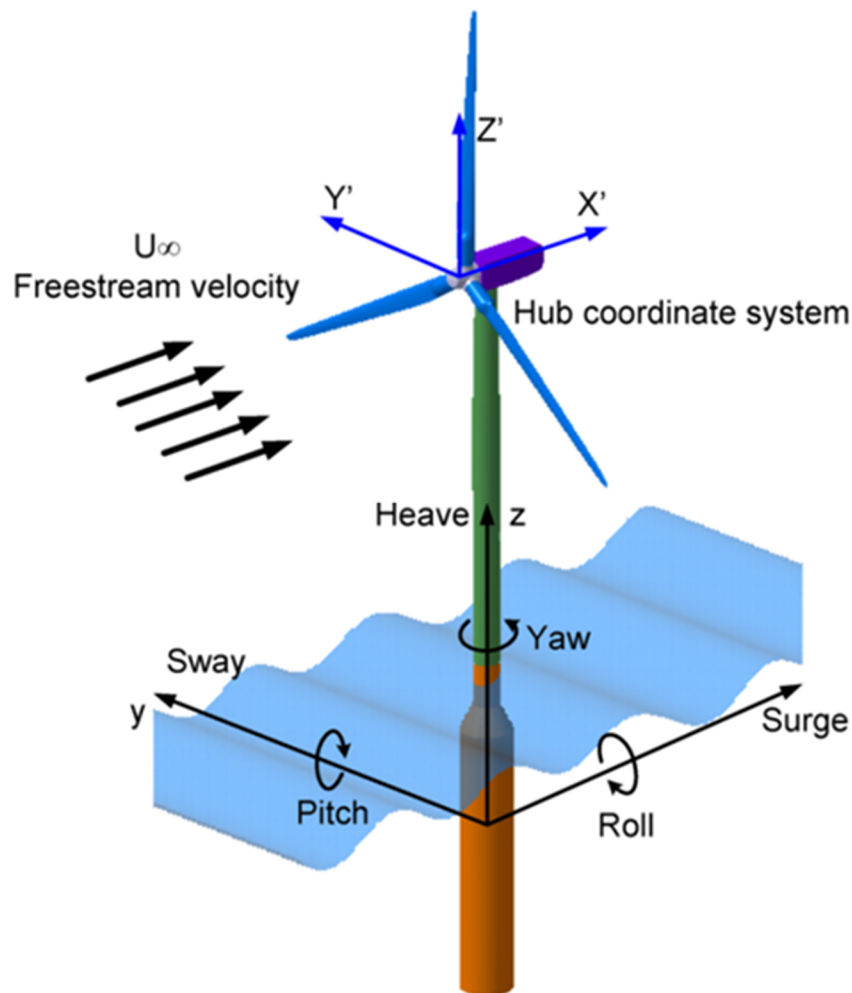


Figure 2-2. Six degrees of freedom acting on a floating wind structure (Tran et al 2014).

From the broad categorisation of a platform's stability, as defined by the predominant restoring moments (found utilizing Equations 2-1 to 2-3):

- Barges and semi-submersible are defined as structures that are stabilised primarily by buoyancy (waterplane stabilised). However, semi-submersibles have also been defined as hybrid systems, due to the combined effects of waterplane area, draft and ballast (Butterfield et al 2005; Thiagarajan & Dagher 2014).
- A TLP is stabilised predominantly through its mooring system.
- A spar is stabilised mainly by the relative position of the CG with respect to the CB, whose separation is enhanced through the utilisation of a large draft and ballast material to lower the CG.

A representation of the main visual characteristics of the different floating types are depicted in Figure 2-3.

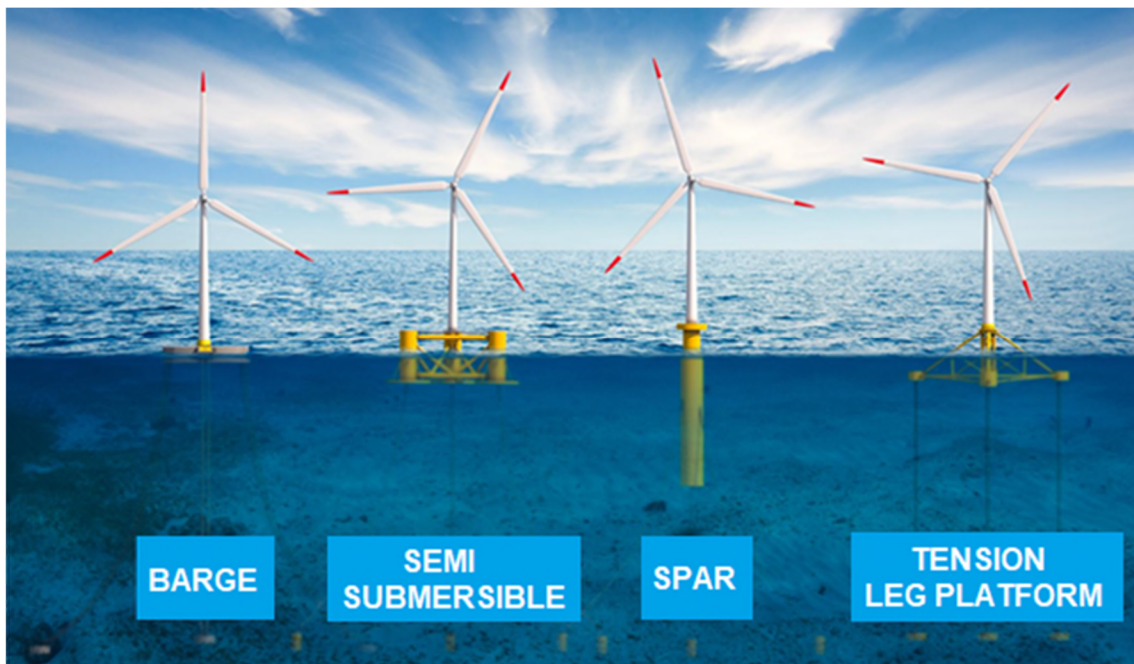


Figure 2-3. Floating platform types (WindEurope 2017)

A barge by definition has a large waterplane area, hence the floating structure's pitch and roll motion usually causes the predominant unwanted loads, but unfavourable heave loads can also be high (Butterfield et al 2005). Barge

systems were used in the early analysis of FOWTs, as they were seen to have less complicated designs, hence leading to fabrication and installation advantages. However, simulations indicated excessive rolling and pitching, causing loads on the tower that were unacceptable except in smooth calm waters (Jonkman 2007; Robertson & Jonkman 2011).

A TLP is much more rigid in pitch, heave and roll than the other types of FOWTs, due to the tensioned mooring cables that provide high stability such that the horizontal component of the mooring system counteracts the forces from the environment (Borg & Collu 2014). The predominant motion, causing the most undesirable loads, is generally surge. A comparison study by Robinson and Jonkman (2011) that included the three basic floating systems plus a semi-submersible, showed that the TLP generally experienced less extreme loads than all the other FOWT types as seen in the loads presented in Figure 2.5. The tensioned cable and anchors, along with a shallow draft, allow the platform to have a smaller mass than other platform types as well as no requirement for active ballast. The outcome was reduced motion, which can be equivalent to the motion seen by fixed turbines. However this is at the expense of high mooring and anchoring costs, due to the tensioned cables experiencing larger stresses as the seabed depth increases (Myhr et al 2014). Installation is also negatively affected by sea depth and, in general, can be more complex for a TLP, as they usually require a purpose-built barge for deployment and servicing. Risks are also higher for both installation and operation, due to the possibility of tensioned cable failure (James & Costa Ros 2015). Thiagarajan and Dagher (2014) also identified that tension loss in cables could lead to a TLP capsizing.

A spar mainly uses ballast in the form of high density material to achieve a low CG, so that the weight and buoyancy force predominantly provide the restoring moment. The floating structure's pitch motion usually causes the predominant unwanted loads, but heave and roll loads can also be high (Butterfield et al 2005). Therefore a large draft is necessary which can be greater than the height of the hub (Thiagarajan & Dagher 2014). The installation of spar structures can be complex, with a requirement for heavy duty cranes and vessels with dynamic

positioning (James & Costa Ros 2015). It is also commonly stated that spar structures are suitable for depths greater than 120 m. However as this was the requirement for the 2.3 MW Hywind demonstration, which had a draft of 100 m (International Consulting Ltd 2012), it is not unrealistic to expect depths exceeding 150 m to be required for the larger 7 MW+ turbines currently being deployed, as the 7.5 MW ENERCON E-126 has a hub height of 135m (Windblatt 2017) and Siemens Gamesa recently launched a 10 MW offshore turbine with a rotor diameter of 193m (Siemens Gamesa 2019).

Current seabed fixed designs are applicable up to 50 m, TLPs and semi-submersibles above 40 m, and spars (as well as TLPs and semi-submersibles) are suitable when water depths are greater than 120 m (James & Costa Ros 2015; Arapogianni & Genachte 2013). The spar platform type, for 5 MW+ turbines, could therefore be classed as within the third range of water depths, as they are generally not applicable for sites where depths are below 120 m. In terms of technology readiness levels (TRL), the spar is arguably the most mature FOWT concept to date, with Statoil (now Equinor) first deploying their 2.3 MW spar 'Hywind' off the coast of Norway in 2009 and a 30 MW farm comprising of five 6 MW turbines that went operational at the end of 2017.

Reducing the draft was identified as one of the key technological challenges for spars within the Carbon Report (James & Costa Ros 2015), whilst Olav et al (2015) highlighted that the blade pitch angle control was identified as a principal challenge during the design of the 2.3 MW Hywind, as it increased both the pitch and surge motions of the floater. Thiagarajan and Dagher (2014) further proposed that the increased platform pitch motion adversely affected the 'gyroscopic stability' of the spar due to the changing angle of thrust acting upon the tower. This observation was also applicable to a semi-submersible.

Currently, the most common floating structure is that defined as a semi-submersible, which has historically been classed as a hybrid system as the platform's second moment of waterplane area is large (a characteristic of a barge) but they also utilise a large draft and ballast (characteristics of a spar). However,

more recently they have tended to be reclassified as a new barge design. Semi-submersibles have a smaller draft (20-30 m) than a spar, often in the form of specifically spaced columns or pontoons which can be flooded with water to provide additional stability through water ballast (Principle Power 2013). The column spacing can be considered to be the predominant contributor to the overall stability of the platform (Thiagarajan & Dagher 2014), which can be enhanced by controlling the water ballast such that it is moved between columns during different environmental conditions and thus actively increases the stability of the platform (Olav et al 2015). As the name suggests, it is semi-submersed and anchored non-rigidly to the seabed, generally utilizing a catenary mooring system. As the draft is not overly deep, it has been proposed that assembly could be initiated at suitable shorelines and then transported to the operational site, which could eliminate the requirement for specialist assembly vessels. The Carbon Trust produced an in-depth report for the Scottish government that found that semi-submersibles on the whole had a lower LCOE and capital expenditure (CAPEX) (Figure 2-4) per MW than other types (James & Costa Ros 2015), which was mainly down to reduced complexities in the installation methods.

Thiagarajan and Dagher (2014) propose that the ease with which a semi-submersible could be towed back to shore for maintenance and repair, along with commissioning advantages, make them an attractive option. However semi-submersibles tend to need a large structural mass to achieve adequate stability and buoyancy, and fabrication can also be complex due to shape and welding requirements.

Myhr et al (2014) also looked into the CAPEX of different concepts and identified that the higher costs of one semi-submersible concept, the WindFloat, were primarily down to the quantity and hence costs of steel. The WindFloat platform size is however dictated by metocean conditions rather than turbine size, therefore steel and hence cost reductions are expected as turbine sizes increase (Maciel 2010).

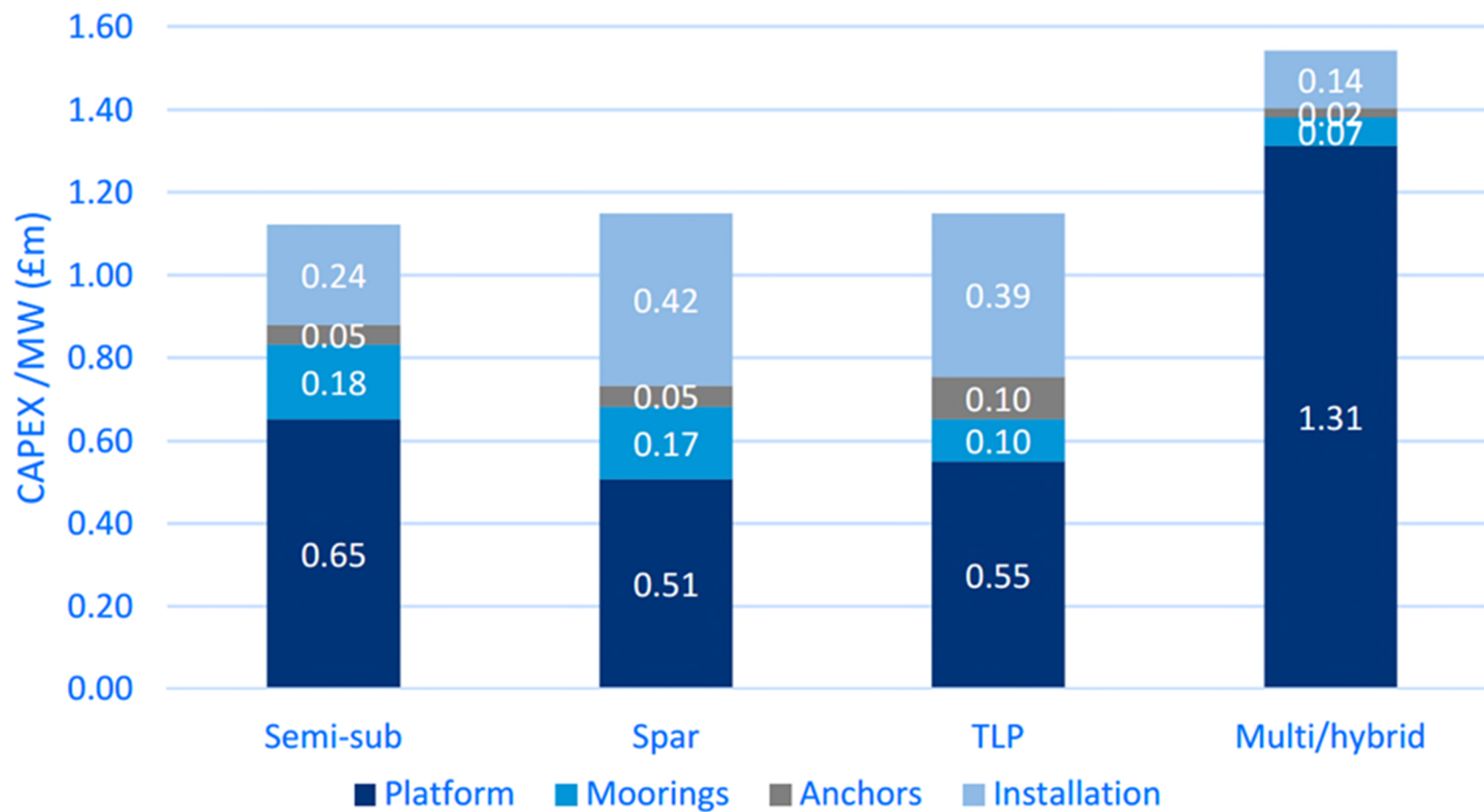


Figure 2-4. Capital expenditure breakdown per MW for each floating offshore platform concept (James & Costa Ros 2015).

It is also worth noting that concrete structures have been shown to have a lower CAPEX than steel versions (James & Costa Ros 2015) and a further reduction in costs of 6% has been projected from the substitution of 10% of the steel for composite and concrete (Maciel 2010). A summary of the main constraints applicable to each platform type are presented in Table 2-1.

Table 2-1. Platform constraints due to type (James & Ros 2015)

Platform type	Water depth	Stability	Main constraints
Barge	>40 m	Mainly from waterplane area	Excessive motions
Semi-submersible	>40 m	Mainly from waterplane area	Increased material costs due to large waterplane area
TLP	>40 m	Mooring	High mooring costs, High risks
Spar	>120 m	Distance between centre of gravity and centre of buoyancy	Increased cable costs associated with water depth

2.2 Tower loads specific to floating platforms

Currently, most floating platforms, whether close to commercialisation, undergoing model experimentation, or at the preliminary simulation stage, utilize a turbine that has been adapted from an onshore design for a fixed offshore scenario. This is mainly because, by utilizing turbine designs that are well understood, the risks associated with new technology are reduced. This approach also allows more freedom in the turbine choices available (Olav et al 2015), as there are many fully commissioned offshore fixed turbines at a researcher or designer's disposal. However, this leads to the use of turbines that are not directly optimised for the loads induced on them through the platform from the combined wave and wind forces. This is not the ideal solution, and in the project 'FORCE' (For Reduced Cost of Energy), Dobbin et al (2014) examined a typical fixed offshore wind turbine project, suggested cost savings of around 10% could be realised. These suggested cost reductions were achieved through

integrating the designs of the wind turbine's monopile or jacket support structures with the turbines. Although it is likely that a more integrated approach to turbine designs for floaters will arise as the industry matures (Olav et al 2015), the predominant emphasis is on applying fewer changes to the controls or turbine components that will allow a FOWT to achieve the desired standard design life of 25 to 30 years.

To identify which turbine responses are the most effected when coupled to a specific floating platform type, Robertson and Jonkman (2011) undertook a study on six different floaters (two TLP floaters, two spars, plus a barge and a semi-submersible). Figure 2-5 presents their findings in terms of different fatigue loads on the turbine, as fatigue must be examined if the design life time is the focus. These were derived from simulated responses utilizing the non-linear, time-domain, aero-hydro-elastic-simulation tool FAST (Fatigue, Aerodynamics, Structures, and Turbulence) (Jonkman and Jonkman 2016b). The results are given as ratios to the corresponding land-based fatigue loads of the NREL (National Renewable Energy Laboratory) 5 MW HAWT. Data is seen for each specific set of Wöhler material exponents (m), where the first number after 'm' in the legend of the figure refers to the blade, and the second to the tower as well as to the shaft. Hence, for example, for 'm' values shown in Figure 2-5 as $m=8/3$, the Wöhler material exponent is eight for the blades and three for the tower and shaft. The Wöhler material exponent, m can be defined by Equation 2-5.

$$\log(N) = m \cdot \log(S) + c \quad [\text{Eq 2-5}]$$

where N is the number of cycles, m is the Wöhler material exponent, S is the stress amplitude and c is a constant term.

Firstly, from the results presented in Figure 2-5, it is clear that the induced loads vary in both magnitude and origin, depending upon the platform dynamics. The barge experienced tower fore-aft fatigue loads that were 8-9 times higher than

those seen by the land based turbine, and are therefore not suitable for most offshore environmental conditions. For all floater types, the increased fatigue due to the tower base fore-aft bending moment is the most significant. Fatigue reaches almost x2.5 that seen by the land-based turbine for all spar scenarios; approach x2 for the semi-submersible; and x1.5 for the TLPs. The tower fore-aft moment also significantly increased, compared to the loads seen on fixed turbines, in several other FOWT studies (Li et al 2017; Bachynski et al 2014; Lackner 2013; Jonkman & Marth 2011). Thus, the increased tower base axial fatigue will cause a reduction in the design life of the turbine, dominated by the axial stress range (Li et al 2017).

The results from the study by Robertson and Jonkman (2011) also highlighted the importance of examining the fatigue responses directly, as the ratio of the tower base fore-aft bending moment for the UMaine TLP indicated that the ultimate load was equivalent to that seen by the land-based turbine, even though the tower fore-aft bending moment fatigue exceeded x1.5. It was also observed that during extreme turbulent events, higher loads on the tower and other system components were seen around the rated wind speed, due to the peak in the rotor thrust for the pitch-to-feather control scenario analysed (Robertson & Jonkman 2011). This caused specific problems for the OC3-Hywind spar where increased surge motion created platform pitch instability.

Therefore, to account for the prominent increase in tower axial fatigue from the induced tower base bending moments, one solution would be for the tower to be strengthened. However, increasing the tower strength and hence weight is likely to require a corresponding increase in the platform size and structural weight, which could lead to a sizable rise in costs for both manufacturing and deployment (James & Costa Ros 2015). This has naturally lead to research to find suitable solutions that can reduce these undesirable tower base fore-aft response increases.

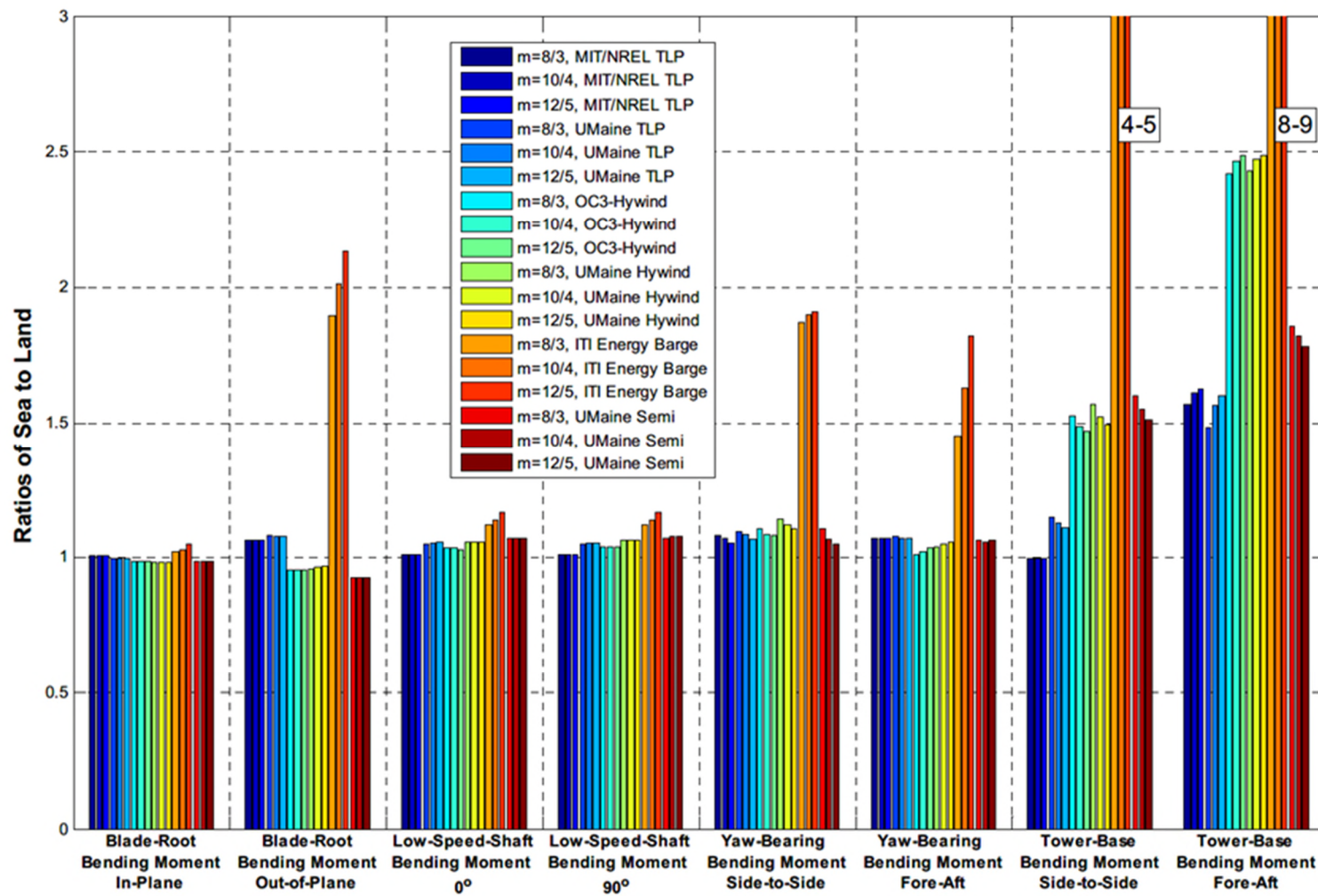


Figure 2-5. The sea-to-land ratios of the fatigue loads experienced by several floating platforms (Robertson & Jonkman 2011)

Many of the proposed methods examined within the rest of this section have however focused on controlling the platform pitch motion, which is generally presented as creating a reduction in the tower fore-aft response and hence tower axial fatigue. However, tower axial stress is created when a relative displacement occurs between the mass of the platform and the mass of the tower. The platform's displacement and acceleration create gravitational and inertial loads upon the tower, respectively (Lackner 2013). Therefore, reductions in the platform pitch do not automatically decrease the tower loads, thus proposed tower fore-aft moment reduction methods should focus on directly reducing the tower motion (Lackner 2013). This reduction in excessive stress and fatigue also needs to be achieved without disproportionately decreasing the overall performance of the controller, thereby protecting energy production and revenue from being adversely affected.

2.2.1 Negative damping

Most large variable speed, variable pitch HAWTs (3 MW+) currently pitch toward feather, such that the angle of attack is reduced to control the rotor speed and hence power output when operating at wind speeds above rated. Pitch-to-feather has become the preferred control strategy as the output is more predictable in the region before the maximum lift coefficient has been reached. However, all pitch-to-feather controlled HAWTs, whether fixed on dry land, the seabed, or floating offshore, experience a phenomena when wind speeds exceed the rated wind speed, generally referred to as the 'negative damping', which is associated with the pitch-to-feather control loop (Fleming et al 2014). As the tower moves towards the wind, the turbine sees a rise in the wind speed and hence rotor speed. Therefore, to attempt to achieve the constant rotor speed set point desired at above rated wind speeds, the blade's angle increases and rotor speed decreases again. This results in a reduction in both the thrust and torque loads, which causes the tower to move further forward into the wind. The opposite effect happens if the tower moves backward, away from the wind. Therefore, this tower fore-aft oscillation would increase the loads on the tower and nacelle if it were not controlled as illustrated by Figure 2-6 (van der Veen et al 2012). For fixed

turbines, the cyclical increase in loads due to the tower fore-aft movement is usually prevented, without creating a reduction in performance, as the pitch control bandwidth has been chosen so that the first resonance modes of the tower are avoided.

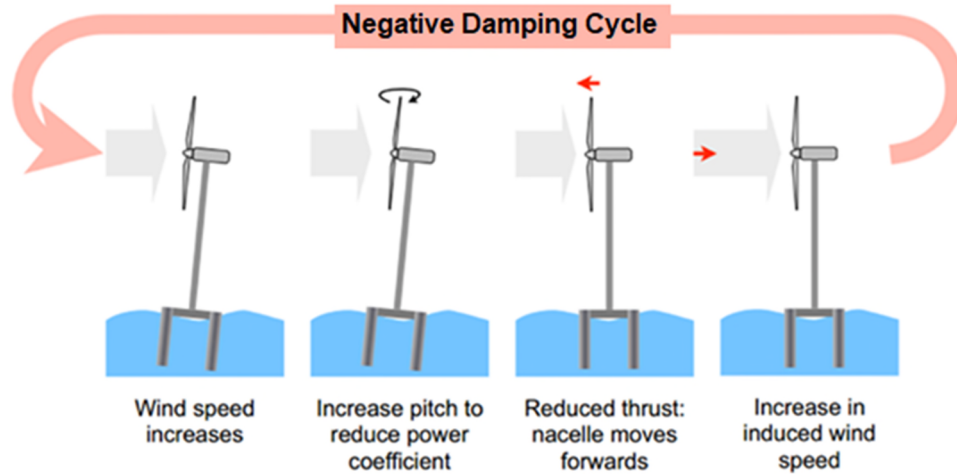


Figure 2-6. Propagation of the oscillation of the tower fore-aft motion under pitch-to-feather control, due to the negative damping cycle (adapted from van der Veen et al 2012).

As discussed in section 1.2, generally the turbines used for floating platforms are those have been designed to have a fixed base and are therefore offshore environment adaptations of the onshore designs. However, the frequency of the motions in surge, sway, roll and pitch of a FOWT are one or more orders of magnitude lower, and therefore they will be within the bandwidth of the pitch controller originally designed for fixed turbines. One approach is to use a band-pass filter to dampen the system, such that the inputs to the blade pitch controller avoid the resonant frequencies of the platform (Olav et al 2015). However this can lead to a less regulated rotor speed and output (Fleming et al 2019). Another method is to lower the natural frequency of the blade pitch controller to below the natural frequency of the platform pitch, hence the gains of the PI (proportional-integral) blade pitch controller are reduced (Larsen & Hanson 2007). Unfortunately, the slowing of the pitch control action created by the lowering of the gains comes at the cost of a reduction in the performance such that, as with the band-pass filter, more variation is seen around the desired constant rotor

speed, which leads to more fluctuations in the power generation (Larsen & Hanson 2007).

2.3 FOWT tower fore-aft load mitigation methods

2.3.1 Detuning the gains

The first step to optimise the performance of a mechanical system that already exists usually involves changing the gain (Harrison & Bollinger 1969). Fleming et al (2014) performed an analysis through numerical simulations using the time-domain AHSE-coupled model of dynamics, FAST, which combined detuning the gains in series with a PI compensator and filters as part of the pitch controller. The first tower base load controlling method utilized involved changing the bandwidth of the controller, often called detuning, so that the dominant surge mode of the floating platform was avoided (Fleming et al 2014). This was done by changing the PI gains and filter parameters, so that the bandwidths were reduced. Greater stability was achieved even though this was utilizing an already stable TLP floating design, but the rotor speed accuracy was also reduced as expected. Also more shutdowns occurred due to over speeding (Fleming et al 2014).

A similar study where the detuning was applied by reducing the natural frequency of the pitch controller was undertaken by Larsen and Hanson (2007). The responses from this research were derived from a specifically designed simulation tool developed from the simulation tools SIMO/RIFLEX and HAWC2. This was for a turbine situated on a spar platform and the detuning provided good tower motion stability, but found that the power and speed varied by +/- 30% compared to the nominal values. They noted that, for stability to be achieved, the controller's natural frequency needs to be below the critical vibration frequency of the tower. Jonkman (2007) suggests that this strategy makes the floating system act more like an open-loop controller rather than the ideal closed-loop one. The Risoe-DTU research (Larsen & Hanson 2007) was further expanded to include non-linear adjustment of the gains and scheduled detuning. Their findings indicated that the same improvements in tower stability could be achieved with

non-linear adjustment, but with a desirable reduction in the power and speed variation down to $\pm 15\%$.

Fleming et al (2014) found that the main benefit of scheduled detuning was to allow a faster controller response time at higher winds, where the pitch angle was greater and where de-tuning was not deemed to be necessary which reduced or eliminated the over-speed. As the thrust sensitivity to collective rotor blade pitch angle is related to the wind and rotor speeds as well as blade pitch angle, scheduled detuning is necessary to achieve a continual increase in damping ratio for a pitch-to-feather controlled turbine (Bossanyi 2003; Jonkman 2007).

2.3.2 Individual blade pitch control

Thapa and Balas (2014) showed through simulation that fast speed individual pitch control (IPC) of each rotor blade could provide damping and reduce the structures pitching motion without undue performance loss when applied to a spar platform. The displacement of the pitch of the platform was fed back to produce an output in terms of the IPC blade angles to provide compensation for the platform pitching motion. A collective blade pitch controller was also utilized to regulate the speed of the rotor. However this study was only carried out with a calm water simulation. Further research during turbulent environmental conditions would therefore be necessary for an assessment of the damping achievable in realistic offshore environment. The simulation tool utilized was not given within this paper, however it states the model was that developed by Jonkman (2007) and therefore was probably achieved utilizing the FAST simulation tool.

Lackner's (2009) research into IPC primarily focused on blade load reduction and was performed on the Jonkman (2007) barge using FAST. The simulations were performed with an irregular sea state and turbulent mean winds of 18 m/s. The IPC angle required was determined using the Coleman transformation which utilizes the blade root flapwise bending moment as an input (Lackner 2009). This approach however was shown to increase the platform roll and tower side-to-side motions with a minor reduction of only 0.3% in the tower fore-aft damage

equivalent load. It was suggested that this may be due to the increased variation in rotor thrust loads created by the platform pitch motion, producing blade loads that overpower any possible reduction from the IPC.

An IPC method was proposed by Namik and Stol (2010) which, by incorporating a feedback controller that returned the platform pitch velocity and included a cost function, improved the overall efficiency. This method also used the periodic gains of the blades as they altered throughout the azimuth angle for each blade (Namik & Stol 2010). The platform motion was controlled as the IPCs produced a tilt moment about the rotor hub which corresponded to a reduction in both pitching and rolling. This control design produced high reductions in the tower fore-aft (19%) and side-to-side (36%) fatigue loads whilst maintaining good power control with fluctuations reduced by 33% (Namik & Stol 2010). However the operational requirements of the blade actuators were greatly increased which could cause saturation of the actuators. The FOWT platform used for this research was the same barge used in the study by Jonkman (2007), which highlighted the excessive motions of this platform design and which was later shown to be unsuitable for offshore conditions (Robertson & Jonkman 2011). Hence, the extent of the fatigue reductions seen were likely influenced by the already-unstable condition of the platform, in other words it is easier to reduce the motion on a platform when it experiences excessive motion to start with. These simulated responses were also generated using FAST.

2.3.3 Pitching to stall

The tower fore-aft moment response range could be reduced by increasing the rotor thrust by actively pitching the blades in the opposite direction to feather, when the wind speeds are above rated (Figure 2-7) (Hölling M 2011). A VSVP-S control methodology therefore works by slowing down the rotor by inducing aerodynamic stall of the blade, as the angle of attack is increased. Active VSVP-S can also be utilized at wind speeds below rated as shown by Maheswari and Tamilvendhan (2012). However, this active pitch control method has generally been put to the side by researchers and industry alike (for 3 MW+ turbines), due

to several actual and perceived problems relating to pitch-to-stall blades, mainly arrived at through passive stall analysis.

One problem seen on passive stall blades, which dictates that they need to be heavier, is the increased deflections and loads that they experience, especially for the softer, larger blades in use on many large turbines (Macquart & Maheri 2019). One aspect of this, which is unlikely to apply to a regulated VSVP-S controlled FOWT, are peak loads occurring on the blades. These arise when the power, extracted by the blades from the wind, at wind speeds above rated, is not being shed as quickly as desired, as often occurs with passive pitch-to-stall blade operation. Another is the unpredictable nature of the aerodynamic behaviour in stall (Bossanyi 2003). However, Bossanyi (2003) also observes that thrust loads vary less and more slowly with changes to the blade pitch angle in stall, therefore, although the thrust loads rise with an increasing angle of attack, the stability of the torque and thrust is increased. Thus the reduced range in their responses tends to lead towards a reduction in the tower axial fatigue.

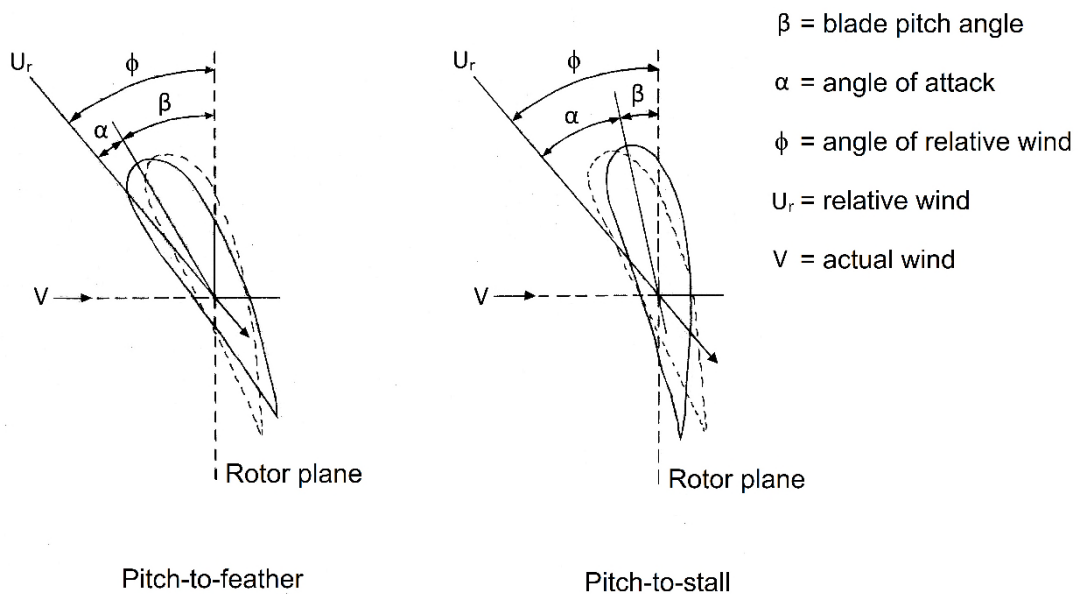


Figure 2-7. Blade pitching direction for pitch-to-feather control and pitch-to-stall control (adapted from Hölling M 2011).

One real benefit of a VSVP-S control strategy is that negative damping can be avoided with this design, as the rotor thrust does not drop as wind speeds rise, allowing for a higher control frequency that results in a more regulated rotor speed and power output. This was confirmed by the two studies that have been conducted to date on large VSVP-S control of a FOWT (Larsen & Hanson 2007; Jonkman 2007). The first of these two simulation studies was conducted on a floating spar in 12 m/s turbulent mean wind speeds that, along with the power regulation improvements, also found that stability problems caused by the coupling of the tower movement, aerodynamics, and the control system, were avoided when using active pitch-to-stall (Larsen & Hanson 2007). These responses were achieved regardless of the fact that the research utilized a blade that was designed for a pitch-to-feather blade controller. The stall results were obtained as the authors accidentally made a sign error when entering the pitch angle into the controller. As VSVP-S was not the actual focus of the Larsen & Hanson (2007) study, it is difficult to compare the stall responses with those seen when pitching-to-feather for the same FOWT design, particularly as the results presented for each control system at the same mean wind speed are clearly in different environmental conditions, with a much more turbulent wind shown for the pitch-to-stall scenario. Further investigation into the feasibility of VSVP-S as a solution to the stability problems for large 5 MW FOWT was proposed.

Jonkman (2007) also explored a VSVP-S system, specifically the platform pitch damping effects on a barge system in turbulent mean winds of 18 m/s. The research derived no benefit in platform damping from this control strategy, in fact the range of platform pitch was greatly increased to 27° compared to 15° pitch-to-feather. Unfortunately, no tower responses were presented in the study for VSVP-S, hence a comparison with those experienced with pitch-to-feather control could not be made. As stated previously, the rotor speed and regulation of the power output were both greatly improved with VSVP-S. Jonkman (2007) also suggested that if the rotor and aerofoils of the turbine used to explore the damping effects were redesigned to ensure that the rotor thrust increased continually within region 3 (from rated to cut off wind speeds), then it may be

possible to achieve an increase in damping that would exceed that seen with a pitch-to-feather strategy. Part of this research was also concerned with the development of the FAST simulation tool to ensure it was upgraded to become suitable for FOWTs. This tool has been used by many researchers (Lobitz & Veers 2003; Jonkman 2007; Lackner 2009; Namik & Stol 2010; Fleming et al 2014), partly due to its open source availability, as highlighted throughout the studies examined as part of this literature review.

The opposing conclusions arrived at by the two studies on the impact of VSVP-S such that it was seen as beneficial on a spar and detrimental on a barge, highlight how the responses may be very platform type specific. Also, as the barge design has since been discounted as a possible open sea FOWT solution, this further emphasises the gap in knowledge on whether suitable VSVP-S systems could provide the much desired reduction in tower axial fatigue needed by FOWTs, specifically by spar and semi-submersible types which seem to suffer the most from induced tower axial fatigue increases (Robertson & Jonkman 2011).

2.3.4 Signal feedback

There are many different controllers that have utilized a feedback signal from some area of a FOWT, with the aim of increasing the damping. Three different signal feedback systems for IPC were outlined in section 2.3.2. Thapa and Balas (2014) utilized the displacement of the platform in pitch, Namik and Stol (2010) the platform pitch velocity, and Lackner (2009) fed back the blade root flapwise bending moment.

A study by Lackner (2013) examined the simulated responses (using FAST) of a control strategy where the platform pitch velocity was fed back, but the power was allowed to vary to produce more load reductions for a collective pitch-to-feather scenario. This damping method is known as a variable power collective pitch control (VPPC) strategy. This achieved a reduction in the platform pitch angle of up to 20% at the cost of a root mean square (RMS) power variance error increase, of up to 7%. However, as this also utilized the barge with an extreme

platform pitch range of 15° , it is not certain if this system would translate to a more viable, stable platform type.

Fleming et al (2019) achieved a reduction in the tower base bending moment damage equivalent loads by up to 20% by combining the feedback of the platform pitch velocity with the feedback from the nacelle velocity on a semi-submersible floating platform. Bossanyi (2000) highlighted that the nacelle acceleration is generally proportional to the tower base loads. Therefore there were three loops in the blade pitch control system: the standard speed controller, the platform pitch velocity, and the nacelle velocity (Fleming et al 2019). The nacelle loop was designed to only feedback at lower wind speeds as, during initial research, it was seen to increase loads at the higher speeds (Fleming et al 2019). An open-loop function was also used to tune the gain. The semi-submersible was based on the WindFloat which utilizes active water ballast such that water is moved between the platform columns in different environmental conditions (Maciel 2010). It was however unclear as to whether active ballast was initiated within the simulation study, which utilized FAST coupled to OrcaFlex (Fleming et al 2019).

Tower-top acceleration feedback (TFB) was found to act against the blade pitch controller for the pitch-to-feather controlled barge investigated by Jonkman (2007). This happens because the relative wind speed is higher when the floating turbine is pitching towards the wind. To reduce the speed, the blades pitch more to feather. However the TFB controller wants to pitch towards stall to generate more damping by increasing the thrust. Hence the speed controller and TFB controller oppose each other.

2.3.5 Rotor blade manipulation

Blade manipulation at the design and manufacturing stage can produce tower load reductions during operation, due to the desired response created in terms of aerodynamic load, and hence rotor thrust response that will directly affects the tower fore-aft motion. Different techniques have been applied to both pitch-to-feather control and passive (fixed-pitch) stall configurations, often with the specified design criteria primarily focusing on reducing loads, vibration, and

hence fatigue of the blades, by ensuring that the power coefficient is maximized. Figures 2-8 to 2-10 present three blade manipulation methods: applying a sweep to the blade such that the blade curves along its length (Figure 2-8) (Larwood 2016), a pre-bend along the whole blade length (Figure 2-9) (Sartori et al 2016), and a back twist which starts at a pre-determined point along the blade length and then twists back to the blade tip (Figure 2-10) (Mecaflux Heliciel 2019). Material properties and layering can also be manipulated to produce load reductions, especially when the effects of the blade material under load are coupled to a twist or bend.

Stäblein et al (2017) investigated the effects of a bend-twist coupling on the 10 MW DTU (Technical University of Denmark) pitch-to-feather land-based turbine, and compared blades with a twist to feather flapwise and edgewise and blades with a twist to stall flapwise and edgewise when compared to the reference blade twist. This was through simulations generated by the aero-servo-elastic tool HAWCStab2. Reductions in the tower fore-aft bending moment were achieved with a flapwise twist to feather blade, as the bend-twist coupling reduced the blade root flapwise bending moment response to the variation in the mean wind speed. The opposite effect was seen with the flapwise twist to stall blade. During edge-twist coupling the blade became unstable due to an increase in flutter. Figure 2-11 shows both the blade flapwise bending moment and tower (fore-aft) bending moment as applied to a turbine, such that it can be seen that by reducing the blade bending moment and hence aerodynamic thrust, the tower fore-aft response will also be reduced (LTI Motion 2019).

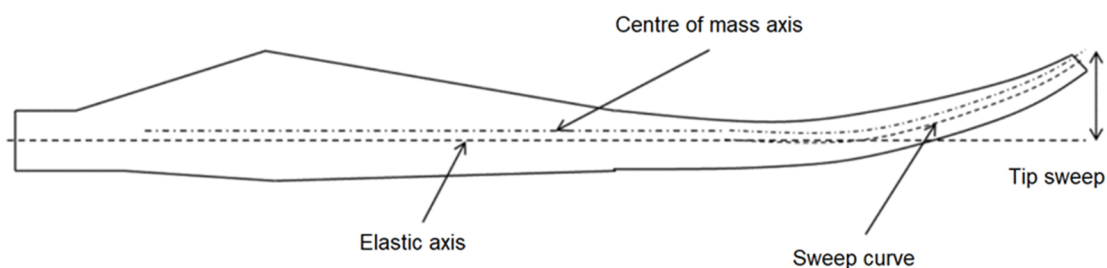


Figure 2-8. Blade sweep curve imposed during manufacture (Larwood 2016).

Lobitz and Veers (2003) looked into the twist effects of a blade that has been designed to twist towards feather under load, when applied to blades that have a pre-twisted to stall when unloaded, with simulations utilising ADAMS and FAST_AeroDyn. Three different control strategies were compared: constant speed with passive stall control, variable speed with passive stall control, and a pitch-to-stall controlled variable speed turbine. The focus was on blade loads, but load decreases in the order of 10% across the turbine were stated from this twist coupling response method.

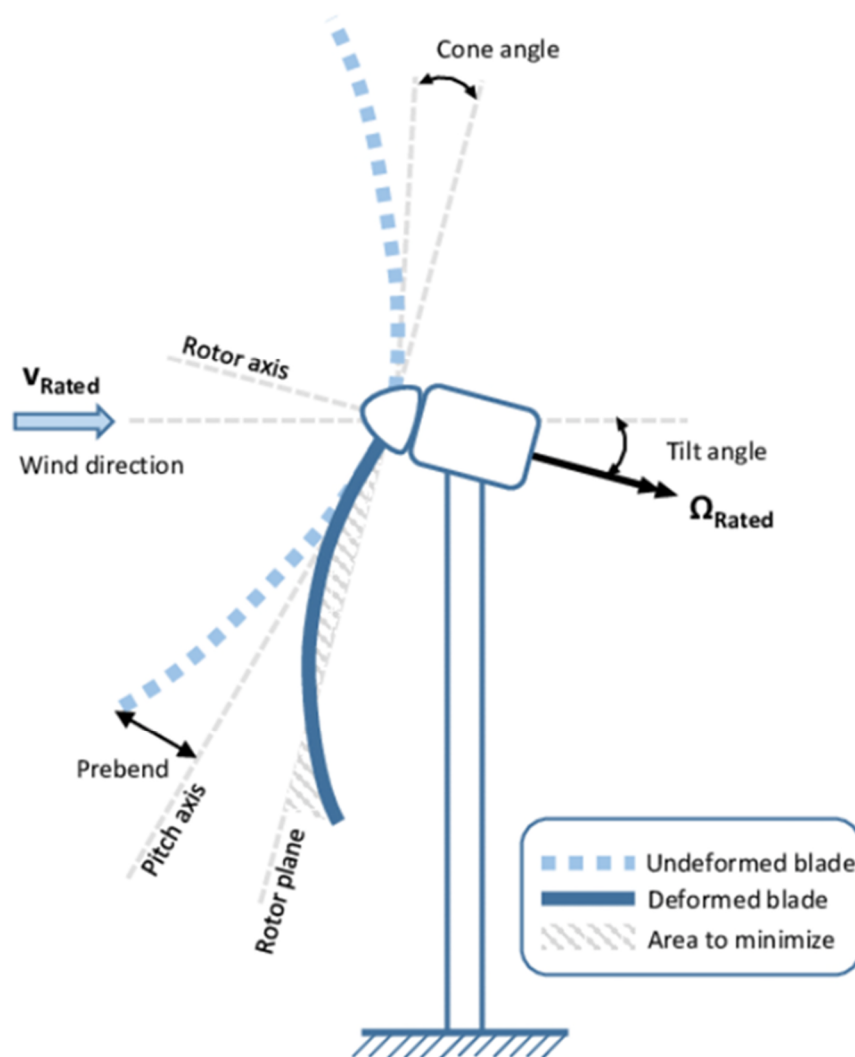


Figure 2-9. Blade pre-bend imposed during manufacture to alter the deformed blade shape experienced during normal turbine operation (Sartori et al 2016).

The bend-twist coupling response of four blades of different length, varying from 30 m (1.6 MW) up to 90 m (12-14 MW) were analysed under load for passive stall blades, hence rigidly fixed at the root (Coxa & Echtermeyera 2013). The obtained results were derived from finite element simulations. As with the Lobitz and Veers (2003) study, a twist towards feather under load was the desired response. Although tower loads were not part of the analysis, the blade flapwise bending moment range was reduced by between 10 and 11% for all blades, hence a reduction in the tower fore-aft moment would be a logical assumption. Unfortunately, a reduction in the coefficient of power (C_p) was also seen with the desirable reduction in the blade flapwise moment and hence the researchers suggested that an active pitch-to-stall controller may help to increase the C_p to ensure a better power output (Coxa & Echtermeyera 2013).

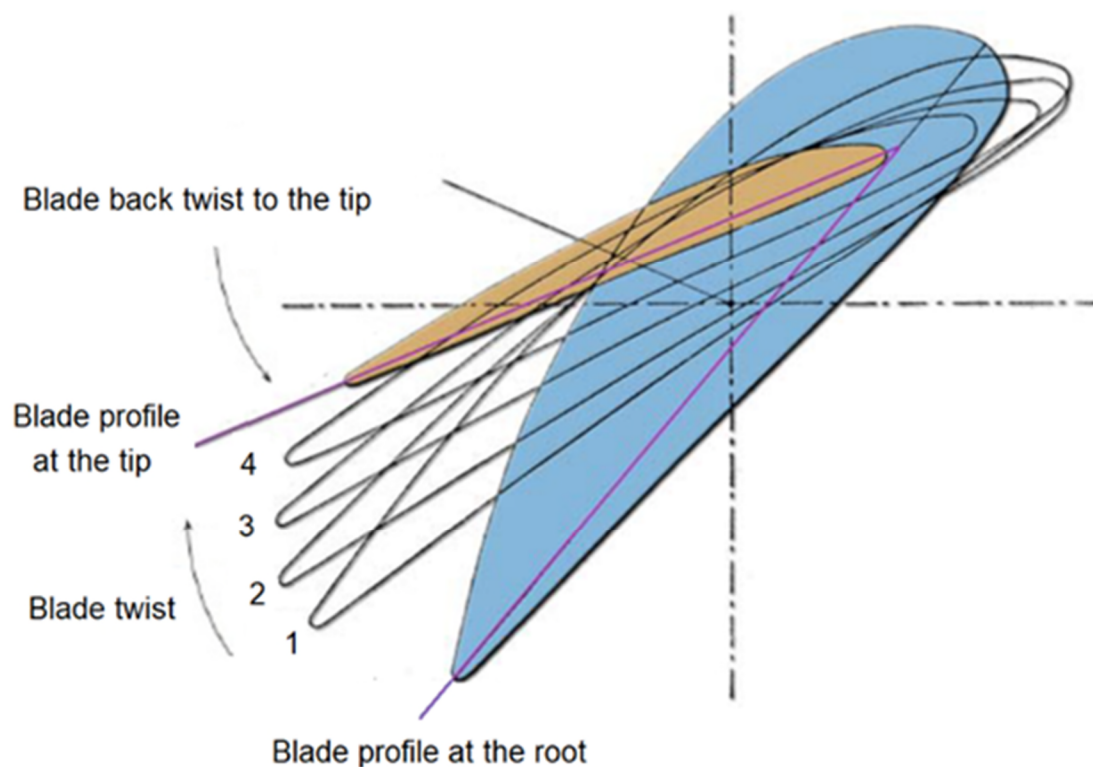


Figure 2-10. Blade twist from root to tip and back twist imposed at some initiation point back towards the original twist origin (adapted from Mecaflux Heliciel 2019).

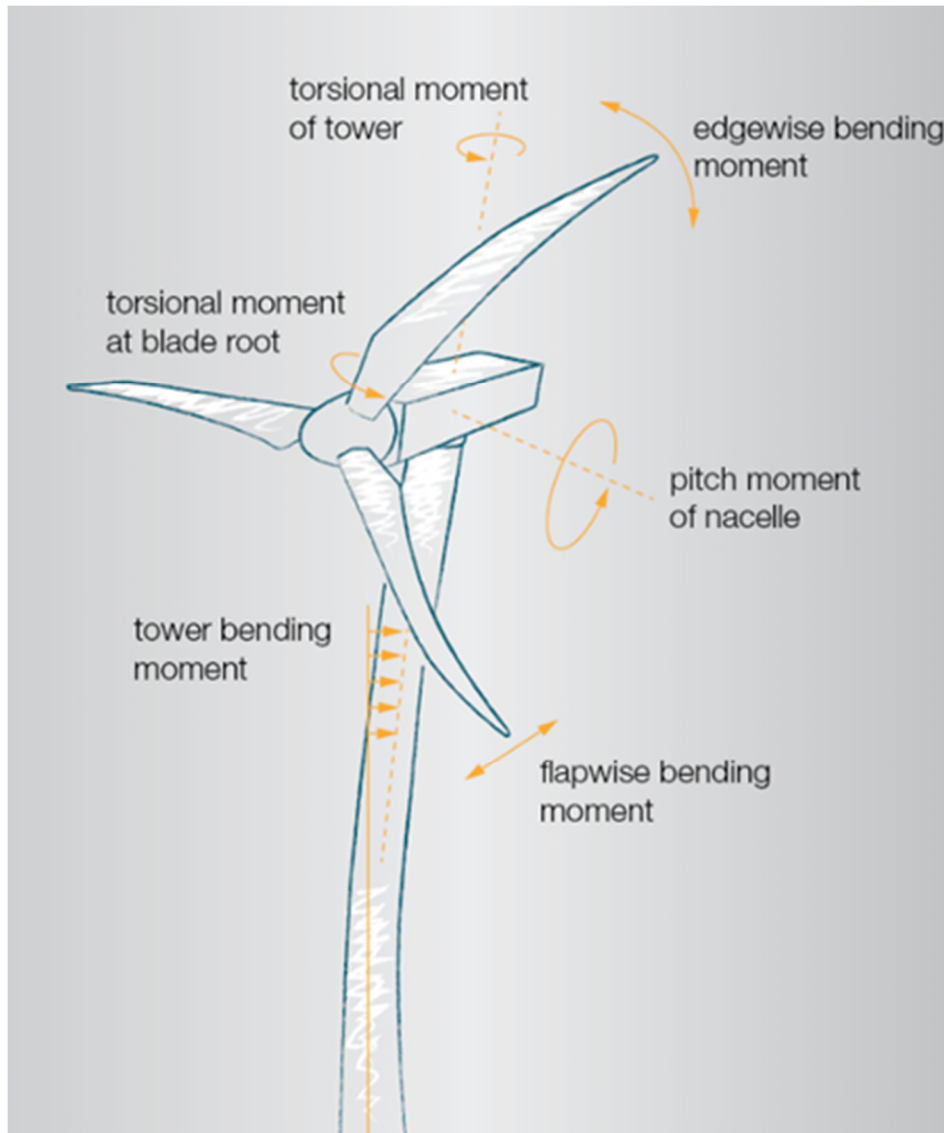


Figure 2-11. Schematic highlighting the direction of the flapwise and tower bending moments as they occur on a HAWT (LTI Motion 2019).

Merz (2011) performed an in-depth numerical study using both ADAMS and FAST_AeroDyn, on large passive stall blades with the aim of designing a series of optimised designs that would minimize the unit cost of energy through simulation in the frequency domain. A high level of aerodynamic damping was seen through the application of the back twist at all wind speeds within the operational range, for twists initiating at different points along the blade length from 5 to 22% from the tip. The back twist was towards feather in the region nearer the tip, such that the air flow would remain attached to the blade tip when

operating in higher mean winds speeds. This therefore created the desired power increase that Coxa and Echtermeyera (2013) had suggested could be achieved with a pitching control system. However, Merz (2011) stated that, as the platform pitch frequency needs to be set below 0.05 Hz for a FOWT so that the frequencies of the (1st order) wave excitation are avoided, an active rotor speed control would be required if damping the platform motion was one of the objectives. Also, as the stall aerodynamic behaviour is very similar whether it is achieved passively or through active pitch, Merz (2011) also suggested that this back twist method would be directly transferable, with increases in the aerodynamic damping and constant power above rated being the objective.

Ostachowicz et al (2016) presents two methods to determine the blade twist, as they highlighted that as the twist distribution on a blade is reliant on wind speed, the blade cannot be designed with a constant tip speed ratio. The first method takes the ideal twist for a chosen tip speed ratio and uses an iterative procedure to compare the unloaded pre-twist necessary to achieve the ideal at a particular wind speed. However problems with this method have been encountered when the angle of attack was not within the range of operation (Lobitz & Veers 2003). The second method proposes the optimisation of the blade twist for a specific wind speed, although the authors felt this method was as yet unexplored (Ostachowicz et al 2016).

2.3.6 Tuned dampers

Research on a FOWT using the FAST simulation tool was performed using two tuned-mass dampers (TMDs) in the nacelle, one to reduce the fore-aft motion and one the side-to-side motion (Lackner & Rotea 2011). This provided a reduction in both tower fore-aft and side-to-side fatigue loads of just over 8%. The blade pitch rate was also reduced. This study was however on a barge, where motions are easier to reduce as previously highlighted in section 2.3.3.

Research has also been carried out using a tuned liquid column damper (TLCD) within the floating structure, tuned to its natural frequency (Coudurier et al 2015).

Motions were controlled; however values were not given within the report, so its effectiveness is hard to judge. This study also utilized a barge.

2.4 Simulating FOWT responses

Although some of the instabilities seen in simulations established to predict the responses of a FOWT may not be significant in a real scenario, the most appropriate computer-aided engineering simulation tools to capture as many responses as accurately as possible are very much desired (Thiagarajan & Dagher 2014). Simulations conducted on floating platforms in the linear frequency domain have been seen to not predict possible instabilities in yaw (Thiagarajan & Dagher 2014), and also other non-linear responses such as tower shadow, wind shear, and dynamic shear (Henderson & Patel 2003). The use of simulations in the linear frequency domain has therefore become practically obsolete for full FOWT dynamic analysis, emphasised by the possibility of also incorrectly predicting natural frequencies and component resonances (Cordle & Jonkman 2011). This has therefore led to the development or upgrading of several time domain simulation packages applicable to the non-linear analysis of FOWTs. The FAST simulation code, developed by NREL, is arguably the most attractive to researchers, not only due to the simulation capabilities, but also due to its worldwide free, open source availability. Both FAST v8 and the more recently available OpenFAST versions are applicable to FOWT analysis.

The FAST code enables coupled AHSE simulations to be generated, which can predict both extreme loads and fatigue loads under different environmental conditions for HAWTs that are either fixed on land, fixed offshore, or floating offshore. Two forms of analysis can be performed, either simulation or linearization. The simulation mode utilizes nonlinear equations of motion in the time domain to produce the predicted turbine responses. Users can specify a range of different control methods which can also be operated within Simulink. The linearization mode allows for a full linearized depiction of the wind turbine system to be extracted. This is specifically useful for control design but also for deriving the system modes utilizing an eigenanalysis. The linearization mode

cannot however be operated through the Simulink interface (Jonkman & Buhl 2005).

The aerodynamic models rely on user specified wind data and can provide solutions for the wake effects of the rotor and the blade element loads incorporating dynamic stall (Jonkman & Buhl 2005). A quasi-steady blade element momentum theory is used for operating wind turbines within AeroDyn v15, which calculates the local 2D forces acting on the wind turbine rotor and tower. These are then integrated to derive the aerodynamic 3D behaviour, taking account of corrections captured in the model such as those created by the skewed wake, tip-losses, hub-losses, tower shadow and dynamic stall. In Figure 2-12, this is represented by the AeroDyn module. Some wind conditions, such as steady winds, are directly entered into this module. Turbulent stochastic winds however need to be externally generated using a wind generator such as the TurbSim code (Kelley & Jonkman 2007).

Both regular and irregular waves, as well as steady and turbulent marine currents, can be simulated by the hydrodynamics models, defined within HydroDyn, and may provide solutions accounting for radiation, diffraction, viscous and hydrostatic loads on the structure. Within HydroDyn, calculation of the hydrodynamic loads can be solved by strip theory, potential flow theory or a combined approach. The waves are generated using either first order (linear Airy theory) or second order wave theory. The potential flow theory implemented in this study requires the first and second order hydrodynamic coefficients, which are frequency dependent, to be independently generated through a frequency domain code such as WAMIT. The forces and motions of the body are generated within WAMIT relative to the un-displaced platform's global coordinate system in HydroDyn. Generated data from WAMIT includes 6x6 matrices for linear hydrostatic restoring forces, hydrodynamic added-mass (frequency dependant) and damping due to linear wave radiation as defined in depth by Jonkman et al (2017b).

The electrical and control models of the system account for the actuators, controller logic and sensors of the blade pitch to either feather or stall, the nacelle yaw, generator torque and the generator and power converter and can be entered directly into the ServoDyn module or externally through an interface with Simulink. The mooring system dynamics can be modelled through a number of modules such as MAP++ or MoorDyn. The mooring system was modelled using MoorDyn which assumes that each mooring line is a series of lumped masses. Mooring system dynamics are therefore predicted based on this premise. The MoorDyn model also incorporates the effects from weight and buoyancy forces, axial stiffness and damping, spring damper forces that arise from the contact that the mooring has with the seabed and hydrodynamic forces derived from Morison's equation. Within ElastoDyn, the dynamic structural models then apply the reactions from the mooring conditions, the electrical and control systems, the hydrodynamic and aerodynamic and gravitational loads and simulate the rotor, support structure and drivetrain elasticity. Full details of the simulation capacity of FAST are provided by Jonkman and Buhl (2005) and Jonkman and Jonkman (2016b).

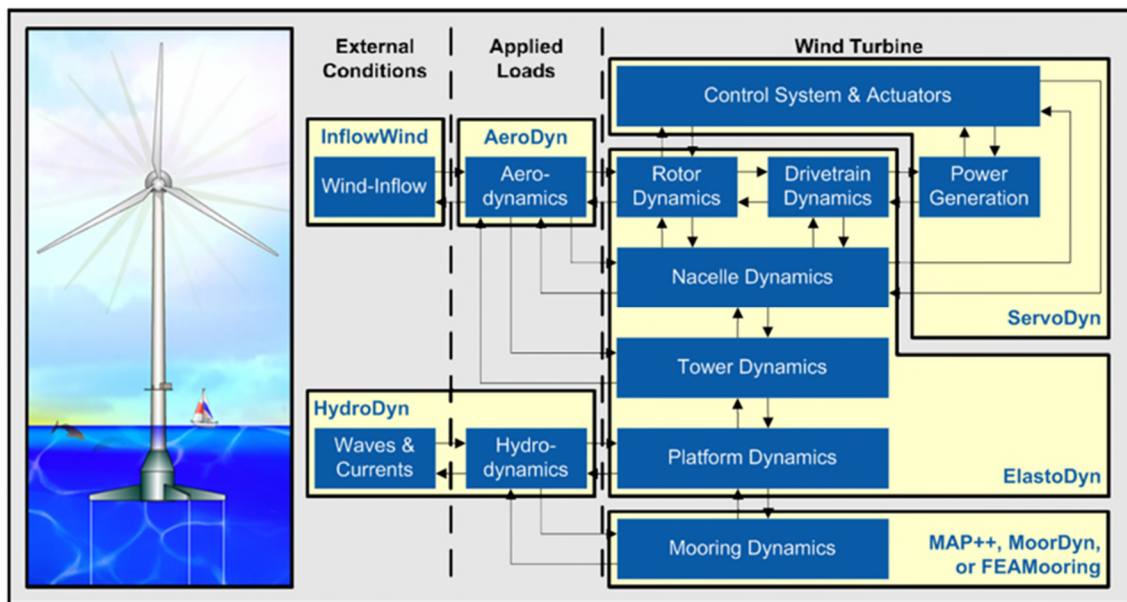


Figure 2-12 The control volumes within FAST that are associated with each module, as applicable to a FOWT (Jonkman & Jonkman 2016b)

2.5 Summary of the key literature findings

- The exact magnitude and origin of loads acting upon a floating turbine tower vary, depending upon the dynamics of each FOWT platform type (Robinson & Jonkman 2011).
- For all platform types, the most significant load increase when passing from fixed to floating wind turbines is the tower base fore-aft bending moment, which negatively effects the tower life. One solution to mitigate the increased tower loads would be for the tower to be strengthened, however, this could lead to a sizable rise in tower costs due to the additional material, manufacturing and higher deployment complexity. A more suitable solution would be to reduce the undesirable tower base fore-aft response increase, in particular focusing on reducing tower axial fatigue, thus the benefits of a reduction in the tower fore-aft moment can be quantified (Robinson & Jonkman 2011; James & Costa Ros 2015; Li et al 2017). Many methods focused on controlling the platform pitch motion, however, reductions in the platform pitch do not automatically lead to a decrease in tower loads, thus proposed tower fore-aft moment reduction methods should focus on directly reducing the tower motion (Lackner 2013).
- Any reduction in excessive stress and fatigue needs to be achieved without disproportionately decreasing the quality of the energy produced (Fleming et al 2019).
- All pitch-to-feather controlled HAWTs experience a phenomena called 'negative damping'. The frequency of the motions in surge, sway, roll and pitch of a FOWT are one or more orders of magnitudes lower than for a fixed wind turbine, hence the avoidance of the negative damping leads to more fluctuations in the power generation (Fleming et al 2014; van der Veen et al 2012).
- A VSVP-S control strategy avoids negative damping of the turbine tower, hence, providing a more regulated rotor speed and power output than the

one achieved with a pitch-to-feather strategy (Larsen & Hanson 2007; Jonkman 2007).

- The opposing conclusions on the impact of VSVP-S (that it was seen as beneficial on a spar and detrimental on a barge) highlight how the tower responses may be very platform type specific. Also, as the barge design has been seen to experience excessive tower loads during operation, this emphasises the gap in knowledge on whether suitable VSVP-S systems could provide the much desired reduction in tower axial fatigue needed by FOWTs, specifically by spar and semi-submersible types which see the most increase in the tower fore-aft loads (Larsen & Hanson 2007; Jonkman 2007; Robinson & Jonkman 2011).
- Blades manufactured with a pre-twist to stall that then twist towards feather under load, could decrease turbine loads by the order of 10% when the blades are passively or actively pitching-to-stall (Lobitz & Veers 2003).
- Back twist towards feather in the blade region nearer the tip also created a desired power increase (Merz 2011).
- Blade twist cannot be designed with a constant tip speed ratio (Ostachowicz et al 2016).
- The optimisation of the blade twist for a specific wind speed has as yet been unexplored (Ostachowicz et al 2016).
- Blade root flapwise moment reductions can decrease the tower base fore-aft moments and therefore increase tower axial fatigue life (Stäblein et al 2017; Coxa & Echtermeyera 2013).
- An active rotor speed controller would be required if damping the platform motion was one of the objectives (Merz 2011).
- FAST provides coupled AHSE simulations that can predict the behaviour of fully coupled FOWTs in the non-linear time domain (Jonkman & Buhl 2005; Jonkman & Jonkman 2016a).

2.6 Identifying the current knowledge gaps

- No studies on VSVP-S control of a turbine coupled to a semi-submersible floating platform have been explored to date.
- The study of a turbine coupled to a barge (Jonkman 2007) found that the responses were negatively increased with a VSVP-S control system, however the study only looked at a mean wind speed of 18 m/s, when damping would be likely to be decreased and the frequency of the wind speed would be reduced.
- The previous study (Larsen & Hanson 2007) that gave favourable findings with VSVP-S control of a turbine coupled to a spar were for only one wind speed very close to the rated wind speed, where damping could be expected to be more beneficial.
- No studies on possible tower load response reductions from blade back twist have been performed on a VSVP-S turbine coupled to a floating platform.

To summarize, optimisation of a back twisted blade when operating at a distinct mean wind speed has not been explored. As will be detailed in Chapters 3, 4 and 5, this research aims to expand the knowledge and hence fill some of those gaps as outlined below:

- Provide further information on tower axial fatigue propagation relative to platform, tower and blade profiles when operating with VSVP-S control (addressed by objectives 6, 7, 8 & 9).
- Increase the data on the effects of a VSVP-S control strategy for different FOWT platform types, and the benefits of avoiding negative damping in terms of a more regulated rotor speed and power output (addressed by objective 6).

- Determine if tower axial fatigue reductions can be achieved utilizing a back twist towards feather blade on a VSVP-S blade pitch control system (addressed by objective 8).
- Present the most appropriate blade back twist configuration in terms of magnitude and initiation point along the blade radius, through a weighted wind frequency analysis for a specific set of environmental conditions, for both a semi-submersible and a spar FOWT platform (addressed by objectives 8 & 9).

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3.1 Title page and abstract

Article

Reducing Tower Fatigue through Blade Back Twist and Active Pitch-to-Stall Control Strategy for a Semi-Submersible Floating Offshore Wind Turbine

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Abstract: The necessity of producing more electricity from renewable sources has been driven predominantly by the need to prevent irreversible climate change. Currently, industry is looking towards floating offshore wind turbine solutions to form part of their future renewable portfolio. However, wind turbine loads are often increased when mounted on a floating rather than fixed platform. Negative damping must also be avoided to prevent tower oscillations. By presenting a turbine actively pitching-to-stall, the impact on the tower fore–aft bending moment of a blade with back twist towards feather as it approaches the tip was explored, utilizing the time domain FAST v8 simulation tool. The turbine was coupled to a floating semi-submersible platform, as this type of floater suffers from increased

fore–aft oscillations of the tower, and therefore could benefit from this alternative control approach. Correlation between the responses of the blade’s flapwise bending moment and the tower base’s fore–aft moment was observed with this back-twisted pitch-to-stall blade. Negative damping was also avoided by utilizing a pitch-to-stall control strategy. At 13 and 18 m/s mean turbulent winds, a 20% and 5.8% increase in the tower axial fatigue life was achieved, respectively. Overall, it was shown that the proposed approach seems to be effective in diminishing detrimental oscillations of the power output and in enhancing the tower axial fatigue life.

Keywords: floating offshore wind turbine (FOWT); pitch-to-stall; blade back twist; tower fore–aft moments; negative damping; blade flapwise moment; tower axial fatigue life

3.2 Introduction

Worldwide, climate policies have encouraged the development of energy from renewable resources, such that, within Europe, 11.6% of energy demand was provided solely from wind energy in 2018 (WindEurope 2019). The installed capacity of offshore wind turbines has increased globally by 87%, between 2016 and 2017, rising to a total of nearly 19 GW (Fried et al. 2017), of which floating turbines currently play only a small part. Indeed, the world’s first floating farm, with a capacity of 30 MW only came online in 2017. However, due to the limited availability of offshore sites with shallow beds and low seabed slope, the industry is looking towards floating solutions in the future, with predictions of 5 GW of installed energy from floating wind by 2030. This would amount to 5% of the offshore wind market (Fried et al. 2017).

Generally, for floating platforms, the horizontal axis wind turbine (HAWT) specifics used for prototypes, model experimentation, and simulation purposes are largely those that have been originally designed for onshore locations. Although they are further modified for the offshore environment, the turbines, including most components and the controllers, have generally been optimized

for a foundation fixed into the seabed. This has implications for the applicability of these simulations to floating platforms. Turbine loads, for example, are often increased when the HAWT is mounted on a floating platform, although the exact load, magnitude, and origin will vary, depending upon the platform design and environmental factors. Prominent load increases are usually the induced tower base bending moments, with extreme loads increasing by a factor as high as 1.6 times that seen in a fixed, land-based turbine (Robertson & Jonkman 2011). Thus, the increased tower base axial fatigue could cause a large reduction in the expected life of the turbine, and therefore, there is a need to have more costly tower and platform structures in order to align with the standard 25–30 year design life of modern offshore wind farms.

Currently, all large (3 MW+), variable speed, variable pitch, employ HAWTs pitch-to-feather to control the power output above rated wind speeds. Whether these turbines are fixed on dry land, the seabed, or floating offshore, they can experience a phenomenon when wind speeds exceed the rated wind speed, which is generally referred to as ‘negative damping’. This is due to a decrease in rotor thrust at constant rotor speed as the wind speed increases. This can then lead directly to tower fore-aft oscillation, hence, decreased tower axial fatigue life if not controlled, as illustrated in Figure 3-1 (van der Veen et al. 2012). Fixed turbines can avoid the negative damping effect without a loss in performance as the natural frequency of the blade pitch control system is lower than the first resonance modes of the tower. However, for floating offshore wind turbines (FOWTs), the frequency of the motions (surge, sway, roll, and pitch) are one or more orders of magnitudes lower than for a fixed-base turbine, and therefore, the pitch controller frequency must be lower to avoid negative damping. This causes a reduction in the performance of the rotor speed when operating at above rated wind speeds, such that the ideal constant rotor speed fluctuates around the desired output, leading to more undesirable fluctuations in the generated power output (Larsen & Hanson 2007).

Horizontal axis wind turbines with variable speed and variable pitch are now considered the industrial standard for large turbines. However, utilising active

pitch-to-stall rather than pitch-to-feather control, where the blade is rotated so that the induced aerodynamic stall slows down the rotor to produce constant rotor speed, has largely been ignored. This omission is because the pitch-to-stall configuration can lead to increased blade deflections in larger, softer blades and reduced predictability in terms of induced lift and drag at a specific angle of attack. The issues related to the negative damping phenomenon can, however, be avoided by design when in pitch-to-stall operation, as the rotor thrust at constant rotor speed does not decrease as the wind speed increases. This increasing thrust allows the control frequency to be higher than typically expected on an FOWT, resulting in a much improved rotor speed performance and high-quality, regulated power. As such, utilising pitch-to-stall configurations could thus offer a solution to the performance reduction seen by current, industry-standard pitch-to-feather floating turbines.

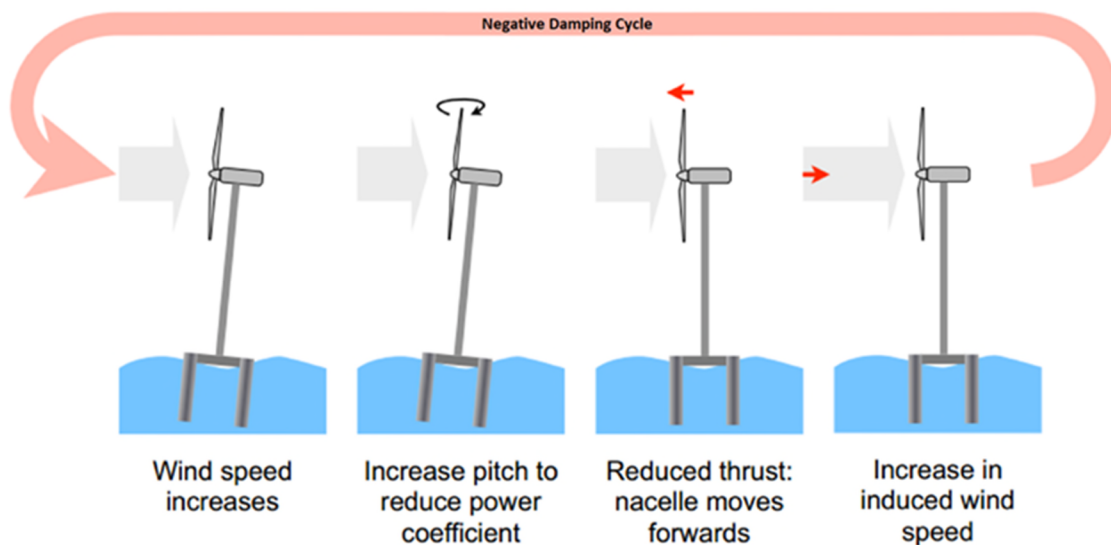


Figure 3-1. Tower oscillation propagation in a pitch-to-feather horizontal axis wind turbine (HAWT) due to the negative damping cycle (adapted from van der Veen et al. (2012))

Only two studies, by Larsen and Hanson (2007) and Jonkman (2007), have been conducted on large, variable speed, floating HAWTs that consider actively pitching the whole blade towards stall as a means to provide a near constant rotor speed at above rated wind speeds. This is partly due to the ambiguity that remains on the aerodynamic behaviour of stalled blades (Bossanyi 2003).

Increased loads and deflection on stalling blades can also dictate that the blades are heavier (Macquart & Maheri 2019), which would have a negative impact upon the rotor and turbine. The peak loads that can occur on a passive stall blade when power is not shed fast enough would, however, be more controlled when the stall blade is being actively pitched as the power control is more regulated at higher wind speed than in a pitch-to-feather control system. Therefore, although the thrust loads acting on a turbine are increased as the angle of attack increases, it also varies less with pitch angle changes, such that the thrust and the torque have increased stability when operating with pitch-to-stall blades (Bossanyi 2003). This reduced variance in the thrust and torque responses will tend to have an overall benefit in terms of tower axial fatigue life. One of the studies simulated turbine, platform, and mooring responses of the Hywind spar concept for a 12 m/s mean turbulent stochastic wind, using a non-linear time domain simulation tool based on SIMO/RIFLEX, developed by Marintex, Trondheim, Norway and HAWC2, developed by DTU (Technical University of Denmark), Risø Campus, Denmark (Larsen & Hanson 2007). The simulation results for active pitch-to-stall control indicated not only improved regulation of rotor speed and power generation, but also saw more tower stability. These results were obtained even though the simulations used a blade designed for pitch-to-feather control. In fact, the authors, by accidentally making a pitch angle sign error in the pitch-to-feather control strategy, were using a pitch-to-feather wind turbine system in a pitch-to-stall mode. Hence, the design of the blades, controller, controller gains, and all components were from that original pitch-to-feather system. In the second study, Jonkman (2007) looked at simulated responses for a floating barge in 18 m/s mean turbulent stochastic winds when actively pitching-to-stall as well as when actively pitching-to-feather. The results were generated with the aero-servo-elastic simulation package, FAST 7. In the simulations, rotor speed and power regulation again increased with stall control, as compared to feather control. However, this was at the expense of an increase in the tower motion. This difference in the impact of pitch-to-stall on tower stability between the two studies, such that for a spar response changes were beneficial, yet they were detrimental

to the barge, indicates that the responses were very platform-type specific. The question of whether tower stability would be improved for a semi-submersible platform operating with a pitch-to-stall rotor has not been addressed to date. The impact of the platform-type is supported by the fact that the barge design also led to instability of the tower in pitch-to-feather control (Jonkman 2007). Although the blade used was also of a pitch-to-feather design (comparable to that used in the Larsen and Hanson (2007) study), it had altered aerofoil lift coefficients, leading to a smoother change in lift coefficient being experienced over the range of angle-of-attack experienced along the blade length, during pitch-to-stall control. It was suggested by Jonkman (2007) that a higher level of damping in pitch-to-stall could possibly be achieved if the aerofoil coefficients and rotor design were altered such that the rotor thrust continually increased from cut-in to cut-out wind speeds.

The optimisation of blade twist and its resultant effects have been extensively studied for pitch-to-feather and fixed-pitch stall configurations using a number of methods (Merz 2011; Stäblein et al. 2017; Méndez & Greiner 2009). In such instances, the design criteria commonly focuses on maximising the power coefficient and reducing blade vibrations and fatigue. Stäblein et al. (2017) achieved increased platform damping, and hence, reductions in tower fore–aft moment from blade twist modifications. For fixed-stall blades, a back twist was employed (the blade twists back towards feather at the tip for a proportion of the blade’s length) which resulted in the air flow remaining attached at the blade tip for higher wind speeds, thus increasing the power production capabilities of these sections of the blade (Merz 2011). By contrast, the benefits of actively pitching blades are often obtained at the expense of an increased blade pitching rate, and hence, actuator action which can impact on component life and operational costs. However, damage to the pitch bearing was not found to be adversely proportional to pitch rate increase when the blade flapwise loading was also reduced (Barlas et al. 2015). Merz (2011) performed in-depth research on fixed-pitch stall blades and designed a family of optimised blades to minimize the cost of a unit of energy using simulations in the linear frequency domain. Investigation of the effects of including a back twist of a few degrees, originating at different points along the

blade's length were performed (starting from 5 to 22% of the blade length as measured from the tip). This resulted in a high level of aerodynamic damping at all operational wind speeds. Stäblein et al. (2017) analysed the effect of additional blade twist from simulations produced utilizing the non-linear time domain aero-servo-elastic simulation tool HAWCStab2, developed by DTU, Risø Campus, Denmark, specifically for wind turbines designed by DTU. This applied a twist to the blades of a land-based 10 MW DTU turbine under pitch-to-feather control. Models investigated changing the blade twist towards both feather and stall from as high up the blade as 70% of the blade radius from the tip. Reductions in both the blade root's flapwise moment and the tower base's fore-aft moment were seen, however, this study was not carried out for a floating turbine. Floating platforms need platform pitch frequencies to be below 0.05 Hz to avoid the wave excitation frequencies, thus the rotor speed would need to be actively controlled to dampen the platform's pitch motion (Merz 2011).

The question of whether a variable pitch-to-stall, variable speed FOWT could reduce the tower base's fore-aft moment through blade design manipulation has not as yet been studied. Reductions in the blade root flapwise moments could decrease the tower base fore-aft moments, and therefore increase tower fatigue life. Improved rotor speed performance, and therefore higher quality energy regulation would also be anticipated due to the higher control frequency available to a variable pitch-to-stall controller. It is also worth noting that, whilst a dominant wind turbine floating platform type has not yet materialised on the market, it is desirable for research to have the potential to benefit more than one platform type.

To investigate the potential of active pitch-to-stall on a semi-submersible floating platform, this study investigates its possible benefits in terms of rotor speed performance, power generation, and tower base fore-aft moment-induced fatigue reduction. This study was conducted for a 5-MW floating turbine with a stall blade incorporating back twist (towards feather) nearer the tip. This research did not concern itself with the optimization of an actively pitching-to-stall blade or other systems loads, but rather focused on the effects of increasing back twist on tower

fore–aft fatigue life, which can in turn be used to optimise the back twist for turbine life extension. This twist optimization was carried out for three specific wind and wave conditions. This is a method proposed by Stäblein (2016), as designing around an optimum tip speed ratio is not possible for a back-twisting blade. The 5 MW turbine was coupled to a floating semi-submersible platform, as this type of floater has not been previously investigated with an active pitch-to-stall control strategy and suffers from increased fore–aft oscillations of the tower, and therefore could benefit from this alternative control approach. Furthermore, the Carbon Trust's report for the Scottish government also found that semi-submersibles had a better levelised cost of energy (LCoE) overall, compared to other platform types (James & Ros 2015). Thus, in combination with other benefits (e.g., that a semi-submersible could possibly be towed back to shore for maintenance, repair, and commissioning), this floating platform type is an attractive option (Thiagarajan & Dagher 2014).

3.3 Methods

The properties of a semi-submersible floating platform coupled to a 5 MW HAWT are investigated by running simulations utilizing the non-linear time domain FAST v8 simulation tool. The FAST v8 allows aero-hydro-servo-elastic analysis of land, offshore fixed, and offshore floating HAWTs and was developed by NREL (National Renewable Energy Laboratory), Colorado, USA (Jonkman & Buhl 2005). The FAST v8 solves equations of motion by numerical integration utilizing the rigid bodies of the system and from these, expressions for velocity and acceleration are derived. The aerodynamic models within FAST v8 require the user to specify a particular wind data profile, which FAST v8 uses to solve the aerodynamic loads on the blades, including dynamic stall and rotor and wake effects. For the analysis of offshore floating turbine analysis, the aerodynamic models not only generate the previously mentioned outputs, but are also linked to hydrodynamic models of the floating structure as well as dynamic structural and control models. This allows fully-coupled non-linear aero-hydro-servo-elastic simulations to be performed within the time domain.

3.3.1 Model parameters

For the purposes of this study, the semi-submersible floating platform was modelled with a three line catenary mooring system. This was based on a 1/50th scale experimental model tested in the MARIN (Maritime Research Institute Netherlands) wave basin, as part of the US DeepCWind project (Goupee et al. 2014). As a result of this, the platform model was used for the offshore simulation code comparison in the international OC4 Phase II study (Robertson et al. 2014; Robertson et al. 2012).

The wind turbine coupled to the semi-submersible was based on the NREL 5MW three-bladed HAWT (Jonkman et al. 2009), but with tower mode shapes that depict the expected flexibility of the tower when coupled to the semi-submersible floating platform (Robertson et al. 2014). The turbine had a hub height above sea water level (SWL) of 90 m, a rotor diameter of 126 m, and was rated at a wind speed of 11.4 m/s, which corresponded to a rated rotor speed of 12.1 rpm. It was designed to cut-in at 3 m/s (rotor speed of 6.9 rpm) and cut-out at 25 m/s. More details on the parameters of both models can be found in Robertson et al. (2014). The tower to platform coupling was represented in the turbine model as a cantilevered connection to capture the motions where the tower base joins to the platform. The environmental conditions were based on a site in the North Sea 100 miles northeast of Aberdeen with estimated water depths of 200 m. Such depths were, therefore, unsuitable for fixed base turbines (Geos 2001)

Three main floating offshore wind turbine models were compared in this study:

1. A conventional 'Feather Base Model' with a pitch-to-feather gain scheduling blade pitch controller. This model was used in the OC4 Phase II code comparison investigation (Robertson et al. 2014). The other models developed were compared to this baseline data.
2. A 'Pitch-to-Stall Model' where the blade aerofoil lift coefficients were manipulated for stall operation in line with the blades used by Jonkman (2007) such that a smoother change in lift coefficient occurred over the range of angle-of-attack experienced during pitch-to-stall control.

- Three 'Back Twist Pitch-to-Stall Models' further build on the blade properties of the 'Pitch-to-Stall Model' by additionally imposing a back twist towards feather on the blade (of 3, 6, and 9°). This third model type operated below rated at a set pitch angle of -4°, as changing the setting of the constant pitch angle below rated wind speed had also been employed to reduce fatigue and optimize the energy output on passive stall turbines (Wright & Fingersh 2008).

The collective blade pitch-to-stall control system that was designed for both the 'Pitch-to-Stall Model' and the 'Back Twist Pitch-to-Stall Model', was a relatively simple feedback proportional-integral (PI) controller with constant gains derived at 18 m/s steady wind conditions, as shown in Figure 3-2.

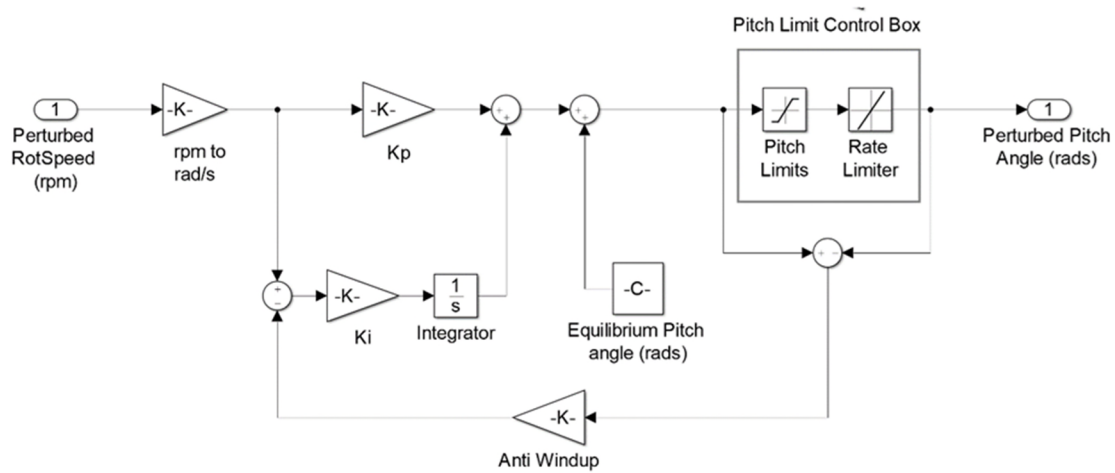


Figure 3-2. Pitch-to-stall proportional-integral (PI) controller for the 'Pitch-to-Stall Model' and all 'Back Twist Pitch-to-Stall Models'.

Utilizing a gain scheduler that relies upon the pitch angle at any moment in time to predict the gain change required would be much more complex with an active pitch-to-stall control. This is due to the double-valued nature of the pitch angle within region 3, as highlighted within section 3.4.1. This controller pitches the blades to achieve a constant rotor speed when winds are above 11.4 m/s and incorporates a pitch-rate limiter set to $\pm 8^\circ/\text{sec}$. This pitch-to-stall controller was implemented in Simulink, which was coupled directly with the FAST v8 simulation

code. It expanded upon a simple 'constant gains feedback' PI pitch controller designed for pitch-to-feather control by Wright and Fingersh (2008).

To derive the pitch-to-stall controller gains that will ensure that the performance of the turbine results in a higher quality regulated power output over the full range of operational wind speeds from rated to cut-out, a single degree of freedom (DOF) system (the angular shaft rotation speed) was considered as presented by Larsen and Hanson (2007) and Jonkman (2007). From this, Equations 3-1 and 3-2 can be derived when the derivative gain, K_D , neglected for simplicity, as proposed by Hansen et al. (2005).

$$K_p = (2 \cdot I_{\text{DRIVETRAIN}} \cdot \Omega \cdot \xi_\phi \cdot w_{\phi n}) / N_{\text{GEAR}} \cdot \left(- \left(\frac{\delta P}{\delta \phi} \right) \right) \quad [\text{Eq 3-1}]$$

$$K_I = (I_{\text{DRIVETRAIN}} \cdot \Omega \cdot w_{\phi n}^2) / N_{\text{GEAR}} \cdot \left(- \left(\frac{\delta P}{\delta \phi} \right) \right) \quad [\text{Eq 3-2}]$$

where $I_{\text{DRIVETRAIN}}$ is the driveshaft inertia (kg/m^2) found from Equation 3-3; Ω is the rotational speed (rad/s); ξ_ϕ is the damping ratio related to the rotor speed error control system; $w_{\phi n}$ is the natural frequency of the control system (rad/s); N_{GEAR} is the gearbox ratio, and $dP/d\phi$ is the sensitivity of the aerodynamic power to the blade pitch angle (W/rad).

$$I_{\text{DRIVETRAIN}} = I_{\text{ROTOR}} + (N_{\text{GEAR}}^2 \cdot I_{\text{GEN}}) \quad [\text{Eq 3-3}]$$

where I_{ROTOR} is the rotor inertia (kg/m^2) and I_{GEN} is the generator inertia (kg/m^2).

The sensitivity of the aerodynamic power to the blade pitch angle for each model was derived in FAST v8.16.00 a-bjj through linearization of the turbine simulation

model utilizing the pitch angles and rotor speed of each wind speed, as predicted in the periodic steady-state simulations detailed in section 3.4.1. This followed the procedure presented for aerodynamic derivatives by Jonkman and Jonkman (2016) such that all the structural DOF were disabled to eliminate convergence issues and frozen wake was applied. Values of 0.6 rad/s were used for the natural frequency of the control system and 0.7 for the damping ratio related to the rotor speed error control system as suggested in Hansen et al. (2005). This system frequency of the pitch-to-stall controller (0.6 rad/s) is much higher than the 0.2 rad/s used by the 'Feather Base Model' pitch-to-feather controller, as negative damping is avoided with the pitch-to-stall control regime.

3.3.2 Blade back twist configuration

The back twists employed in this study were chosen after investigative research of the altered dynamic coupling effects on the tower, due to the changes in the blade geometry, specifically in terms of tower base fore–aft moment. The initial selection process looked at back twist applied at initiation points from 5% to 35% in 10% intervals along the blade length (measured from the tip), with a 'best guess' back twist angle of 3°, based on previous research involving back twist on passive stall blades (Merz 2011) and blades that pitch-to-feather (Stäblein et al. 2017).

Responses during mean turbulent winds of 18 m/s for short 600 s simulations were examined. The effects on tower fore-aft bending moment were then analysed when both increasing and decreasing the back-twist angle, which indicated a reduction in tower fore-aft moment range could be achieved with a higher back twist angle of 9°. The initiation point of the back twist was chosen to be at 25% along the blade length, from the tip. Figure 3-3 gives a visual reference to the three back twist angles applied to the 'Back Twist Pitch-to-Stall Model', alongside the original twisted NREL 5 MW blade which is used for both the 'Feather Base Model' and the 'Pitch-to-Stall Model'.

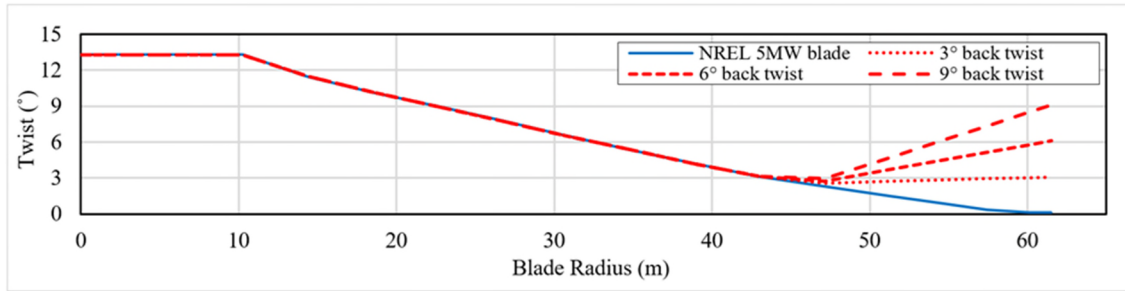


Figure 3-3. Twist profiles for pitch-to-stall blades in the tower axial fatigue life study.

A constant -4° pitch angle was also applied at all winds below rated to the three 'Back Twist Pitch-to-Stall Models'. This was introduced as both fatigue life and energy generation, which were increased when it was incorporated into the back-twist designs, as compared to a constant pitch angle of 0° or -2.5° . Model specifications and controller gains for each stall model are shown in Table 3-1.

Table 3-1. Model parameters in terms of back twist, pitch below rated setting, and blade pitch controller gains.

Model ID	Feather Base Model	Pitch-to-Stall (P-S) Model	3° Back twist P-S Model	6° Back twist P-S Model	9° Back twist P-S Model
Constant pitch angle below rated ($^\circ$)	0	0	-4	-4	-4
Twist starting distance from blade root (%)	N/A	N/A	75	75	75
Back twist angle increase towards feather at the tip ($^\circ$)	0	0	3	6	9
Proportional gain at 18m/s, K_p (s)	Inbuilt gain scheduler*	-0.865	-0.917	-1.105	-1.414
Integral gain at 18 m/s, K_i		-0.371	-0.391	-0.474	-0.606

* As applicable to the OC4 (Offshore Code Comparison Collaboration Continuation) Phase II simulation model

3.4 Results

3.4.1 Periodic steady wind characteristics of a blade pitching-to-stall

To compare the FOWT characteristics of the 'Feather Base Model', represented by the blue dashed lines in Figure 3-4, with the 'Pitch-to-Stall Model', represented by the solid red lines, periodic steady-state curves were derived from simulations.

The periodic nature of the steady state was created as the variables did not have a constant value but a range of values that repeat over a given period. For all of the FOWT models presented here, the periodic influence was due to the tilt applied to the rotor shaft and the variables were repeated after each full rotation of the rotor. These simulations were run with steady uniform wind speeds from cut-in to cut-out, in 1 m/s increments, with all the platform DOF disabled (i.e., like a fixed land-based wind turbine) as suggested by Jonkman (2007) to ensure that the semi-submersible floating platform is not excited by the applied wind and waves.

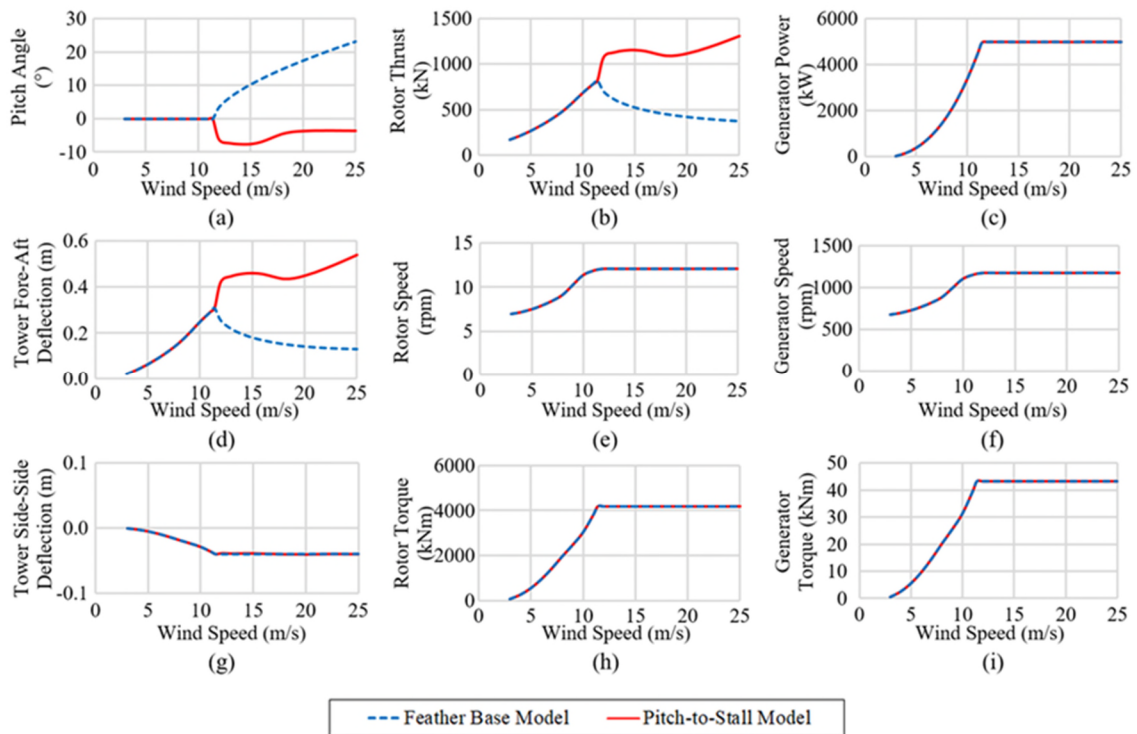


Figure 3-4. Simulated FOWT characteristics from periodic steady winds for two different blade models: (blue) pitch-to-feather and (red) pitch-to-stall.

Figure 3-4a highlights the difference in the pitch angles required for both control methods. For feather control, a continuous, smooth rise in the blade pitch angle required was seen from 0° at the rated wind speed of 11.4 m/s, to just exceeding 23° at the cut-out wind speed of 25 m/s. For stall control, the negative pitch angle requirement rose steeply at wind speeds just above rated, the area of operation often referred to as Region 2.5, and a maximum negative pitch angle

(approaching -8°) was experienced at wind speeds as low as 15 m/s. The pitch angle then slowly decreased in magnitude again as wind speeds increase to over 20 m/s, after which the required blade pitch angle was maintained at a fairly constant level of approximately -3.5° before the FOWT cut-out at 25 m/s.

From the simulated rotor thrusts in Figure 3-4b, it can be seen that, at wind speeds above rated, the rotor thrust curves were the inverse of the required pitch angle curves for both the pitch-to-feather and pitch-to-stall control methods. The tower fore–aft deflections curves, shown in Figure 3-4d, followed the same pattern as the rotor thrusts experienced by the relative control method. The outputs of all other parameters observed in Figure 3-4 were identical and are presented to show the specific responses for both control methods.

3.4.2 Integrator saturation issue

Initial investigation into the response and load analysis of the 'Pitch-to-Stall Model' in turbulent winds, when the floating wind turbine was operating near to the rated wind speed, highlighted a problem with the rotor speed increasing with simulation time to velocities beyond the design limit, as seen in Figure 3-5a. As rotor speed directly influences the generated power, this was also negatively affected, as seen in Figure 3-5b. This rotor speed increase occurred during sudden changes from wind speeds below rated to wind speeds above rated and was due to the pitch controller actuator reaching its upper limit. When this occurred, it caused the feedback loop to become an open loop, thus the saturated actuator remained at its upper limit even when the output changed. This error then continued to be integrated by the PI controller, which caused the integrator to be 'wound up', as observed by Wright and Fingersh (2008).

As well as a large overshoot in the blade pitch angle, such that the angle increases from around -8° to nearly -12° (Figure 3-5e), oscillations were also seen as the system returned to a stable state. This can clearly be seen by the response shown in red in Figures 3-5c,d for the platform pitch motion and the tower fore–aft bending moment, respectively. These oscillations lasted for up to 100 s after each rotor over-speed occurrence. These undesirable responses,

along with rotor speeds far exceeding the design limit, cannot be tolerated by the turbine, hence, an anti-windup filter was incorporated to feed back into the pitch-to-stall controller design (Figure 3-2). The anti-windup filter changes the gain value of the integral during saturation and prevents the rotor speed from erroneously over-shooting. The anti-windup filter is inactive except when the floating wind turbine is operating near to the rated wind speed, as the pitch angle is the same at the input and output of the pitch-limit control box under these conditions (Figure 3-2).

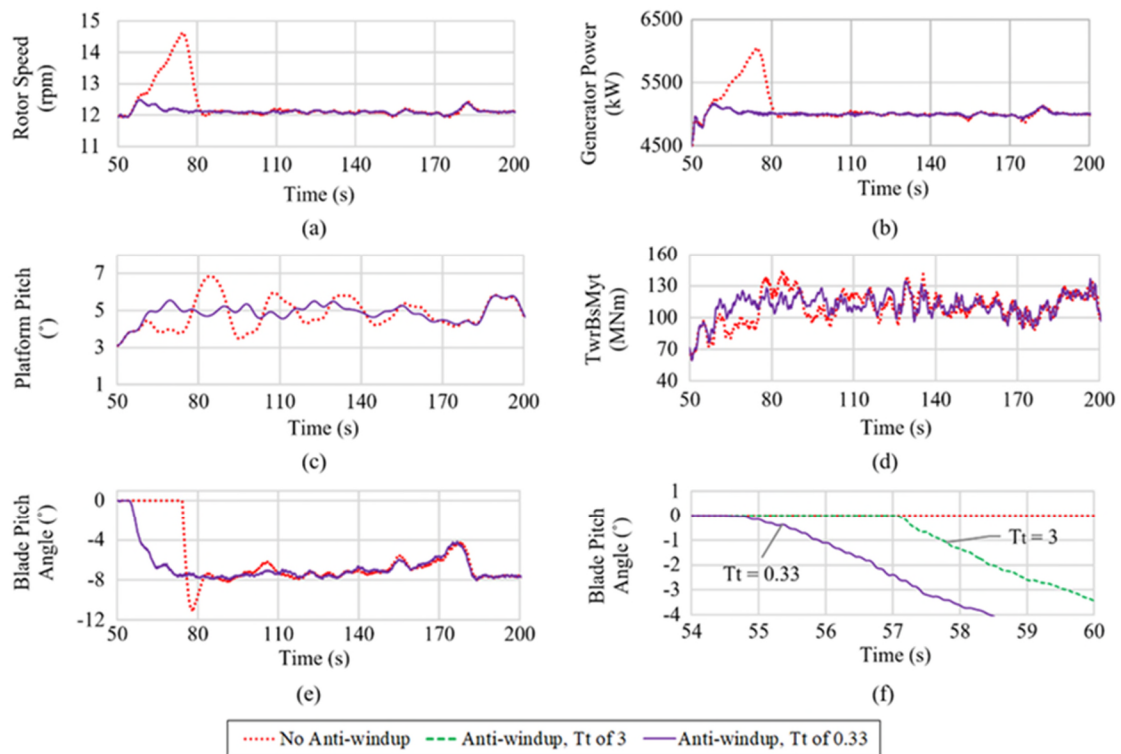


Figure 3-5. Simulated responses of the 'Pitch-to-Stall Model' with and without anti-windup at 13 m/s mean turbulent winds.

3.4.3 Normalized outputs in turbulent wind conditions

A selection of the most relevant load analysis results are presented as ratios against the 'Feather Base Model', in Figure 3-6, obtained with all the DOF enabled except for the rotor-teeter DOF, which is not applicable to a three-bladed turbine. Each output was calculated from 3×3 hr simulations each generated with three different random wind and wave seeds, compiled from periodic winds

files, such that the wind distribution was repeated every 10 mins throughout the full simulation time. The 3 hr simulation length was chosen to improve the fatigue analysis, as the responses of FOWTs vary more with time than fixed turbines. The tower axial fatigue life was derived using a Rainflow cycle counting algorithm and Miner's Rule within MATLAB, developed by The MathWorks, Natick, Massachusetts, USA (Kvittem & Moan 2015). The stochastic turbulent mean winds were generated using the Kaimal wind spectrum. Results presented as a range represent the full range of motion experienced from the maximum to the minimum values for the combined simulations. Simulations are presented under mean winds of 8, 13, and 18 m/s each with an IEC (International Electrotechnical Commission) turbulent intensity model B (0.14) (EN 2006), a power law exponent of 0.14, and a surface roughness length of 0.03 m. The significant wave heights (H_s) were 1.25, 2.5 and 4.5 m, at 8, 13 and 18 m/s mean wind speeds respectively and the spectral peak periods (T_p) were 5.5, 8 and 10 s. The significant wave height is calculated by finding the mean of the highest third of all the waves experienced and the spectral peak period is derived from the highest energy waves. All environmental conditions are the same for each model at each mean wind speed. The first 300 s of each simulation was discarded to avoid transient responses.

At 8 m/s mean wind speed, the tower base axial fatigue life of the untwisted Pitch-to-Stall Model, was seen to be identical to the 'Feather Base Model' and higher than all 'Back Twist Pitch-to-Stall Models' (Figure 3-6a). For mean winds of 13 m/s, seen in Figure 3-6b, the tower axial fatigue life increased for all stall scenarios, with a maximum extension in life of over 20% when the back twist was 3°. However, at the 18 m/s mean wind speed, shown in Figure 3-6c, it was only with the more extreme back twist of 9° that the tower life expectancy exceeded that achieved with pitch-to-feather control. The increase in tower axial fatigue life for this high back twist was 5.8%; however, the average generated power had a slight decrease for the back twisted pitch-to-stall models at the below rated wind speed (Figure 3-6d).

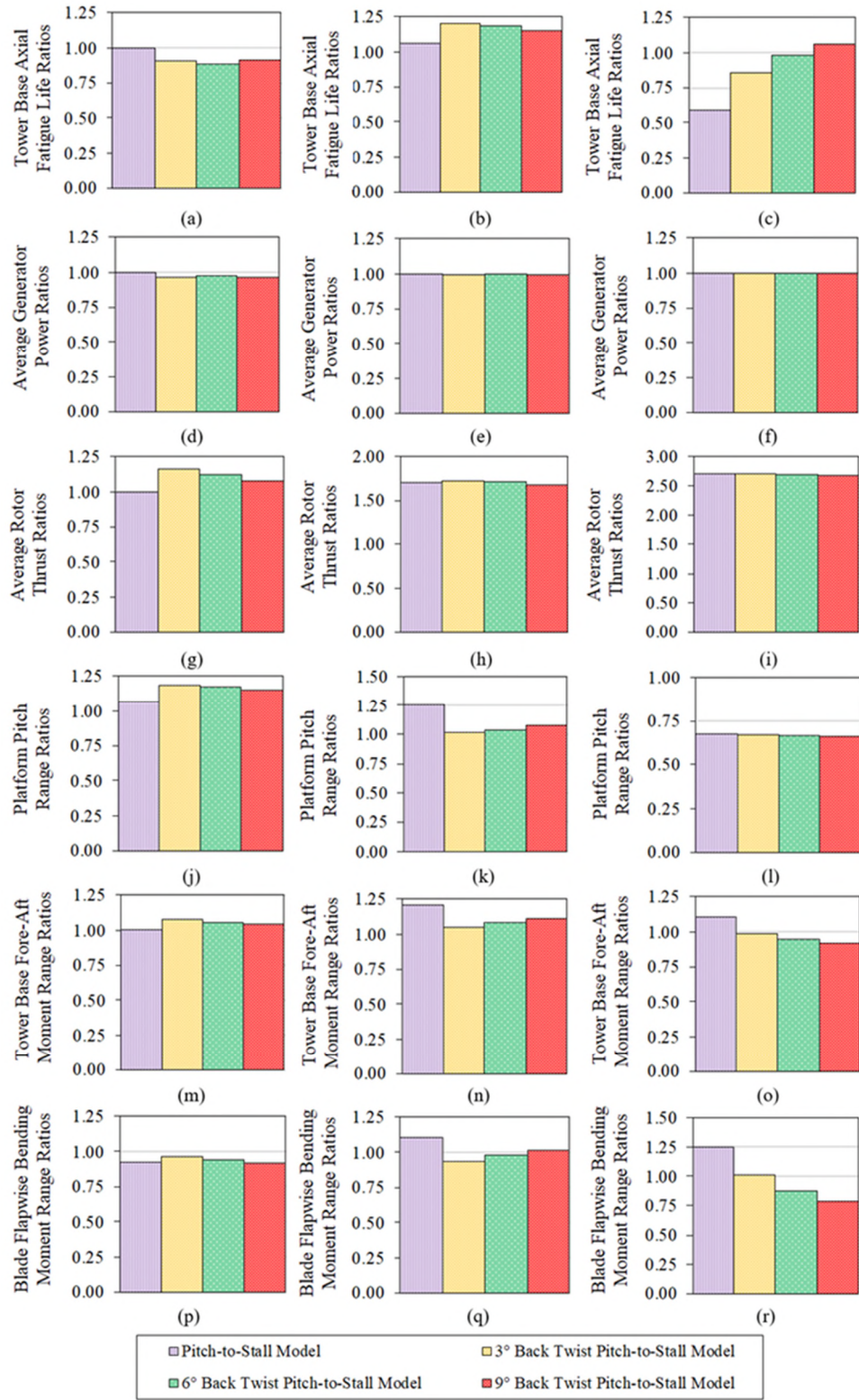


Figure 3-6. Simulation outputs for pitch-to-stall blade models with and without back twist. Outputs were normalized against the 'Feather Base Model' and given for 8 (left), 13 (centre), and 18 m/s (right) mean turbulent winds.

The rotor thrust was higher for all the blade models with a back twist for mean winds of 8 m/s (Figure 3-6g); however, the thrust decreased as the twist angle increased. The variation in rotor thrust was higher when moving from pitch-to-feather to pitch-to-stall at both mean wind speeds above rated; an increase of around 1.7× at mean winds of 13 m/s (Figure 3-6h), rising to 2.7× at 18 m/s (Figure 3-6i).

The variation between pitch-to-stall models, however, was negligible. The platform pitch response at mean wind speeds of both 8 and 13 m/s, as seen in Figure 3-6j,k, was in accordance with the tower base fore–aft moment range (Figure 3-6m,n), and hence corresponded inversely to the tower base axial fatigue life (Figure 3-6a,b).

At the higher mean wind speed of 18 m/s, the platform pitch range, shown in Figure 3-6l, was much lower for all stall blades than for the 'Feather Base Model' at a ratio of approximately 0.67 with only a 1.2% variation between stall blades' responses. Reductions in tower base fore–aft moment range were seen with back twist angle increases (Figure 3-6o). The blade flapwise bending moment was much reduced by the introduction of back twist when simulated in 18 m/s mean turbulent winds (Figure 3-6r) by over 20% for the most extreme back twist angle of 9°, when compared to the 'Feather Base Model'.

3.4.4 Performance characteristics in turbulent winds

Relevant turbine responses for the 'Feather Base Model' are shown alongside the original 'Pitch-to-Stall Model' and the 9° 'Back Twist Pitch-to-Stall Model' in Figure 3-7. These were derived with all DOF enabled (excluding rotor-teeter). The presented data are for one randomly selected wind and wave seed combination and highlight the performance of the relevant responses arising from mean wind speed, model, and controller variations. However, all numerical comparisons are the averages from the 3 × 3 hr simulations, as detailed in section 3.4.3. It should be noted that the results between the two stall models are within 1% of each other for the variables presented in Figure 3-7g–l, making no apparent distinction visible.

In Figure 37e, at mean turbulent winds of 13 m/s, the blade pitch angle range was reduced by over 2° with the 9° 'Back Twist Pitch-to-Stall Model' compared to the 'Pitch-to-Stall Model'. At 13 m/s, the variation in the rotor speed response seen in Figure 3-7h was 4.7 rpm for the 'Feather Base Model' and 1.4 rpm for all pitch-to-stall models. The rotor speed range at 18 m/s was approximately 0.2 rpm for the pitch-to stall models, whereas the 'Feather Base Model' range was 4.8 rpm (Figure 3-7i).

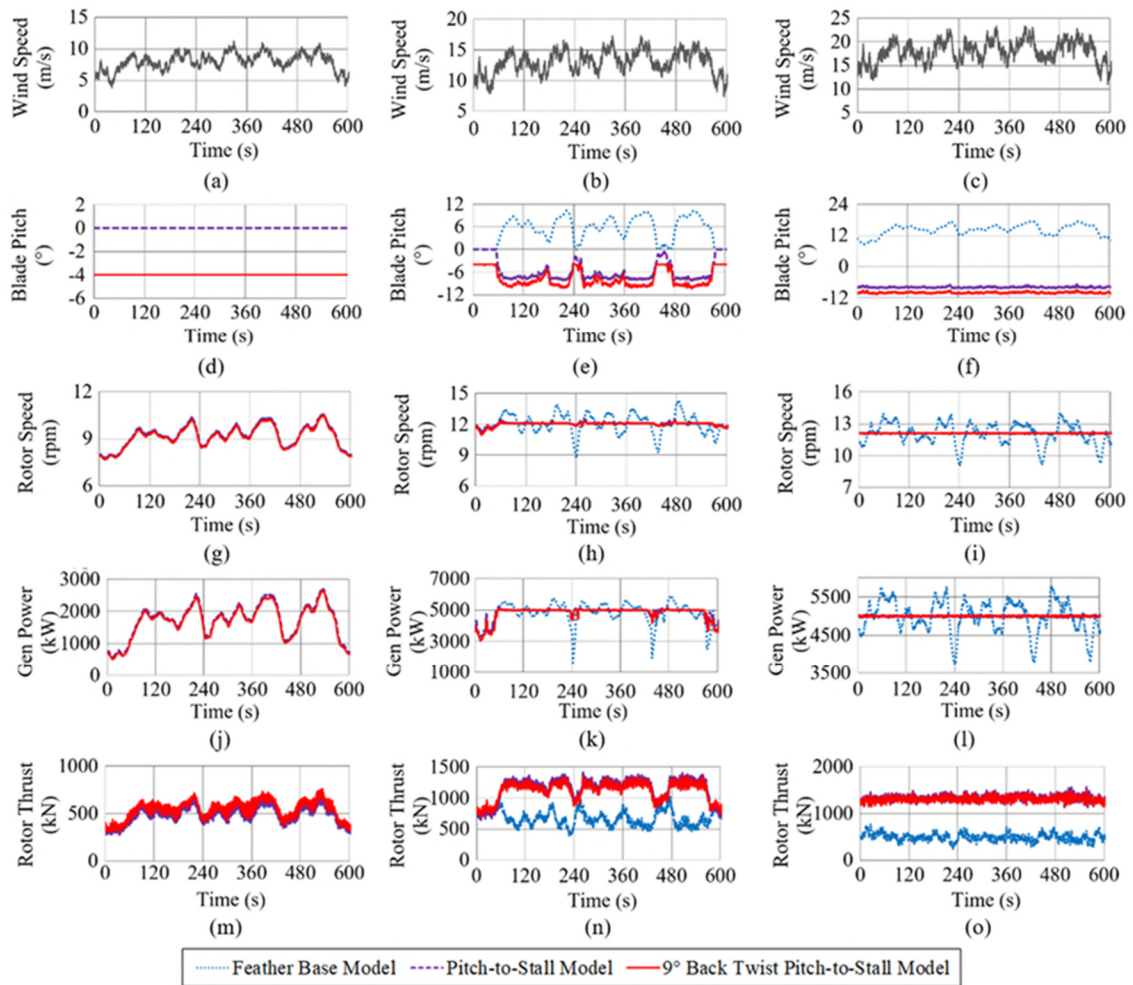


Figure 3-7. Simulation outputs for pitch-to-feather and pitch-to-stall blade models without and with 9° back twist with mean turbulent winds and sea states of 8 m/s, $H_s=1.25$ m, $T_p=5.5$ s (left), 13 m/s, $H_s=2.5$ m, $T_p=8.0$ s (centre), and 18 m/s, $H_s=4.5$ m, $T_p=10.0$ s (right).

The generated power also had a smoother response with pitch-to-stall control in above rated winds, with an average variance for all pitch-to-stall controlled models of 1980 kW compared to 3718 kW for pitch-to-feather control at 13 m/s

(Figure 3-7k). The variation in generated power at 18 m/s was approximately 101 kW for all pitch-to-stall models, compared to 1997 KW with pitch-to-feather control (Figure 3-7l).

The rotor thrust response range shown in Figure 7n at 13 m/s was not lower overall for the pitch-to-stall models; however, the variation was reduced with the implementation of the 9° 'Back Twist Pitch-to-Stall Model', which smoothed the response by 10% compared to the 'Pitch-to-Stall Model'. At 18 m/s mean winds shown in Figure 3-7o, the rotor thrust was more constant overall with pitch-to-stall control, with the 9° 'Back Twist Pitch-to-Stall Model' again have a further 10% thrust reduction compared to the 'Pitch-to-Stall Model' response.

3.5 Discussion

For stall operation, a big reduction in the blade pitch actuation range (defined as the pitch angle) was seen (Figure 3-4a), a requirement of approximately 8° compared to a 23° for feather pitch control. This does not, however, correlate into a reduction in blade pitch actuation rate, as this tends to increase whenever control frequencies are higher, as allowed in pitch-to-stall control.

For the 'Feather Base Model', the continuous reduction in rotor thrust for above rated wind speeds (Figure 3-4b) would contribute to negative damping, and hence turbine tower instabilities and oscillations, if negative damping was not avoided by reducing the natural frequency of the pitch-to-feather control system. The 'Pitch-to-Stall Model' also experiences a dip in the rotor thrust seen at around 17 to 18 m/s wind speeds. This negative derivative of the thrust versus the wind speed could introduce negative damping of the platform pitch mode, as the thrust does not increase within this section because excess power is discarded to keep the rotor speed constant. Ideally a pitch-to-stall model could be designed to produce a continuous rise in rotor thrust.

All turbine responses at 8 m/s mean turbulent winds, shown in the left hand column of Figure 3-6, are not influenced by the blade pitch control method as the pitch angle is constant below 11.4 m/s. Therefore, the increase in the simulated

platform pitch response in Figure 3-6j and decrease in blade flapwise bending moment range in Figure 3-6p experienced by the 'Pitch-to-Stall Model' compared to the 'Feather Base Model', must be solely due to the changes in blade aerofoil lift coefficients. The 'Back Twist Pitch-to-Stall Models' are further influenced at 8 m/s mean wind speeds by the -4° constant blade pitch angle and the specific back twist angle for each model.

When operating in mean winds of 13 m/s, all the pitch-to-stall models experienced a beneficial increase in the tower axial fatigue life, shown in Figure 3-6b, when compared to the 'Feather Base Model'. This was further increased by the introduction of a back twist that extended the tower axial fatigue life by over 20% when the back twist was 3° . At this mean wind speed, a correlation between tower fore-aft moment's range reduction (Figure 3-6n) and platform pitch (Figure 3-6k) and blade flapwise bending moment (Figure 3-6q) reductions can be made.

At 18 m/s mean turbulent winds, the tower axial fatigue life of the 'Pitch-to-Stall Model' was very low and the influence of applying and then increasing the back twist are very apparent. However, it is only with the more extreme 9° 'Back Twist Pitch-to-Stall Model' that the tower axial life expectancy was exceeded, achieved by the 'Feather Base Model' (Figure 3-6c). The increase in tower axial fatigue life is a very desirable 5.8%. A strong correlation between the tower fore-aft base moment (Figure 3-6o) and the blade flapwise bending moment (Figure 3-6r) was apparent at 18 m/s mean winds, such that as the flapwise bending range reduces so does the tower base fore-aft moment, and hence the fatigue life increases. However, this does not hold true when compared against the 'Feather Base Model', as there are scenarios where the blade flapwise bending moment range is higher than that seen for feather control, but the fatigue life is still improved for the stall cases and vice versa. This could be due to the different profile shapes of the blade relative to the axial bending direction, when pitching-to-feather versus pitching-to stall. Further investigation would be necessary to explore this theory. The platform pitch range seen in Figure 3-6l does not influence the tower fore-aft moment, and hence the tower fatigue life at this mean wind speed.

An account of the site wind speed probability density function for the three wind profiles was taken, such that the tower axial fatigue life was weighted depending upon its frequency of occurrence for the three mean wind speeds examined. A larger increase in tower base axial fatigue life was achieved with this weighting; with the higher 9° 'Back Twist Pitch-to-Stall Model', a 2.8% increase was achieved compared to the 'Feather Base Model'. This came at the expense of a decrease in the power generation of 1%.

Pitch-to-stall control of the HAWT coupled the semi-submersible floating platform provided a more regulated energy output than was achieved with the 'Feather Base Model'. The average variance for both pitch-to-stall models was 1980 kW compared to 3718 kW for the 'Feather Base Model' at 13 m/s (Figure 3-7k), and 101 kW compared to 1997 kW at 18 m/s (Figure 3-7l). This is due to the higher pitch-to-stall control system frequency setting allowed, as negative damping is avoided by design.

3.6 Conclusions

In the present day, the requirement to increase the renewable portion of our energy supply worldwide is becoming more imperative each day. The offshore wind capacity has been increasing rapidly, by 87% between 2016 and 2017, in order to meet these needs (Fried et al. 2017) and due to the limited shallow bed and low seabed slope, the industry is looking more towards floating offshore wind solutions in the future. However, turbine tower loads are often increased when a turbine is mounted on a floating platform and unless these undesirable motions can be significantly reduced, then the strength of the tower must be increased.

This research is therefore concerned with reducing excessive motions and loads associated with FOWTs and their effects on the turbine tower, while improving energy generation by pitching the turbine to stall, instead of feather, to control rotor speed which avoids the negative damping issues by design, resulting in an improvement in the regulation of the power generated. The example FOWT presented is a semi-submersible floating platform, coupled to a 5 MW HAWT, investigated through simulation.

Overall, it has been shown that the proposed approach seems to be effective in diminishing detrimental oscillations of the power output and in enhancing the tower axial fatigue life. This is achieved by variable speed, variable pitch-to-stall control, reducing the negative damping phenomenon (more regular power output), and through manipulating the blade design by the introduction of a back twist towards feather (reductions in the blade root flapwise moment leading to reductions in the tower bending moments, and hence increasing the tower axial fatigue life). This research, therefore, highlights that active variable speed and variable pitch-to-stall control has potential benefits specific to FOWTs.

More specifically, tower base axial fatigue life was increased for all pitch-to-stall scenarios, when operating in 13 m/s mean turbulent winds. The introduction of a back twist added an additional desirable increase of over 20% when the back twist was 3° . This correlated with a corresponding decrease in both platform pitch and blade flapwise bending moment ranges of motion.

At 18 m/s mean winds, the more extreme 9° 'Back Twist Pitch-to-Stall Model' provided a tower base life expectancy that exceeded that achieved by the 'Feather Base Model' by 5.8%. No correlation between the platform pitch response and tower base fore–aft moment was apparent at this mean wind speed. However, a strong correlation between the ranges of motion from the blade flapwise bending and the tower base moment was seen, which strongly indicates that decreasing the blade flapwise bending range decreases the tower fore–aft moment range.

Overall, the 9° 'Back Twist Pitch-to-Stall Model' achieved the best tower base axial fatigue life with a 2.8% increase on the 'Feather Base Model' when accounting for the relevant frequencies of occurrence of the three mean turbulent wind speed profiles, for the specific site, at the expense of a decrease in the power generation of 1%. At wind speeds above rated, the performance of pitch-to-stall in terms of rotor speed regulation and generated power output far exceeds that achieved with pitch-to-feather.

Further investigation with more variations in terms of twist initiation point, back twist angle, and constant pitch below rated angles would be recommended. Additional research on a complete back-twisted stall blade design would also be required to enable an in-depth analysis of all the blade loads as well as loads on the nacelle, gearbox, drive train, and other system components. Hence, enabling an overall assessment of the pros and cons of a back twist blade for a FOWT with active pitch-to-stall control. A study on the benefits of this blade and pitch control system on other FOWT types would also be beneficial.

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4 PAPER 2

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4.1 Title page and abstract

Analysis of the effect of a series of back twist blade configurations for an active pitch-to-stall floating offshore wind turbine

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Abstract. For a turbine mounted on a floating platform, extreme induced loads can be increased by up to 1.6 times those experienced by a turbine situated on a fixed base. If these loads cannot be reduced, towers must be strengthened which will result in increased costs and weight. These tower loads would be additionally exasperated for a pitch-to-feather controlled turbine by a phenomenon generally referred to as 'negative damping', if it were not avoided. Preventing negative damping from occurring on a pitch-to-feather controlled floating platform, negatively affects rotor speed control and regulated power performance. However, minimising the blade bending moment response can result in a reduction in the tower fore-aft moment response, which can increase the tower life. A variable speed, variable pitch-to-stall floating semi-submersible wind turbine, which does not suffer from the negative damping and hence provides a more regulated power output, is presented. This incorporates

a back twist blade profile such that the blade twist, starting at the root, initially twists towards stall and, at some pre-determined 'initiation' point, changes direction to twist back towards feather until the tip. Wind frequency weighting was applied to the tower axial fatigue life trends of different blade profiles and a preferred blade back twist profile was identified. This had a back twist angle of -3° and started at 87.5% along the blade length and achieved a 5.1% increase in the tower fatigue life.

Keywords: floating offshore wind turbine (FOWT); pitch-to-stall; blade back twist; tower axial fatigue life

4.2 Introduction

Increasing the proportion of our energy that comes from renewable sources is imperative. Across the globe, extreme environmental events are increasing driven by indisputable anthropogenic contributions to climate change (Knutson et al 2018). Unfortunately, this disproportionately effects the world's poorest people, which has likely contributed to the lack of adequate speedy action on the part of the world's economic leaders. If greenhouse gas emissions continue to rise, then it is predicted that the planet will experience a 1.5°C human-orchestrated global warming impact by 2030 (First 2018). This will cause wide spread issues with food, water security, flooding, droughts and storm conditions, which will shadow the devastating impact from global warming, that has already been seen in recent years.

Some countries are moving towards renewable energy faster than others and, within Europe, over 11% of energy was derived from wind power in 2018, with an increasing proportion of nearly 10% of that wind energy coming from offshore farms (Europe 2018). Floating offshore wind turbines (FOWTs), which permit the use of a wider range of offshore sites, thus increasing global offshore wind potential, are still in the developmental stage. However, worldwide predictions are for a 5% contribution of the global offshore wind energy market by 2030 (Fried et al 2017).

The loads experienced by turbines situated on floating platforms, rather than a fixed base, are often increased, varying in both magnitude and origin, depending upon the platform design as well as on environmental conditions. Extreme induced tower base bending moments of a FOWT, have been shown to increase by up to 1.6 times those experienced by the same turbine with a fixed base (Robertson and Jonkman 2011). If these loads cannot be reduced, towers will need additional strengthening, resulting in increased costs and weight.

As the frequencies of the floating platform's motions (surge, sway, roll and pitch) are generally one or more orders of magnitudes lower than for fixed turbines, when the turbine pitches-to-feather to control the rotor speed above rated wind speeds, a reduced performance is seen. This results in the rotor speed regulation not achieving a smooth response, and hence, negatively effecting the generated power output (Larsen and Hanson 2007). This performance drop is caused by the need to set the pitch control bandwidth at a lower frequency to avoid the first resonance modes of the turbine tower and thus avoid the negative damping, which can occur due to the continuous reduction in rotor thrust seen when pitching-to-feather. If unchecked, negative damping can create instability in the tower fore-aft response, as well as oscillations and hence increased tower fatigue. One solution to improve the regulation of the rotor speed and power generation of floating turbines could be to utilise turbines that still provide variable-speed, variable-pitch control but by, instead, pitching towards stall. This is because, as found by Larsen and Hanson (2007), this control method is not susceptible to 'negative damping' issues. The avoidance of negative thrust issues occurs since, as the wind velocity increases (in the above rated wind speed range), the rotor thrust increases for a stall controlled turbine, whereas for a feather controlled turbine the thrust diminishes, creating a negative derivative with respect to the wind speed (Ward et al 2019). Hence, active pitch-to-stall control enables a higher control frequency setting to be employed within the blade pitch controller, which improves both rotor speed regulation and power quality. However, pitching to stall often results in higher blade loads as well as deflection (Macquart and Maheri 2019), although the peaks seen in passive stall blades are

less likely to occur on an actively pitching-to-stall turbine. Also, thrust and torque are more stable as the pitch angle variations during operation in Region 3 are small for stall control compared to feather (Bossanyi 2003).

There have been only two studies (unrelated to this research), which have looked at the simulated responses of a floating turbine with active variable speed, variable pitch-to-stall (VSVP-S) control. However, these both utilized blades predominantly designed for feather control (Larsen and Hanson 2007; Jonkman 2007). Also, although reducing the tower response is often highlighted as a main design criteria for floating turbines due to the increased loads, research has generally focused on platform pitch damping (Jonkman 2007; Lackner 2013; Fleming et al 2019). However, reducing the blade bending moment response can also dampen the tower response, as has been observed with bend-twist coupled blades. These blades can be created by changes to the curved blade geometry in terms of twist, pre-bending, or the deflection that occurs under loads (Stäblein et al 2017). Twist, pre-bending or sweep are generally designed into the blade and implemented during manufacture and, under load, additional twist and bend will also be experienced. The blade can also be designed such that a deflection under load creates a reduction in the blade bending moment as the wind speed increases. Blade twist is standardly employed on large blades (Stäblein et al 2017; Merz 2011; Méndez and Greiner 2009) and has been shown to reduce blade vibrations and fatigue as well as tower fore-aft frequency response on the 10 MW DTU (The Technical University of Denmark) turbine, when pitching-to-feather (Stäblein et al 2017). Reversal of the direction of the blade twist profile at some point along the length, referred to as 'back twist' throughout the remainder of this study, has also been employed for fixed-stall blades. Thus, the blade twist, starting at the root, initially twists towards stall and, at some pre-determined 'initiation' point, changes direction to twist back towards feather until the tip. This helps to keep the airflow attached to the blade nearer the tip at higher wind speeds, which increases the power production for that section of the blade (Merz 2011). Generally the back twists explored have been of only a couple of degrees but have varied in initiation point from approximately 5 to 70% along the blade

radius, measured from the tip (Merz 2011; Stäblein et al 2017). The design criteria of blade twist often focuses on maximising the turbine's power, as such, changing the setting of the constant pitch angle below rated wind speed has also been employed to optimize the energy output (Bossanyi 2003). This work builds on the research presented on a VSVP-S FOWT by Ward et al (2019), which investigated the effect on tower axial fatigue of a blade back twist that started at a distance of 75% along the blade radius, as measured from the root. For the semi-submersible platform analysed, an increase in the tower axial fatigue life of over 20% was achieved when operating in turbulent mean winds of 13mps. These results highlighted the requirement for a further systematic investigation into the benefits in terms of tower life extension, due to changes in the back-twist magnitude or on the role of its initiation point on a VSVP-S controlled FOWT.

Ostachowicz et al (2016) state that, as the twist distribution of a coupled blade is dependent upon the wind speed, the blade cannot therefore be designed with a set tip-speed-ratio. Two methods to determine the non-optimal blade twist are proposed by (Ostachowicz et al 2016). The blade twist of a coupled blade is classed as non-optimal since fatigue is often reduced, but this may be at the expense of a reduction in the power generated. The first method is an iterative procedure that starts with the ideal blade twist for a specific tip-speed ratio, and which is then compared to the pre-twist required to achieve this at a specific wind speed. Iterative procedures used to optimise both blade twist and chord of a site specific passive stall blade, have however experienced difficulty at the early stages of the process, as the required angle of attack was outside the operational range (Lobitz and Veers 2003). The second method suggested was to optimise the blade twist at a specific wind profile. However, the authors that proposed this approach believed it has not yet been explored (Ostachowicz et al 2016). Currently there are no large, VSVP-S blade designs in use on floating platforms, partly because of a lack of understanding of a stalled blades aerodynamic behaviour (Bossanyi 2003). Thus the iterative procedure would be more complex to apply than optimisation at a specific wind speed, as assessing the suitability of

a specific twist is not a question of optimising an already commissioned blade design with an ideal twist for a specified tip-speed ratio.

This paper therefore aims to explore the effects of both the back twist's initiation point and its twist angle under a specific wind profile. The main desired outcome of presenting a preferred blade back twist for a specific site, is to reduce the tower fore-aft moment response and hence increase the tower fatigue life of a floating offshore semi-submersible wind turbine without overly adversely affecting the energy generated. The effect on both tower fatigue and energy generation of the constant pitch angle below rated wind speed setting will also be examined. A comprehensive optimisation would be beyond the scope of this work, since it should include a more advanced aero-elastic model of the blades and tower.

4.3 Simulation Model

4.3.1 Dynamics model approach

The aero-hydro-servo-elastic simulation models used in this study are based on the open source semi-submersible floating platform coupled to a 3 bladed 5 MW horizontal axis wind turbines (HAWT) and moored with 3 catenary mooring lines modelled utilizing MoorDyn. The mooring system dynamics are predicted assuming that each of the 3 mooring lines are a lumped mass and also accounts for the effects due to the buoyancy forces, weight, damping and axial forces as well as the hydrodynamic forces that have been derived utilizing Morison's equation. More details of the mooring system design can be found in the international OC4 Phase II study (Robertson et al 2014a; Robertson et al 2014b; Jonkman et al 2009). This OC4 Phase II study compared several offshore simulation code packages. The open source aero-hydro-servo-elastic fully coupled time domain simulation code package, FAST v8 (Jonkman and Buhl 2005), was employed to generate a range of platform and turbine responses in different environmental settings. FAST v8 can predict aerodynamic loading as well as rotor and wake effects on the blades and, for a floating structure, the aerodynamic models are linked to hydrodynamic, dynamic structural and control models, allowing fully-coupled nonlinear aero-hydro-servo-elastic simulations

within the time domain to be performed. FAST utilizes the Leishman-Beddoes dynamic stall model executed through AeroDyn. The potential flow theory hydrodynamic approach was implemented in this study and utilized the frequency domain code WAMIT to derive the 1st and 2nd order hydrodynamic coefficients (Robertson et al 2014a; Robertson et al 2014b; Jonkman et al 2009). Identifying errors within aero-hydro-servo-elastic simulation codes and/or models can be challenging due to the complex nature of the loads under analysis, however the OC4 Phase II study simulation results from the different simulation code packages are all open source, which allowed for model and initial response validation. More details of the capabilities of the FAST simulation code can be found in the documentation by Jonkman and Buhl (2005).

4.3.2 Methodology

The 1/50th Froude-scaled experimental model as used as part of the US DeepCWind project (Goupee et al 2014), is the foundation of the simulation model of the semi-submersible floating platform, and is connected to the seabed by three catenary mooring lines. The tower of the 5 MW NREL (National Renewable Energy Laboratory) turbine was amended as part of the OC4 phase II study (Robertson et al 2014a), such that the mode shapes of the tower were altered to make them suitable for the additional flexibility required when coupled to this type of floating platform. Hence, the connection between the tower base and the platform is represented as a cantilever beam rather than the rigid connection used for a fixed base turbine. The turbine has a rotor diameter of 126 m and a hub height of 90 m above sea water level (SWL). The rated rotor speed is 12.1 rpm, which is achieved at a wind speed of 11.4 mps and it is a variable speed, variable pitch-to-feather wind turbine. Further details on all aspects of the simulation models can be found in Robertson et al (2014a) and Jonkman et al (2009).

There are three main models defined in the present work.

1. A conventional 'Feather Base Model' against which all other models are compared and which pitches-to-feather utilizing a constant-torque pitch

controller with gain scheduling that avoids negative damping, as defined within the OC4 Phase II study (Robertson et al 2014a).

2. A VSVP-S wind turbine, which has all the same simulation model characteristics as the 'Feather Base Model', with the exception that the lift coefficients of the blade aerofoils, which have been altered so that a smoother transition occurs with changes in the angle-of attack, as suggested and provided by (Jonkman 2007). This model, which pitches-to-stall is generally referred to as the 'Stall Test Model'.
3. A 'Stall Back Twist Model', which pitches-to-stall and which incorporates the changes made to the blade lift coefficients of the 'Stall Test Model' and further imposes a linear back twist towards feather. Thus, the blade initially starts to twist at the root, first towards stall and then at some pre-determined point changes direction to twist back towards feather until the tip, whereupon the specified back twist angle is reached. The basic 'Stall Back Twist Model' is further divided into a series of 12 models, each with a unique equispaced combination of back twist angle and initiation point as outlined in Table 4-1.

Initially, short 600s simulations were carried out at twist distances (at equally spaced intervals) for most of the blade length. However, at higher initiation points from the tip more blade vibrations were observed along with other simulation problems. Hence, the twists initiated have been confined to the last 25% of the blade (closer to the tip). Further details on the rotor thrust, power curves and pitch angles for the Feather Base Model and Stall Test Model, as derived through steady state analysis over the full range of operational wind speeds, are provided by Ward et al (2019).

Table 4-1. Model parameters

Test ID	Active variable pitch blade control	Twist starting distance from blade root		Twist angle increase at the tip (°)	Proportional gain at 18mps, K _p (s)	Integral gain at 18mps, K _i
		(%)	(m)			
Feather Base Model	Feather	0	0	0	Inbuilt gain scheduler	
Stall Test Model	Stall	0	0	0	-0.865	-0.371
Stall Back Twist Model 1	Stall	75.0	46.1	-3	-0.917	-0.393
Stall Back Twist Model 2	Stall	87.5	53.8	-3	-0.895	-0.383
Stall Back Twist Model 3	Stall	92.8	57.0	-3	-0.880	-0.377
Stall Back Twist Model 4	Stall	75.0	46.1	-6	-1.105	-0.474
Stall Back Twist Model 5	Stall	87.5	53.8	-6	-0.981	-0.421
Stall Back Twist Model 6	Stall	92.8	57.0	-6	-0.934	-0.400
Stall Back Twist Model 7	Stall	75.0	46.1	-9	-1.414	-0.606
Stall Back Twist Model 8	Stall	87.5	53.8	-9	-1.104	-0.473
Stall Back Twist Model 9	Stall	92.8	57.0	-9	-1.000	-0.429
Stall Back Twist Model 10	Stall	75.0	46.1	-12	-1.706	-0.731
Stall Back Twist Model 11	Stall	87.5	53.8	-12	-1.216	-0.521
Stall Back Twist Model 12	Stall	92.8	57.0	-12	-1.016	-0.435

4.3.3 Control strategy approach

To pitch the turbine blades towards stall to control rotor speed by keeping the rotor torque constant when wind speeds are above the rated speed of 11.4 mps, a feedback Proportional-Integral (PI) controller was built in Simulink and coupled to the FAST code as depicted in Fig 4-1. The controller gain settings are constant throughout the wind speed range with values derived at 18 mps steady winds for each model. The controller also incorporated a pitch rate limiter set to the industrial norm of $\pm 8^\circ/\text{s}$ (Namik and Stol 2010) and an anti-windup filter (Wright

and Fingersh 2008). At wind speeds below rated, the controller did not change the pitch angle for either the feather or stall designs. More details of this controller and the process to obtain the gain settings can be found in Ward et al (2019).

The proportional and integral gains were unique to each stall model and were derived using a single degree of freedom (DOF) model of the angular shaft rotation as detailed by Larsen and Hanson (2007), and Jonkman et al (2009). The derivative gain, K_D , has been set to zero as proposed by Hansen et al (2005). A constant gain derived at steady winds of 18 mps was chosen for each model that was actively pitching-to-stall, as the pitch angle becomes double-valued, such that the same blade pitch angle is seen at different wind speeds within Region 3 which would make the implementation of a gain scheduler more complex (Jonkman et al 2009).

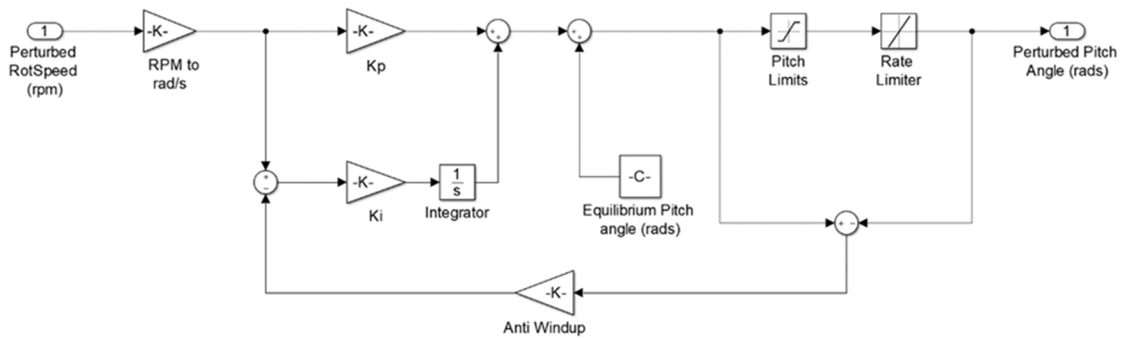


Figure 4-1. Pitch-to-stall feedback proportional-integral controller

4.4 Test conditions

To better understand the trends and effects of both back twist magnitude (BTM) and back twist initiation point (BTIP), a selection of relevant responses at 3 separate mean turbulent wind speeds were analysed. The specific environmental conditions were for a site based in the North Sea approximately 100 miles north-east of Aberdeen (Geos 2001). The sea depth for the site was unmeasured and so has been estimated at 200 m. Table 4-2, shows the conditions applicable for a turbine with a hub height of 90 m above SWL, as derived from the data accumulated by Geos (2001), with the highlighted pathways applicable to the 3 mean stochastic turbulent wind speeds analysed.

Table 4-2. Average annual environmental conditions at grid point 59.300N 0.475E

Hub height wind speed (mps)	Hub height (m)	Hellman exponent (unstable air)	Wind measureme nt height (m)	Wind measureme nt at site (mps)	Significant Wave Height Hs (m)	Spectral Peak Period Tp (s)	Windspeed Band Range at site (mps)	% of total operating time	
							0.3 - 1.6		
							1.6 - 3.4		
3	90	0.06	10	2.63	0.5	5.0		1.92	
4	90	0.06	10	3.51					
5	90	0.06	10	4.38				3.4 - 5.5	13.72
6	90	0.06	10	5.26	1.0	6.0			
7	90	0.06	10	6.14					
8	90	0.06	10	7.01	1.25	5.5	5.5 - 8	23.11	
9	90	0.06	10	7.89					
10	90	0.06	10	8.76	1.5	7.0	8 - 10.8	25.72	
11	90	0.06	10	9.64					
12	90	0.06	10	10.52					
13	90	0.06	10	11.39	2.5	8.0	10.8 - 13.9	20.03	
14	90	0.06	10	12.27					
15	90	0.06	10	13.15					
16	90	0.06	10	14.02	4.0	9.0			
17	90	0.06	10	14.90					
18	90	0.06	10	15.78	4.5	10.0	13.9 - 17.2	11.33	
19	90	0.06	10	16.65					
20	90	0.06	10	17.53	5.0				
21	90	0.06	10	18.41				17.2 - 20.8	3.91
22	90	0.06	10	19.28					
23	90	0.06	10	20.16					
24	90	0.06	10	21.04	7.0	12.0	20.8 - 24.5	0.26	
25	90	0.06	10	21.91					

The mean turbulent wind speed of 8 mps was chosen to represent the below rated wind speed conditions, as the 1st tower fore-aft bending natural frequency occurs when the rotor speed is estimated to be approximately 9.2 rpm. The second mean turbulent wind speed chosen was 13 mps, as this is representative of the wind speed region around the rated wind speed of 11.4 mps. Lastly, a mean turbulent wind of 18 mps represents the upper operational range of the turbine, where the wind speed reached, due to turbulence, an upper limit approaching the 25 mps cut off wind speed, at which the turbine would be expected to close down to prevent damage occurring.

For the wind files the Kaimal wind spectrum and IEC turbulent intensity model B was used throughout (EN 2006), along with a power law exponent of 0.14 and a surface roughness length of 0.03 m. These turbulent wind velocity time histories were derived from 10 minute periodic stochastic turbulent mean winds, as

recommended in the IEC 61400-3-1 standard (EN 2017). The 10 minute interval is based on the wind variation spectral gap between the diurnal and turbulent peaks. However, analysis was conducted on 3 hour simulations, after the first 300 seconds was discarded to avoid transient responses. The choice of 3 hour simulation length was made partly due to the results presented by Li et al (2017) where the relative error for 1 hour simulations exceeded 23% compared to two hour simulations. The other factor in this choice was that the statistical content of 1 x 3 hour simulation resembles that of 3 x 1 hour simulations, allowing the random seed requirement to be reduced (Kvittem and Moan 2015). This enabled the wind inflow to remain the same throughout a long simulation, but the floating turbine's response to vary, thus allowing adequate estimations of the fatigue of the tower to be obtained from the axial stress at different wind speeds, using a Rainflow cycle counting algorithm within MATLAB (Nieslony 2009).

As the cross sectional area of the tower base is symmetrical, the axial stress can be found utilizing Equation 4-1 (Li et al 2017).

$$Axial\ Stress = (F_{zt}/A) + ((M_{yt}.Cos(\varnothing) - M_{xt}.Sin(\varnothing)) * (r_o/I)) \quad [Eq\ 4-1]$$

where; F_{zt} is the axial force at the base of the tower (kN), A is the cross-sectional area of the tower base ($0.55\ m^2$), M_{yt} is the fore-aft moment at the base of the tower (kN/m), $\varnothing$ is the wind angle, M_{xt} is the side to side moment at the base of the tower (kN/m), r_o is the tower base cylinder central radius (3.24 m) and I (as $I_x = I_y$) is the sectional moment of area (m^4).

Outputs are normalised with respect to the 'Feather Base Model' results, and are from the combined results from 3 x 3 hour simulations, each with 3 unique sets of random wind and wave seeds. The significant wave height and spectral peak period for each sea state are those specified in Table 4-2 at the relevant wind speed of a specific simulation run. All responses in turbulent wind conditions were

obtained with all of the 16 wind turbine and six platform DOF enabled as detailed in depth by Jonkman et al (2009).

4.5 Results

4.5.1 Constant pitch angle below rated trends

To enable the analysis of the effects of BTM and BTIP on tower axial fatigue life, an initial study on the effects on the constant pitch angle setting below rated was performed at mean turbulent winds of 8 and 13 mps. The responses at 18 mps winds were unaffected as the wind speed did not drop below the rated speed of 11.4 mps, throughout the simulations. These were obtained with all the DOF relative to a 3 bladed HAWT enabled. Fig 4-2 shows the normalized ratio outputs as compared to the 'Feather Base Model' of a selection of load responses for a blade with a back twist angle of -6° as measured at the blade tip and applied at 3 initiation points along the blade length. The three initiation points presented are 75%, 87.5% and 92.75% as measured along the blade length from the root. Three different constant pitch angles below rated were analysed, 0° , -2° and -4° .

When winds of 8 mps were experienced, the tower axial fatigue life was highest when the constant pitch angle was set at 0° and when the back twist initiation point started higher up the blade (Fig 4-2(a)). However the average generated power was only equal to the 'Feather Base Model' when the twist was either initiated close to the tip at a constant pitch angle of 0° or when the angle was increased to -2° and closer to the root (Fig 4-2(c)). The rotor thrust, platform pitch, blade deflection and blade flapwise bending moment ranges decreased as the tower axial fatigue life increased, when the constant pitch angle was either 0° or -2° (Fig 4-2(e, g, i, k)).

The tower axial fatigue life at 13 mps steadily increased as the constant pitch angle increased from 0° to -4° , with the maximum seen at the initiation point of 92.75%, hence the point closest to the tip (Fig 4-2(b)). However the generated energy was slightly reduced compared to that available from the 'Feather Base Model' at the higher fatigue life (Fig 4-2(d)).

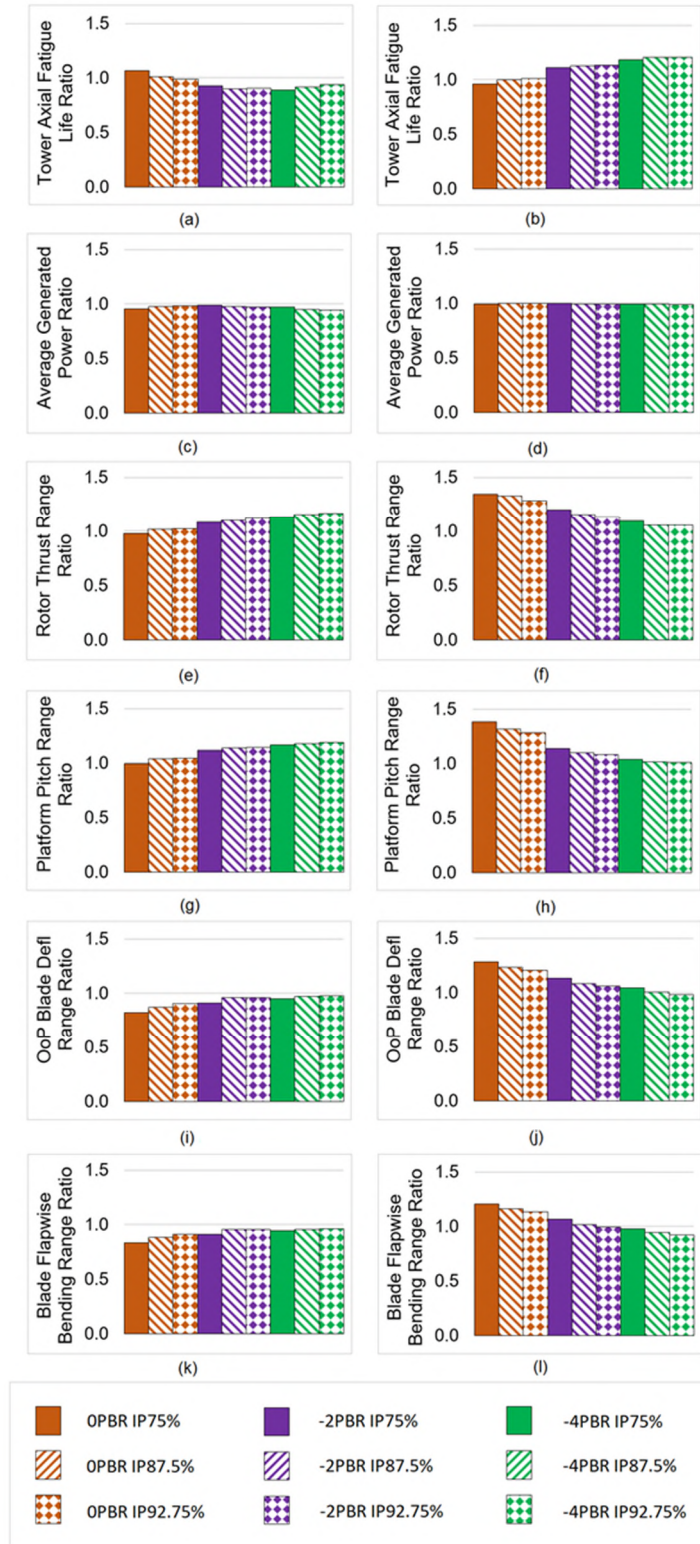


Figure 4-2. Normalized ratios to the 'Feather Base Model' of various outputs with increasing constant pitch angle below rated wind speed (PBR) and an increasing initiation point (IP), as measured from the blade root at 8 mps (left) and 13 mps (right) mean turbulent winds.

The rotor thrust, platform pitch, blade deflection and blade flapwise bending moment range responses all decreased with a corresponding increase in the tower axial fatigue life (Fig 4-2(f, h, j, l)). The decision was therefore made to have an intermediary constant pitch angle, such that the analysis stipulated a constant pitch angle setting of 0° when the mean turbulent wind was 8 mps and -4° when the mean was 13 mps.

4.5.2 Back twist angle and initiation point trends

Fig 4-3 shows the normalized ratio outputs as compared to the 'Feather Base Model', of a selection of relevant load analysis results at four different BTMs and 3 different BTIPs along the blade radius (measured from the blade root). The tower fore-aft bending moment range was not included as this duplicated the trend of the tower axial fatigue life for all scenarios and hence was well represented by the fatigue life responses. The four different equispaced back twist angles were -3° , -6° , -9° and -12° , as measured from the blade tip such that they all start to twist back towards feather at a specific initiation point. Three BTIPs are presented at 75%, 87.5% and 92.75% as measured along the blade length from the root. A constant pitch angle below rated of -4° was also imposed at 13 mps as higher fatigue reductions were achieved with this setting. The original constant pitch angle of 0° was applied when the mean winds conditions were lower at 8 mps. The constant pitch angle was not relevant when the higher 18 mps winds were experienced as conditions remained within Region 3 throughout the simulations.

At mean turbulent winds of 8 mps, the tower axial fatigue life decreased as the back twist initiation point became closer to the blade tip at all back twist angles and increased as the back twist angle increased (Fig 4-3(a)). Therefore, a maximum fatigue life increase of over 12% compared to the 'Feather Base Model' was realised at a back twist angle of -12° and an initiation point of 75%. However, the trend clearly showed that increases in the tower axial fatigue life came at the expense of the generated power for all models, with an unacceptable drop in generated energy of 16% at the maximum fatigue life (Fig 4-3(a, d)).

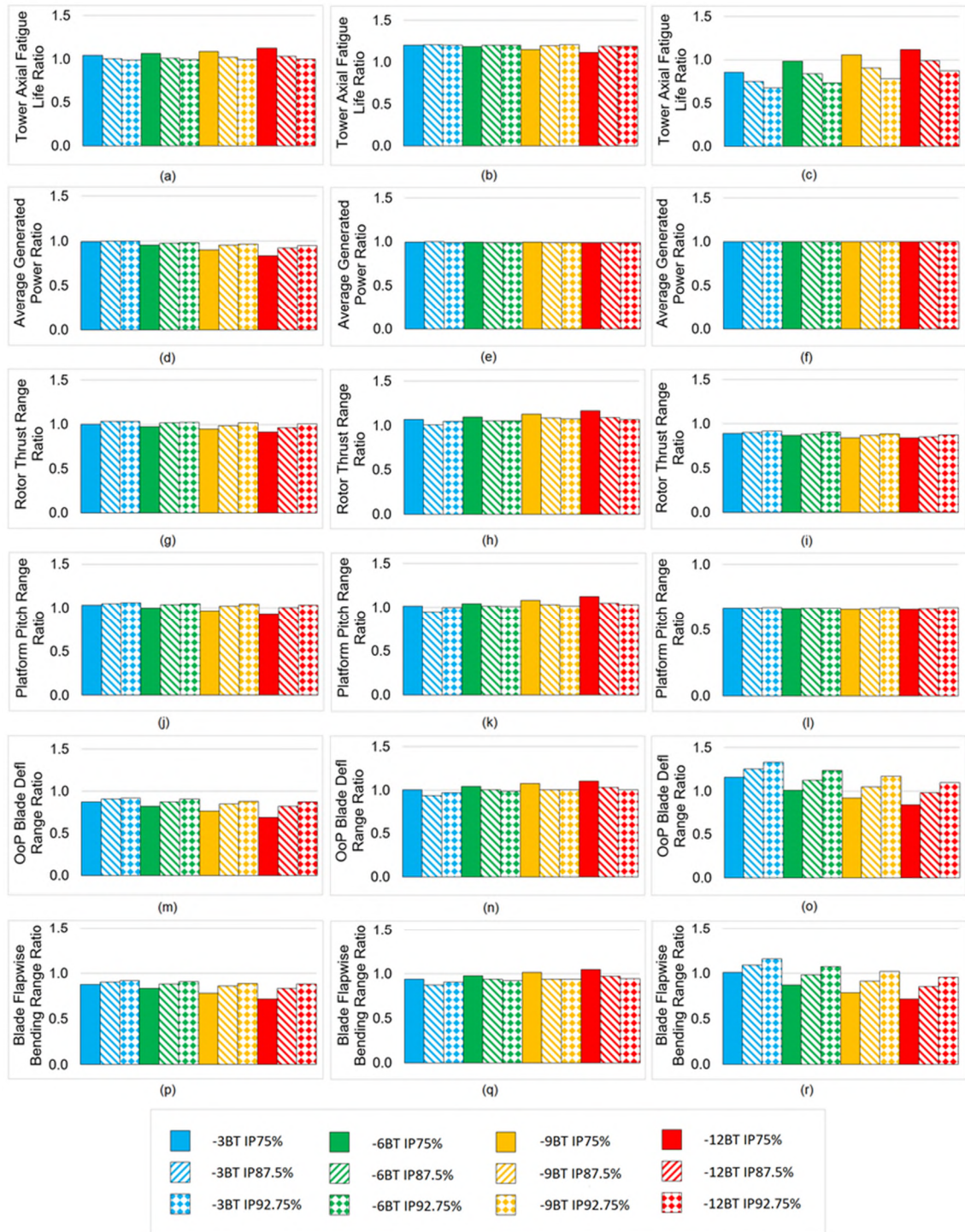


Figure 4-3. Normalized ratios to the 'Feather Base Model' of various outputs with increasing back twist angles (BT) and an increasing initiation point (IP), as measured from the blade root at 8 mps (left), 13 mps (centre) and 18 mps (right) mean turbulent winds.

Decreases in the rotor thrust, platform pitch, blade deflection and blade flapwise bending moment ranges, all resulted in tower axial fatigue life increases (Fig 4-3(g, j, m, p)).

The tower axial fatigue life at 13 mps mean turbulent winds achieved an increase +20% compared to the 'Feather Base Model' for all back twist angles initiated at 92.75% from the blade root, hence the initiation point closest to the tip (Fig 4-3(b)). The back twist angle had little influence except for a notable drop for both -9° and -12° at the initiation point of 75%, the point closest to the blade root. A slight drop of less than 1% in generated energy was also seen (Fig 4-3(e)).

The rotor thrust, platform pitch, blade deflection and blade flapwise bending moment range responses followed the same trend as at 8 mps, such that a decrease in all these ranges generally corresponded with an increase in the tower axial fatigue life (Fig 4-3(h, k, n, q)).

At 18 mps the variation in tower axial fatigue life due to blade twist angle and initiation point was more pronounced such that the fatigue life increased by 12% compared to the 'Feather Base Model' as the BTM increased to 12° but reduced as the BTIP approached the tip (Fig 4-3(c)). Generated energy was unaffected by both back twist angle and initiation point (Fig 4-3(f)).

Decreases in the rotor thrust, blade deflection and blade flapwise bending moment ranges had corresponding increases in tower axial fatigue life (Fig 4-3(i, o, r)), however the platform pitch response range varied little, although the fatigue life variation between models was up to 44% in range.

In order to take into account the likely occurrence of the different wind speed cases, a weighted analysis that takes account of the distribution of probability of occurrence was conducted. This was applied to the tower axial fatigue life and average generated power for each model, corresponding to the '% of total operating time' seen in Table 4-2 within the section 4.4, for each of the 3 mean turbulent wind speeds analysed. These results were then compared against the weighted 'Feather Base Model' results and are presented in Table 4-3. For each

back twist model an overall increase in fatigue life was seen, ranging from approximately 3% to 12%. The higher fatigue life increases were seen when the twist was initiate closer to the root at a distance of 75% along the blade and with higher back twist angles. However, increases in fatigue life was at the expense of the generated power, with a maximum loss from the combined results over all three wind speeds of 3.88%.

Table 4-3. Weighted tower axial fatigue life and generated power for each back twist model.

Test ID for VSVP-S 'Stall Back Twist Models'	BT 1	BT 2	BT 3	BT 4	BT 5	BT 6	BT 7	BT 8	BT 9	BT 10	BT 11	BT 12
Initiation point along the blade, measured from the root (%)	75.00	87.50	92.75	75.00	87.50	92.75	75.00	87.50	92.75	75.00	87.50	92.75
Back twist angle at the tip (°)	-3	-3	-3	-6	-6	-6	-9	-9	-9	-12	-12	-12
Tower axial fatigue life change from 'Feather Base Model' (%) (+ve number means a longer tower life)	8.29	5.10	3.14	10.22	6.50	4.11	10.98	7.53	4.94	12.09	8.85	5.91
Average generated power change from 'Feather Base Model' (%)	-0.47	-0.14	-0.55	-1.14	-0.81	-0.80	-2.36	-1.36	-1.16	-3.88	-2.03	-1.58

4.6 Discussion

From the analysis of the effects on the tower axial fatigue life of varying the constant pitch angle setting (when the winds are below the rated wind speed of 11.4 mps), it was clearly highlighted that reductions in the variance of both blade flapwise bending moment and blade deflection created a corresponding reduction in the range of the rotor thrust (Fig 4-2). The reduced thrust force range then reduced the range of both the platform pitch and tower fore-aft motion, which consequently increased the tower axial fatigue life. Although the range of the thrust force is lower, there is a significant rise in the thrust force from rated wind speed to the cut-out wind speed of 25 mps. This could cause the mean inclination of the floating turbine to increase. To account for this a semi-submersible floating turbine can incorporate an active water ballast system that can be adjusted as required during the different environmental operating conditions.

The responses in mean winds of 8 and 13 mps winds to the constant pitch angle changes were opposed to each other. Hence, the rotor thrust range decreased

as the constant pitch angle became smaller and the angle of attack induced at 8 mps was reduced, but the opposite response was observed when operating in 13 mps such that increasing the angle of attack at the higher wind speeds reduced the thrust range and hence increased the tower axial fatigue life.

At both 8 and 18 mps mean turbulent winds, the tower axial fatigue life decreased as the back twist initiation point became closer to the blade tip at all back twist angles and increased as the back twist angle increased (Fig 4-3(a,c)). Thus the aerodynamic damping and hence thrust reduction provided by the back twist angle was at its highest for an angle of -12° initiated at the point closest to the blade root for both environments. However, the damping provided by this blade profile is lower at 18 mps than at 8 mps when compared to the 'Feather Base Model' responses at these wind speeds. Also, although the tower axial fatigue life increase with this back twist blade profile is 12% higher at 8 mps than for pitch-to-feather control, this comes at an unacceptable loss of 16% in the average energy generated. Thus the chosen back twist profile must find a compromise between tower fatigue life increase and energy generation.

For all blade profiles a large increase in fatigue life was seen for all the pitch-to-stall back twist models at 13 mps winds, which exceeded 20% for all back twist angles initiated at 92.75%, compared to the 'Feather Base Model' (Fig 4-3(b)). There was no noticeable trend however, as changes to the back twist angle and initiation point had much less influence at 13 mps, except for a notable drop in fatigue life for the higher back twist angles when the initiation point was closest to the blade root. This drop corresponds to an increase in the platform pitch, blade deflection and blade flapwise bending moment response ranges, however, the same increases were seen at lower back twist magnitudes nearer the root without causing a fatigue life reduction. A slight drop (of up to 1%) in generated energy was also seen for all back twist models at this wind.

The rotor thrust, blade deflection and blade flapwise bending moment range responses followed the same trends, such that if their response to variations in

the wind speed was reduced, a corresponding increase was seen in the tower fatigue life as the tower motion was also reduced.

Reductions in the platform pitch response at 8 and 13 mps also created an increase in the tower axial fatigue life. However, at 18 mps the platform pitch response was unaffected by rotor thrust reductions, even though these reductions directly translated into reduced tower fore-aft motion and hence increased tower axial fatigue life that varied by up to 44% in range. This therefore concurs with the findings of Lackner (2013), where tower load reductions are not always achieved through decreases in the platform pitch response, and hence tower motion reduction, that impedes the inertial and gravitational loads, should be the target.

A weighted analysis of all the back twist profile results allowed a compromise between tower fatigue life increase and energy generation reduction to be considered. From that weighted analysis an optimum back twist profile for the presented semi-submersible FOWT in the defined environment conditions can be identified. When specifying maximum energy generation, then a back twist angle of -3° initiated at 87.5% along the blade from the root is optimum, with a tower axial fatigue life increase compared to the 'Feather Base Model' of 5.1%, achieved with just a 0.14% reduction in energy. However, if an energy loss of up to 1% was acceptable then although this would stipulate that the back twist angle did not exceed -6° , suggesting an optimum initiation point would be more complex as a defined trend does not appear within the weighted results.

4.7 Conclusions

Within most numerical studies, the turbines mounted on floating platforms are generally those that have been designed for fixed bases, however the induced tower base bending moments of a FOWT have been shown to increase by up to 1.6 times. If these loads are not reduced, then towers must be strengthened which results in increased costs and weight for both the tower and floating platform. The regulation of the power generation is also seen to suffer for a

FOWT, due to the need to avoid the negative damping created by the drop in rotor thrust of a turbine with pitch-to-feather control.

The aim of this research was to investigate the effects on the tower axial fatigue life of both increasing the back twist angle and the point along the blade where the back twist initiates at, for a VSVP-S controlled 5 MW HAWT. This was coupled to a semi-submersible floating platform with a constant pitch angle setting below rating. Then, through examination of the aerodynamic damping, and hence changes to the rotor thrust created by the different blade profiles, the trends were identified when the FOWT was operating in three different mean turbulent wind environments. This then allowed a further weighted analysis accounting for wind frequency at the specific site, so that an optimum blade profile for minimum energy loss could be presented. Also, by utilizing VSVP-S control, the issues relating to the negative damping phenomenon were avoided.

The proposed approach has achieved its aim by highlighting the trends at each mean wind speed analysed, due to the introduction of a back twist towards feather along part of the blade length, which then allowed an optimum blade profile for tower fatigue reduction, with minimum energy loss to be presented from combined weighted responses.

The rotor thrust range was seen to decrease when the constant pitch angle decreased, and hence the angle of attack decreased at 8 mps winds, which resulted in a reduction in the fore-aft motion of the tower. Hence, the optimum constant pitch angle of 0° was the most appropriate at this wind speed. For 13 mps winds, the trend from the effects of a constant pitch angle were the complete opposite, such that increases in the angle of attack reduced the thrust range and hence increased the tower axial fatigue life. Therefore, the optimum constant pitch angle of -4° was the most applicable for this environment. Two constant pitch angles were therefore imposed, that came into effect when the turbine was operating in winds below rated, such that at wind speed between 8 mps and 13 mps, the constant pitch angle setting would increase from 0° to -4° .

The trends for both increases in the back twist angle and in the initiation point distance along the blade were the same in both 8 and 18 mps winds, such that the tower axial fatigue life was seen to decrease as the back twist initiation point moved closer to the blade tip (for all of the back twist angles), and increased as the back twist angle increased.

There were no noticeable trends seen due to changes in either the back twist angle or initiation point at 13 mps. However, the tower fatigue life was seen to exceed that achieved by the 'Feather Base Model' for all the back twist models at 13 mps winds, with a 20% increase achieved for all back twist angles initiated at 92.75% along the blade length.

At 18 mps the platform pitch response was unaffected by rotor thrust reductions, which agrees with the findings of Lackner (2013) such that decreased tower loads do not always correspond to reductions in the platform pitch response range.

A weighted analysis, where maximum energy generation was chosen as the overriding constraint, identified the optimum blade profile, for this FOWT in this specific environment, to have a back twist angle of -3° that initiated at a point 87.5% along the blade as measured from the root. This is identified as 'Stall Back Twist Model 5' in Table 4-1 of section 4.3.2. This provided a tower axial fatigue life increase compared to the 'Feather Base Model' of 5.1%, achieved with just a 0.14% reduction in energy.

The effect of a higher constant pitch angle below rated for operation in mean winds around 13 mps could identify even higher reductions in tower fatigue. This knowledge could also be particularly applicable for turbine life increase, as the decommissioning date approaches, such that the constant pitch angle below rated of a VSVP-S blade could be increased to extend the life of a turbine tower, a situation where the energy loss may be deemed to be worth the increased operational life achieved.

The blade profiles presented in this study give an initial indication of the trends and possible benefits for turbine towers mounted on floating platforms that utilize

a VSVP-S and back twisting blades. However, the blade designs are preliminary, and a fully detailed design that could provide a smoother transition in the thrust-speed curve could be beneficial, as would more detailed analyse of the loads experienced by the rotor and all of the other turbine systems, by the introduction of a back twist to the blade. A future study would also need to examine the effects on the tower fatigue life from shear stress due to torsion. Further analysis on acceptable energy loss for tower fatigue life increase would also be beneficial in selecting an optimum back twist blade profile for a specific site.

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5 PAPER 3

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5.1 Title page and abstract

Back twisted, active pitch-to-stall blade for floating offshore wind turbine tower damping

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Abstract: Floating offshore wind turbines are subjected to higher tower fatigue loads than their fixed-to-seabed counterparts, which could lead to reductions in turbine life. The worst increases are generally seen in the tower axial fatigue, associated with the tower fore-aft bending moment. For a spar type platform this has been shown to increase by up to x2.5 and, for a semi-submersible platform, by up to x1.8. Reducing these loads would be beneficial, as the alternative of strengthening the towers leads to increases in cost. Here, two offshore floating wind turbine systems, of the spar type, are analysed and selected responses and tower fatigue compared: one incorporates a variable speed, variable pitch-to-stall blade control system and a back twisted blade, and the other a conventional pitch-to-feather control. The results are then compared to those obtained in an earlier study, where the same turbine configurations were coupled to

a semi-submersible platform. A weighted wind frequency analysis at three mean turbulent wind speeds of 8, 13 and 18 m/s highlights that the impact of the back twist angle magnitude and initiation point on tower axial fatigue life extension was the same for both platform types. Compared to their respective feather base models, an increase in the tower axial fatigue life of 18.8% was seen with a spar platform and 10.2% with a semi-submersible platform, when a back twist angle to the tip of -6° was imposed along with the variable speed, variable pitch-to-stall control.

Keywords: floating offshore wind turbine (FOWT); spar; semi-submersible; pitch-to-stall; blade back twist; tower axial fatigue life

5.2 Introduction

The amount of energy harvested directly from wind has been increasing around the world at a tremendous rate, with 11.6% of the electricity requirement of Europe being provided from wind energy during 2018 (WindEurope, 2019). Offshore wind farms can have many advantages, compared to land-based turbines, including a higher energy resource, as the wind is more constant and stronger off shore than onshore (Robertson and Jonkman 2011). Also, as such farms are situated away from inhabited areas, the individual machines and overall farm sizes can be bigger. This has led to a global increase in offshore wind resources of nearly 24% in 2018 with a total global capacity of 23 GW (Ohlenforst et al 2019). Most of the offshore wind turbines adopt a 'fixed-to-seabed' support structure, such as a monopile or jacket. However interest and research and development into floating offshore wind turbines (FOWT) are growing, with predictions that an additional 5 GW will be provided from floating devices by 2030 (Fried et al, 2017). This has arisen as technological advances have enabled floating devices to be situated at depths or on seabed conditions that would not be suitable for fixed-to-seabed devices.

The floating platforms used to support wind turbines have been categorised by the restoring moment that dominates the design. Hence barges and semi-submersibles are classed as being water stabilised (buoyancy); tension leg

platforms (TLP) are predominantly stabilised through their mooring system; and spars utilize a long draft filled with ballast material, and so are stabilised by the relative position of the centre of gravity to their centre of buoyancy. Historically, semi-submersibles were often classed as hybrid systems as they tend to have a large second moment of the waterplane area (a feature of a barge) and a large draft (a feature of a spar) and also utilize ballast for further stabilization (Butterfield et al 2005; Thiagarajan & Dagher 2014). A depiction of the different floating platform types for single horizontal axis wind turbines (HAWTs) can be seen in Figure 5-1.

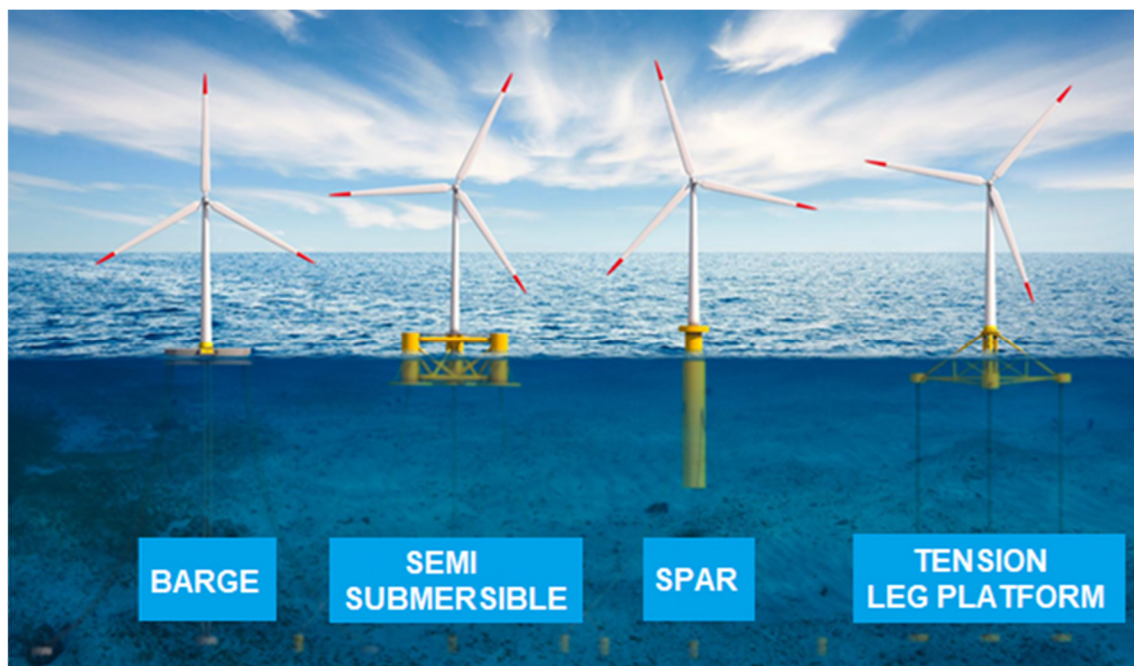


Figure 5-1. Artist's impression of the main FOWT platform types for HAWTs (WindEurope 2017)

One area of concern for researchers, designers and industry is the increased system loads that a floating turbine can be subjected to in comparison to a fixed base device. Robertson and Jonkman (2011) conducted a comprehensive study on six platform types, and analysed how their responses would be likely to increase extreme and fatigue loads on the NREL (New and Renewable Energy Laboratory) 5 MW HAWT system. The study included two types of TLP, two spars, a barge and a semi-submersible. The simulation results for the fatigue loads of these six platforms are given in Figure 5-2; quoted as a ratio between

the floating wind turbines' responses to that of the corresponding land-based wind turbine. The fatigue for each device was generated with three different sets of Wöhler material exponent (m) values (Robertson & Jonkman 2011). The first of the two ' m ' numbers given for each floating platform on the legend within Figure 2 refers to the value adopted for the blades and the second number is for the tower and shaft. Hence, where the ' m ' values are given as $m=8/3$, the Wöhler material exponent value for the blades is eight and for the tower and shaft it is three (Robertson & Jonkman 2011).

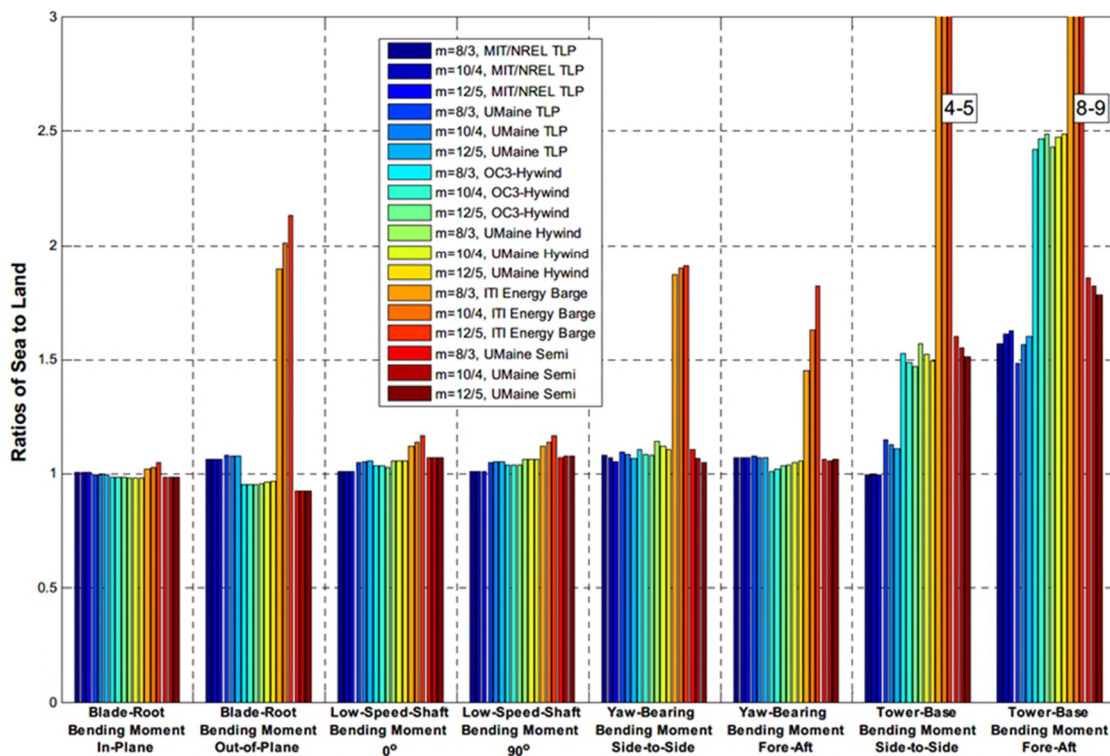


Figure 5-2. Fatigue loads as experienced by six FOWT platforms presented as sea-to-land ratios (Robertson & Jonkman 2011)

From these results and other studies (Li et al 2017; Bachynski et al 2014; Lackner 2013; Jonkman & Marth 2011), it was clear that the tower base fore-aft induced fatigue loads were those that increased the most for all types of platform, when moving from a land-based to floating structure. From the Robertson & Jonkman (2011) study, the tower base fore-aft fatigue loads were around x1.5 times higher for TLPs than land-based turbine fatigue, x2.5 higher for spars, x1.8 higher for the semi-submersible and up to x8-9 higher for the barge. If these fatigue loads

are not reduced, through such measures as control, blade design or tower strengthening, the lifetime of the turbine will be dramatically reduced (Li et al 2017).

This paper aims to investigate possible mechanisms for tower axial fatigue reduction for a wind turbine tower on a spar platform. Simulations of the responses of the turbine and platform will be compared to those experienced by a semi-submersible in similar environmental conditions. The study builds on the previous work carried out by Ward et al (2019, 2020), which analysed the effects on the tower axial fatigue of a back twisted stall blade with active variable speed and variable pitch-to-stall (VSVP-S) control, when applied to the NREL 5 MW turbine coupled to a semi-submersible platform. A VSVP-S blade pitch control system was chosen, as this avoids negative damping problems. Negative damping becomes more of an issue with floating platforms, as the frequencies of the platforms' responses in surge, sway, pitch and roll are generally lower than those experienced by a fixed wind turbine. Thus, for a pitch-to-feather control system on a FOWT, a less regulated rotor speed and power output are produced.

5.3 Simulation models

5.3.1 Spar model

The aero-hydro-servo-elastic simulation model for the spar platform is the open source model identified as the 'OC3 Hywind' configuration, provided by NREL (Jonkman 2010), which was based upon the 'Hywind' spar-buoy full-scale prototype, designed by Statoil (now Equinor) of Norway. The OC3 (Offshore Code Comparison Collaboration) study examined the accuracy of the simulated responses produced by six different contributing companies or research facilities, each using different simulation approaches (Jonkman & Musial 2010). The draft of the 'OC3 Hywind' is 120 m below sea water level (SWL), with the platform top 10 m above the SWL. Its total mass (including ballast) is 7,466,330 kg, and its centre of mass (CM) is just under 90 m below the SWL. The mooring system utilized three catenary lines.

5.3.2 Semi-submersible model

The simulation model for the semi-submersible platform is also an open source model provided by NREL, and identified as the 'OC4-DeepCwind semi' configuration (Robertson et al 2014a). The 'OC4-DeepCwind semi' model was based upon the 1/50th scale experimental prototype, which was part of the US DeepCWind project and which had undergone tests in the MARIN (Maritime Research Institute Netherlands) wave basin (Goupee et al 2014). The 'OC4-DeepCwind semi' configuration was used for the OC4 (Offshore Code Comparison Collaboration Continuation) Phase II study, which was a continuation of the OC3 project, but that had been extended to include simulations from 23 participants using 19 different codes (Robertson et al 2014b). The draft of the 'OC4-DeepCwind semi' is 20 m below SWL, and the platform top is 10 m above SWL. The structure's total mass is 13,473,000 kg (including ballast) and the CM is at 13.46 m below SWL. Three catenary lines were used for mooring.

5.3.3 Wind turbine model

The turbine models coupled to both the spar and semi-submersible platforms are based upon the NREL three-bladed 5 MW HAWT. There were minor variations between the turbine towers used for each platform, such that the mode shapes of each tower was altered. This was due to the difference in the boundary conditions between the tower and the support structure, due to the individual platform designs and mooring system conditions (Jonkman 2010; Robertson et al 2014a). Further changes were made to the controller and the blade for all VSVP-S control models, as outlined in sections 5.3.4 and 5.3.5 respectively. The two pitch-to-feather base models identified within this study, are the 'Spar Feather Base Model' that utilizes the 'OC3 Hywind' platform, and the 'Semi-sub Feather Base Model' that employs the 'OC4-DeepCwind semi' control configurations provided by NREL. The blades for these two baseline models are the same as the blades used on the open source NREL 5 MW turbine. The hub height of the turbine is 90 m above SWL for both platforms and it has a 126 m rotor diameter.

The turbine cuts-in at a wind speed of 3 m/s (rotor speed of 6.9 rpm), and cuts-out at 25 m/s. The rated wind speed is 11.4 m/s, corresponding to 12.1 rpm (Jonkman et al 2009).

5.3.4 Blade pitch controller design for the VSVP-S models

The VSVP-S collective blade controller is a proportional-integral (PI) control system implemented within Simulink, which feeds back the actual rotor speed and uses the error relative to the rated rotor speed to derive and set the required pitch angle. Each blade model and platform configuration has a unique pair of gain settings, derived when steady winds were at 18 m/s. A constant gain setting has been imposed throughout Region 3 (from the rated to cut-out wind speed), as a gain scheduler blade pitch control system would be more complex for pitch-to-stall control. This is because the pitch angles required for the VSVP-S can be double-valued, such that the same pitch angle is required at different wind speeds (Ward et al 2019).

5.3.5 Blade designs for the VSVP-S models

This study builds upon previous research presented by Ward et al (2019, 2020). A study on tower axial fatigue loads and other prominent responses was presented for twelve different back twist (BT) blade configurations for the NREL 5 MW turbine coupled to the 'OC4-DeepCwind semi' floating platform (Ward et al 2020). These BT blades were all initially twisted towards stall from the root towards the tip. A back twist was then applied such that, at a pre-determined distance from the root, the twist direction reversed. This back twist then continued until the tip of the blade was reached.

From analysis of the tower axial fatigue life extension and power generated, the six blade profiles that did not exceed a BT angle of -6° were seen to be the most favourable variants (Ward et al 2020). These six blade profiles, as shown in Table 5-1, have been chosen for further analysis in this paper to address their potential benefits when used in a turbine coupled to a spar platform. This then allows an

assessment to be made on the suitability of specific back twisted blade profiles for more than one type of FOWT.

Table 5-1. Model parameters for the FOWT utilizing the ‘OC3 Hywind’ platform

Test ID	Active variable pitch blade control	Twist starting distance from bade root		Twist angle increase at the tip (°)	Proportional gain at 18mps, K _p (s)	Integral gain at 18mps, K _i
		(%)	(m)			
Spar Feather Base Model	Feather	0	0	0	Inbuilt gain scheduler	
Spar VSVP-S BT 1	Stall	75.0	46.1	-3	-0.903	-0.387
Spar VSVP-S BT 2	Stall	87.5	53.8	-3	-0.893	-0.383
Spar VSVP-S BT 3	Stall	92.8	57.0	-3	-0.878	-0.376
Spar VSVP-S BT 4	Stall	75.0	46.1	-6	-1.120	-0.480
Spar VSVP-S BT 5	Stall	87.5	53.8	-6	-0.979	-0.420
Spar VSVP-S BT 6	Stall	92.8	57.0	-6	-0.933	-0.400

5.4 Methodology

Simulations during turbulent winds were carried out utilizing the FAST v8 (Fatigue, Aerodynamics, Structures, and Turbulence), time domain aero-hydro-servo-elastic (AHSE) simulation tool. Throughout each simulation, all of the degrees of freedoms (DOF) (excluding rotor-teeter) were enabled within the FAST code. Three hour simulations were generated (the first 300 s of each simulation was removed to ensure that no transient effects were considered in the analysis). Three hour simulations were chosen as this is recommended as the minimum by the DNV-OS-J103 standard (DNV 2013), to allow more accurate fatigue analysis, as responses vary more over time for a FOWT than a fixed turbine. Periodic 10 minute wind files were generated, using TurbSim, for three different mean turbulent, stochastic, wind speeds: 8, 13 and 18 m/s. These were generated using the Kaimal wind spectrum and an IEC (International Electrotechnical Commission) turbulent intensity of 0.14 (model B) (EN 2006). The sea depth was 320 m for the spar configuration (as used within the OC3 study (Jonkman 2010)) and 200 m for the semi-submersible (as used in the OC4 study (Robinson et al 2014a)). The sea state was generated using the JONSWAP spectrum (DNV 2004). The significant wave heights (H_s) were 1.25, 2.5 and 4.5 m, respectively at 8, 13 and 18 m/s mean wind speed and had 5.5, 8 and 10 s peak periods (T_p), as extrapolated from the environmental conditions in Geos (2001), for a northern North Sea location. All of the environmental and simulation

test conditions were the same as those used for the earlier semi-submersible studies (Ward et al 2019, 2020). The constant pitch angle setting, applicable for all wind speeds below rated, was 0° when the mean turbulent wind speed was 8 m/s and -4° when the wind had a mean speed of 13 m/s. Fatigue was generated using Miner's Rule and a rainflow cycle counting algorithm provided as MATLAB code by Niesłony (2009).

5.5 Results

5.5.1 Weighted turbulent wind test comparisons

Simulations for each of the six spar VSVP-S models (based on the six blade geometries) were generated for the three separate mean turbulent wind speeds of 8, 13 and 18 m/s. Each of these models had a back twisted angle of -3° or -6° at the blade tip, each BT being applied at one of three different initiation points (IPs) along the blade length, 75%, 87.5% or 92.75%, as presented in Table 5-1. The results at each mean turbulent wind speed, for each model, were then weighted according to the wind frequency at the site, as outlined in Ward et al (2020). The individual and total weighted results, as compared to the feather base model for each spar VSVP-S model, are presented in Table 5-2.

From the results at each wind speed, it can be seen that the VSVP-S control with a back twisted blade produces a beneficial increase of the tower axial fatigue life for all BT profiles when operating at both 8 and 13 m/s mean turbulent winds. The range of benefit seen at 8 m/s, in terms of tower axial fatigue life percentage increase from the feather base model due to the different BT profiles, varies from 1.1 to 18.7%. At mean winds of 13 m/s, the variation in tower axial fatigue life is small between the BT profiles, with all BT profiles leading to an estimated 21.5 to 22.8% fatigue life increase. By contrast, only the BT 4 profile produces an increased fatigue life at the higher mean wind speed of 18 m/s. From a comparison with the weighted 'Spar Feather Base Model', all VSVP-S models with a back twisting blade experienced an increase in the total weighted tower axial fatigue life (beneficial effect): for example, an increase of up to 18.8% is obtained with the blade used in the 'Spar VSVP-S BT 4' model. This model had

a BT angle of -6° which initiated at 75% along the blade length (from the root). This large increase in fatigue life came at a reduction in the average overall power by 0.8%, when compared to the power generated by the 'Spar Feather Base Model'.

Table 5-2. Weighted tower axial fatigue life and average generated power for each Spar VSVP-S Back Twist (BT) Model.

Test ID	Spar VSVP-S BT 1	Spar VSVP-S BT 2	Spar VSVP-S BT 3	Spar VSVP-S BT 4	Spar VSVP-S BT 5	Spar VSVP-S BT 6
Initiation point along the blade, measured from the root (%)	75.0	87.5	92.8	75.0	87.5	92.8
Back twist angle at the tip ($^\circ$)	-3	-3	-3	-6	-6	-6
Tower axial fatigue life change from Spar Feather Base Model at 8 m/s mean wind speed (%)*	5.9	1.3	1.1	18.7	7.4	4.7
Tower axial fatigue life change from Spar Feather Base Model at 13 m/s mean wind speed (%)*	21.9	21.5	22.1	21.8	22.3	22.8
Tower axial fatigue life change from Spar Feather Base Model at 18 m/s mean wind speed (%)*	-5.8	-16.6	-23.1	8.4	-6.6	-17.1
Total weighted tower axial fatigue life for each scenario (years)	22.8	22.0	21.9	24.9	23.1	22.6
Tower axial fatigue life change from Spar Feather Base Model (%)*	8.8	4.9	4.5	18.8	10.0	7.6
Total generator power average for each scenario (kW)	1897	1897	1896	1885	1891	1891
Average generated power change from Spar Feather Base Model (%)	-0.2	-0.2	-0.3	-0.8	-0.5	-0.5

* (-ve number means a shorter tower life, i.e. detrimental effect.)

The results for the same blade BT models, when the VSVP-S turbine was coupled to a semi-submersible FOWT as used in the earlier study by Ward et al (2020), are presented in Table 5-3. Comparison between the spar and semi-submersible platforms show that the same trend occurs in the total weighted tower axial fatigue life, i.e. the life is extended as the BT initiation point gets closer to the blade root and as the BT magnitude increases. Thus, the same 'BT 4' profile that produces the highest total weighted tower axial fatigue life in the spar, also produces the highest total weighted tower axial fatigue life increase for the semi-

submersible (10.2%, as compared to the semi-submersible feather base configuration).

Table 5-3. Weighted tower axial fatigue life and generated power for each Semi-submersible VSVP-S Back Twist Model.

Test ID for semi-submersible variable-speed variable-pitch-to-stall models	Semi-sub VSVP-S BT 1	Semi-sub VSVP-S BT 2	Semi-sub VSVP-S BT 3	Semi-sub VSVP-S BT 4	Semi-sub VSVP-S BT 5	Semi-sub VSVP-S BT 6
Initiation point along the blade, measured from the root (%)	75.0	87.5	92.8	75.0	87.5	92.8
Back twist angle at the tip (°)	-3	-3	-3	-6	-6	-6
Tower axial fatigue life change from Semi-sub Feather Base Model at 8 m/s mean wind speed (%)*	4.3	0.2	-1.3	6.5	1.0	-1.1
Tower axial fatigue life change from Semi-sub Feather Base Model at 13 m/s mean wind speed (%)*	20.5	20.9	20.1	18.5	20.5	20.5
Tower axial fatigue life change from Semi-sub Feather Base Model at 18 m/s mean wind speed (%)*	-14.3	-25.3	-32.3	-1.8	-16.3	-27.1
Total weighted tower axial fatigue life for each scenario (years)	27.6	26.8	26.3	28.1	27.2	26.6
Tower axial fatigue life change from Semi-sub Feather Base Model (%)	8.3	5.1	3.1	10.2	6.5	4.1
Total generator power average for each scenario (kW)	1901	1907	1899	1888	1894	1895
Average generated power change from Semi-sub Feather Base Model (%)	-0.5	-0.1	-0.5	-1.1	-0.8	-0.8

* (-ve number means a shorter tower life, i.e. detrimental effect.)

5.5.2 Platform response characteristics in turbulent winds

In Figure 5-3 the platform responses for the spar 'OC3 Hywind' (in red) and semi-submersible 'OC4-DeepCwind semi' (in blue) are presented for each of the three mean wind speeds. The feather baseline models are represented with the dashed lines and the VSVP-S BT 4 models, which achieved the highest fatigue life extension for both platform types, are represented by the solid lines. To eliminate

as many potential source of difference in platform response as possible, identical wind and wave realisations were used for all the models. The responses seen in Figure 5-3 are time signals, so only one set (only one wind and one wave seed) are considered. Response range values, however, are those derived from three different combinations of random wind and wave seeds for each wind speed. A reduction in the range of a response indicates a more stable platform which would be beneficial.

In Figures 5-3(d-f), the platform surge is seen to be higher for the feather spar platform configuration at all mean wind speeds than that experienced by the semi-submersible feather configuration. The introduction of the 'Spar VSVP-S BT 4' turbine creates a further increase in surge when the conditions are above the rated wind speed. With 8 m/s mean winds, (Figure 5-3(d)), the surge response range decreased by nearly 6% when the spar 'OC3 Hywind' platform was coupled to the 'Spar VSVP-S BT 4' turbine model instead of the spar feather base model. The average surge response at 13 m/s was nearly 30 m (Figure 5-3(e)), rising to 33 m at 18 m/s for the 'Spar VSVP-S BT4 Model' (Figure 5-3(f)). The surge response range at 13 m/s increased by nearly 9% with the introduction of the 'Spar VSVP-S BT4 Model' when compared to the response with feather control (Figure 5-3(e)), however, at 18 m/s it was reduced by nearly 28% (Figure 3(f)). At 18 m/s the variation in the platform surge range between the semi-submersible models was over 22%, with the reduction achieved with the introduction of the VSVP-S BT 4 configuration (Figure 5-3(f)).

For the sway responses, the VSVP-S BT 4 configurations reduce the sway ranges for both platforms, by over 9% for the 'Spar VSVP-S BT 4' and by 30% for the 'Semi-sub VSVP-S BT 4', when compared to their respective feather base models and when operating in mean winds of 8 m/s (Figure 5-3(g)). With 13 m/s winds, an increase in the sway response range of motion occurred for both VSVP-S BT 4 models of up to 18% (Figure 5-3(h)). An increase in the sway response of the 'Spar VSVP-S BT 4' was also experienced at 18 m/s (Figure 5-3(i)). However, the 'Spar VSVP-S BT 4' model's sway response at 18 m/s also changed much more frequently with time (Figure 5-3(i)).

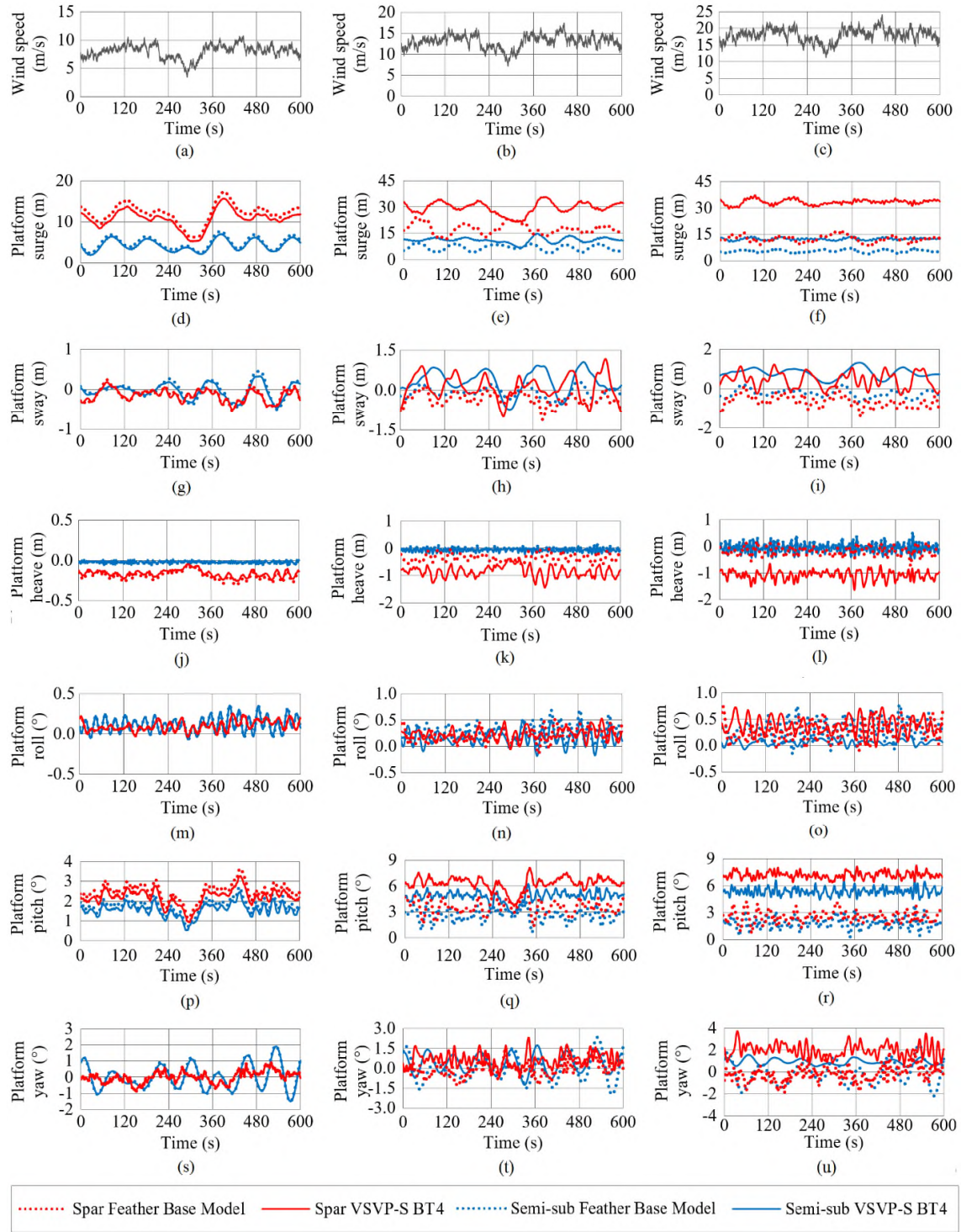


Figure 5-3. Simulation outputs for the platform responses of the spar 'OC3 Hywind' and semi-submersible 'OC4-DeepCwind semi' floating platforms, when coupled to either a pitch-to-feather or VSP-S BT 4 turbine with mean turbulent winds and sea states of 8 m/s, $H_s=1.25$ m, $T_p=5.5$ s (left), 13 m/s, $H_s=2.5$ m, $T_p=8.0$ s (centre), and 18 m/s, $H_s=4.5$ m, $T_p=10.0$ s (right).

The average platform heave response was lower for both spar configurations compared to the semi-submersible platform configurations at both 8 and 13 m/s winds (Figures 5-3(k,l)). However, at 18 m/s winds this only applied to the 'Spar VSVP-S BT 4' configuration (Figure 5-3(j)). The heave response range also increased for the 'Spar VSVP-S BT 4' model, by over 20% at 13 m/s winds and by 17% at 18 m/s.

Although some variation was seen in the platform roll ranges, the actual change at all wind speeds was small, with the variations for all models being less than 1° (Figures 5-3(m-o)). In 18 m/s winds however, the range of the roll response was reduced by over 61% for the 'Semi-sub VSVP-S BT 4' model as compared to the 'Semi-sub Feather Base Model' (Figure 5-3(o)).

The platform pitch response range was seen to reduce by nearly 6% at 8 m/s winds for the 'Spar VSVP-S BT 4' compared to the 'Spar Feather Base Model' (Figure 5-3(p)), with the average pitch angle also reducing marginally. No significant change was seen at 8 m/s between the semi-submersible configurations (Figure 5-3(p)). At 13 m/s the pitch range increased by over 15 % with the VSVP-S BT 4 turbine coupled to the spar platform and by 4% with the semi-submersible stall model (Figure 5-3(q)). At 13 and 18 m/s winds the average platform pitch angle was higher for both models when the VSVP-S BT 4 was employed (Figures 5-3(q,r)). The platform pitch response range however, reduced for both VSVP-S BT 4 models at 18 m/s, by nearly 40% and 34% for the spar and semi-sub models respectively, compared to their feather base models (Figure 5-3(r)).

The yaw response range was much lower at 18 m/s for the 'Semi-submersible VSVP-S BT4' configuration (Figure 5-3(u)) but no significant variation was seen at lower wind speeds. For the 'Spar VSVP-S BT 4', at 13 m/s the yaw range increased by 21% although this amounted to less than a half degree change and at 18 m/s it decreased by 6%. The frequency of the yaw response was significantly increased by the introduction of stall and BT to the spar platform, for both 13 and 18 m/s mean winds (Figures 5-3(t,u)).

5.5.3 Turbine response characteristics in turbulent winds

The most relevant turbine responses when analysing the tower axial fatigue life are presented in Figure 5-4, again with the spar 'OC3 Hywind' shown in red; while the semi-submersible 'OC4-DeepCwind semi' in blue; and each feather model has dashed lines while each stall model has solid lines. As detailed in section 4.2, the response values are generated from the combined results of three different random wind and wave seeds for each mean wind speed which are all 3 hrs in length. The figure's second row (Figures 5-4(d-f)) refers to the 'blade out-of-plane deflection' (BOoPDef); the third row (Figures 5-4(g-i)) to the 'blade out of plane bending moment at the blade root' (BOoPBmBr); the fourth row (Figures 5-4(j-l)) to the 'blade flapwise bending moment' (BFwBm); the fifth row (Figures 5-4(m-o)) to the 'tower base side-to-side bending moment' (TwrBsSSBm); and the last row (Figures 5-4(p-r)) to the 'tower base fore-aft bending moment' (TwrBsFABm). As with the platform responses, a reduction in the range of a turbine response also indicates more stability which would be beneficial.

The 'BOoPDef' response range is beneficially reduced by 12 and 18% respectively for the spar and semi-submersible VSVP-S BT 4 configurations at mean wind speeds of 8 m/s, compared to their respective feather base models (Figure 5-4(d)). Their averages also drop. At 13 m/s, both the range and the average 'BOoPDef' are higher for both VSVP-S BT 4 models (Figure 5-4(e)), giving an undesirable increase in the deflection of over 3 m. This increase in the average 'BOoPDef' values with the VSVP-S BT4 configurations is carried through for both platforms and all three of the blade responses presented, when winds are at a mean of 13 m/s or above (Figures 5-4(e,f,h,i,k,l)). At 18 m/s, again, the BT models' average 'BOoPDef' response is higher than that of the feather models but the ranges of motion are practically the same (Figure 5-4(f)).

The 'BOoPBmBr' range reduces by over 5% and 10% at 8 m/s wind speed, for the VSVP-S BT 4 spar and semi-submersible configurations respectively (Figure 5-4(g)). At 13 m/s there is more variation in the 'BOoPBmBr' responses of the two

VSVP-S systems, with nearly a 3% reduction in range for the spar platform but a 16% increase for the semi-submersible (Figure 5-4(h)).

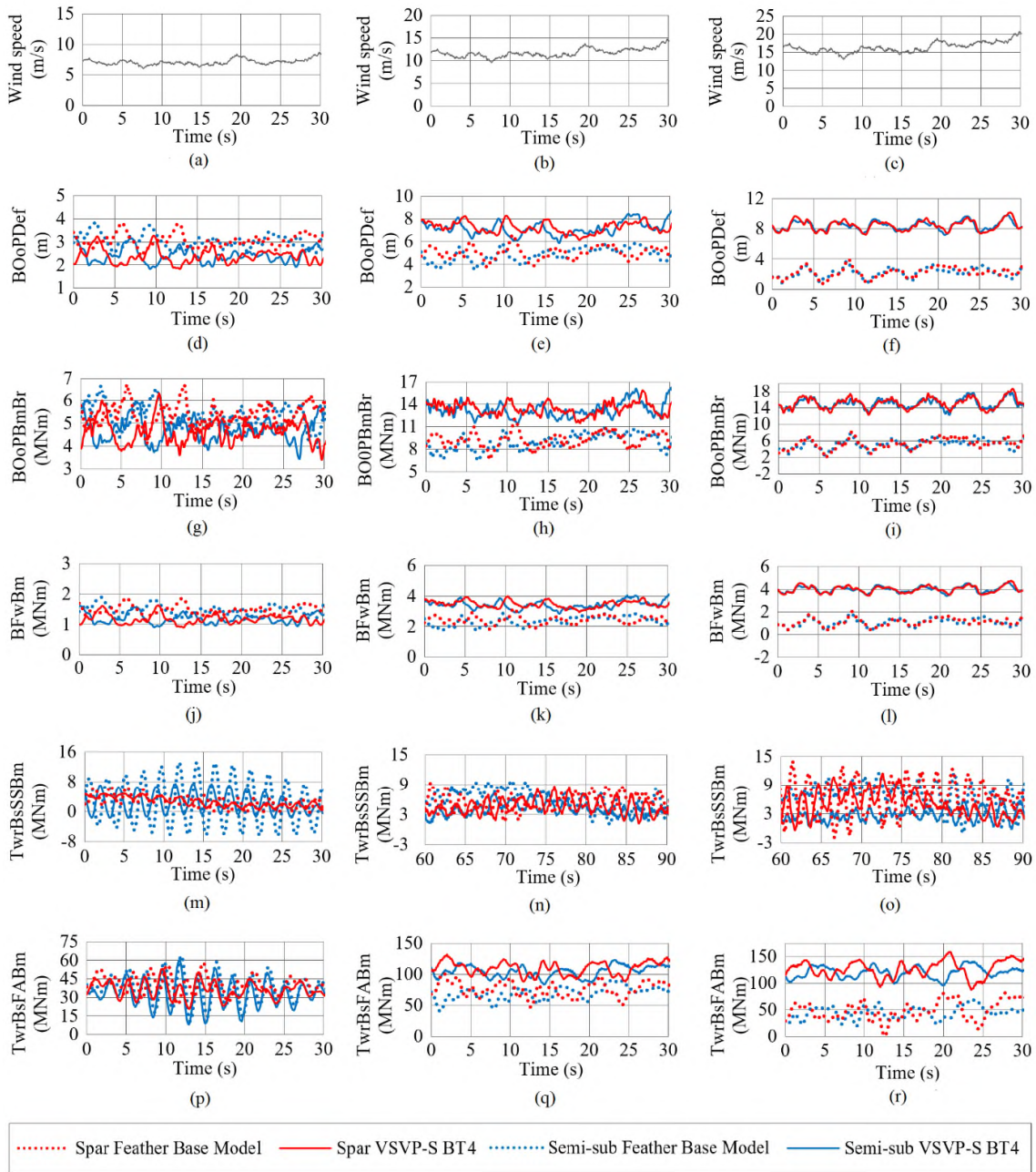


Figure 5-4. Simulation outputs for turbine responses of the spar 'OC3 Hywind' and semi-submersible 'OC4-DeepCwind semi' floating platforms, when coupled to either a pitch-to-feather or VSVP-S BT 4 turbine with mean turbulent winds and sea states of 8 m/s, $H_s=1.25$ m, $T_p=5.5$ s (left), 13 m/s, $H_s=2.5$ m, $T_p=8.0$ s (centre), and 18 m/s, $H_s=4.5$ m, $T_p=10.0$ s (right).

At 18 m/s both VSVP-S BT 4 models experience an increase in BOPBmBr range; this is just 2% for the spar but, again, a larger increase (of nearly 9 %) is observed for the semi-submersible (Figure 5-4(i)).

A reduction approaching 11 and 17% in the 'BFwBm' response range is seen for the VSVP-S spar and semi-submersible configurations respectively at 8 m/s mean winds (Figure 5-4(j)). This trend continues for the 'BFwBm' response range at both 13 and 18 m/s, with reductions of over 9 and 12% experienced at 18 m/s for the spar and semi-submersible BT VSVP-S systems (Figures 5-4(k,l)).

From the responses for the 'TwrBsSSBm', shown in Figures 5-4(m-o), it can be clearly seen that the ranges reduce with the introduction of a VSVP-S BT 4 configuration, regardless of which platform it is coupled to. Thus the 'TwrBsSSBm' range saw a 50% reduction for the semi-submersible and 29% for the spar at 18 m/s, compared to their feather counterparts (Figure 5-4(o)). A reduction of approximately 5% in the 'TwrBsFABm' response range was seen for the semi-submersible VSVP-S BT 4 configuration at winds of both 8 and 18 m/s. The same trend was seen in the spar VSVP-S BT 4 model, but with a 4 or 8% decrease occurring at 8 and 18 m/s respectively (Figures 5-4(p,r)).

5.5.4 Responses' Power Spectral Densities

The power spectral densities for the rotor thrust, platform pitch, and tower base fore-aft bending moment are presented in Figure 5-5, as these responses all have a strong impact on the tower base axial fatigue. As in Figures 5-3 and 5-4, the spar 'OC3 Hywind' is depicted in red and the 'OC4-DeepCwind semi' is in blue. The VSVP-S BT 4 models have a solid line and the feather baseline models are depicted by dashed lines.

The maximum amplitude of rotor thrust is reduced for the VSVP-S BT4 configurations, as compared to that seen with each corresponding feather base model by nearly 19% for the spar and 20% for the semi-submersible at mean wind speeds of 8 m/s (Figure 5-5(a)). At 13 m/s, the rotor thrust maximum amplitude is over 50% higher with the VSVP-S systems, and remains higher up

until 0.023 Hz, after which it drops below that seen by the feather configurations until around 0.04 Hz (Figure 5.5(b)). At the higher mean wind speed of 18 m/s, the rotor thrust amplitude is greatly reduced with both VSVP-S systems, until the frequency exceeds 0.2 Hz, after which all systems approach zero (Figure 5.5(c)).

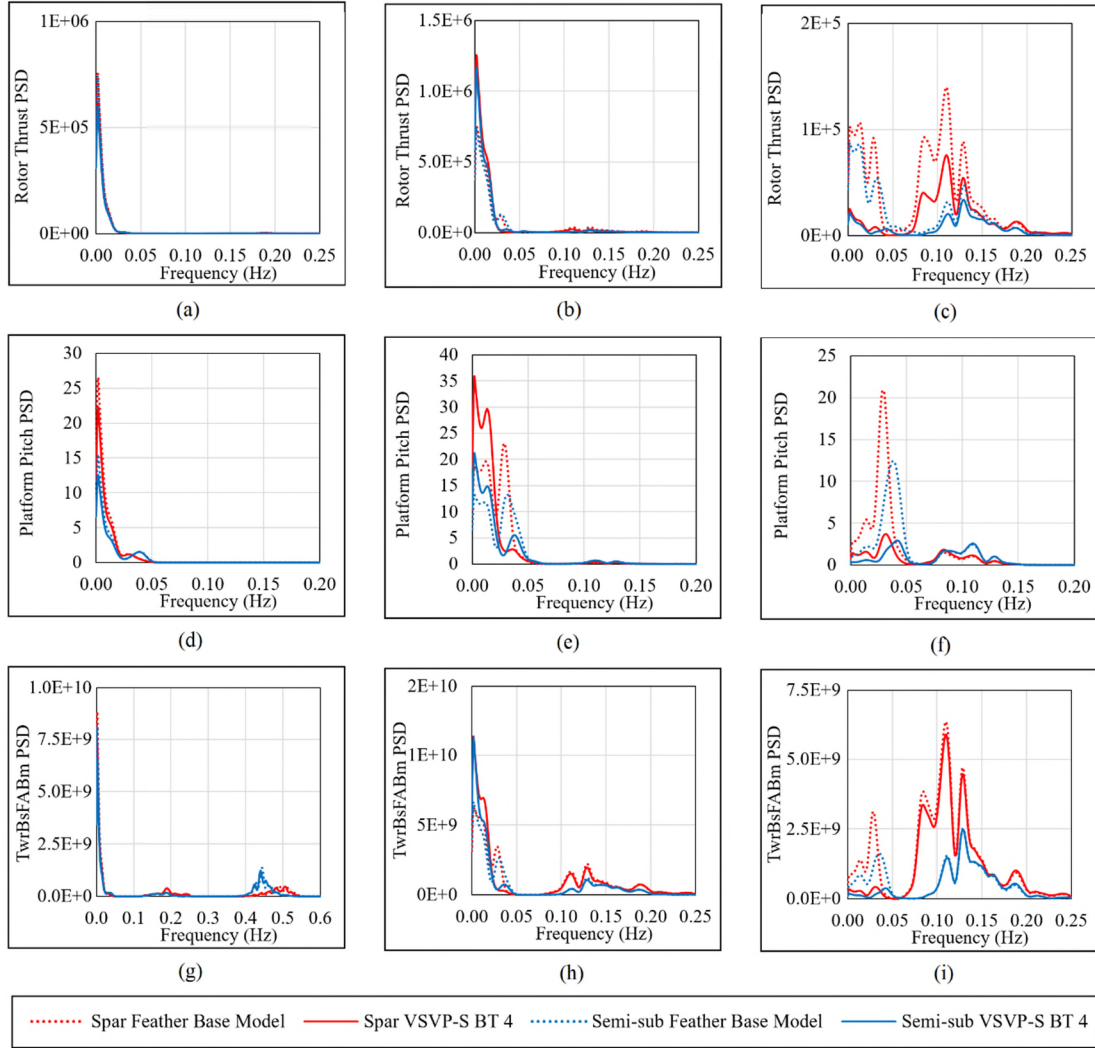


Figure 5-5. Power spectrum densities for the rotor thrust, platform pitch and tower base fore-aft bending moment of the spar ‘OC3 Hywind’ and semi-submersible ‘OC4-DeepCwind semi’ floating platforms, when coupled to either a pitch-to-feather or VSVP-S BT 4 turbine with mean turbulent winds and sea states of 8 m/s, $H_s=1.25$ m, $T_p=5.5$ s (left), 13 m/s, $H_s=2.5$ m, $T_p=8.0$ s (centre), and 18 m/s, $H_s=4.5$ m, $T_p=10.0$ s (right).

For the platform pitch and the tower base fore-aft bending moment spectrums, the introduction of a back twisted blade with VSVP-S control at 8 m/s mean winds resulted in a reduction in the amplitude peak (that occurs at approximately

0.0017 Hz) by nearly 16% or 19% for the spar and semi-submersible respectively (Figures 5.5(d,g)). At 13 m/s each of the 4 systems experiences two noticeable spikes in the amplitude of the platform pitch spectra. The maximum of both platform pitch spectra is higher for the VSVP-S systems, however they occur at the lower frequency of 0.017 Hz compared to 0.0283 Hz for the 'Spar Feather Base Model' or 0.0317 Hz for the 'Semi-submersible Feather Base Model' (Figure 5.5(e)). Also, between approximately 0.2 to 0.5 Hz, the VSVP-S systems platform pitch spectrum peaks are up to 88% or 77% lower for the spar and semi-submersible VSVP-S BT4 configurations respectively (Figure 5.5(e)). The maximum tower base amplitudes occur at 0.017 Hz for all systems at the 13 m/s wind speed, however the two feather systems are also subjected to another spike occurring at the same frequencies as the corresponding peaks seen in platform pitch (Figures 5.5(e,h)). At 18 m/s the reduction in the maximum peak amplitude of the platform pitch for both VSVP-S systems is over 82% for the spar and 76% semi-submersible platforms when compared to their respective feather base models (Figure 5.5(f)). This again results in a higher amplitude for the tower base fore-aft bending moment at the corresponding frequencies of 0.0283 Hz for the 'Spar Feather Base Model' and 0.0383 Hz for the 'Semi-submersible Feather Base Model' (Figure 5.5(i)). For the VSVP-S model on the spar platform, a noticeable decrease compared to feather control is also seen at the higher frequencies (from approximately 0.08 to 0.13 Hz; Figure 5.5(i)).

5.6 Discussion

The analyses of the tower axial fatigue life for both the spar and semi-submersible platforms, at each mean turbulent wind speed, and with combined weighted results that take account of the wind frequency estimated at the specific site, highlight how each turbine model performs (Tables 5-2 & 5-3).

The responses in terms of the total weighted tower base axial fatigue life for the spar VSVP-S BT models (Table 5-2) were aligned with those of the semi-submersible VSVP-S BT models (Table 5-3). Hence, the fatigue life increased by up to 18.8% and 10.2% for the spar and semi-submersible BT models

respectively, as the BT initiation point moved higher up the blade, towards the root, and as the BT angle became larger. The weighted power generated was slightly reduced as the BT angle increased with a drop of 0.8% for the spar VSVP-S BT model and 1.1% for the semi-submersible VSVP-S BT model. However, if the fatigue life increase was realised, a longer overall life expectancy of the turbine would allow for a higher energy generation on the whole.

The tower axial fatigue results at each wind speed, as provided in Tables 5-2 & 5-3, indicate the benefits or disadvantages gained from each back twist profile throughout the operational range. At 8 m/s mean turbulent winds, the fatigue life trend matches the total weighted fatigue life trend, such that the tower axial life increases with increased BT angle and as the initiation point moves closer to the blade. The same trends at this wind speed were seen for both VSVP-S systems in terms of lower range and averages in the 'blade out-of-plane deflection' (BOoPDef), 'blade out of plane bending moment at the blade root' (BOoPBmBr) and 'blade flapwise bending moment' (BFwBm) (Figure 5-4). As there is no pitch control at this mean wind speed, due to the wind not exceeding rated throughout the simulation, this indicates that the blade profile facing the wind at 8 m/s experiences a reduced aerodynamic force with the BT 4 profile.

At 13 m/s mean wind, the rotor is subjected to more variation than at either of the other two wind speeds analysed. This occurs as the wind speed is seen to drop below the rated wind, hence the control system goes from a constant pitch angle of -4° , below rated, to a continuously varying pitch angle designed to shed power, at winds above rated, throughout the simulation. However, for both the spar and semi-submersible, introducing a VSVP-S BT profile produces a large increase in tower axial fatigue life of around 20% for all BT profiles (Tables 5-2 & 5-3). This indicates that the benefits are mainly due to the VSVP-S control, which creates an increase in rotor thrust just above rated, instead of the decrease seen with pitch-to-feather control. This is because, although the rotor thrust during stall control increases, it also experienced a reduction in the range of the oscillations, which corresponded to a reduction in the amplitude of the power spectrum densities at frequencies above 0.023 Hz (Figure 5-5(b)). The platform pitch

spectra also decreased at corresponding frequencies, creating a reduction in the tower axial fatigue (Figure 5-5(e)).

At the higher wind speeds around 18 m/s, it is only the spar, when it has the VSVP-S BT 4 system, that shows benefit in terms of tower axial fatigue life (Table 5-2), however the same blade profile has the lowest detrimental effect on the semi-submersible (Table 5-3). It is only with the BT 4 profile that the range of the BFWBm is lower for both platforms (Figures 5-5(j-l)). However, as the higher wind speed occurs less frequently in a wind turbine's lifetime, its impact on the tower fatigue is decreased compared to the fatigue induced by the more frequently occurring lower speed winds. This is highlighted by the overall wind frequency weighted results seen in Tables 5-2 and 5-3.

From the total weighted tower axial fatigue life results presented in Tables 5-2 and 5-3, it is shown that the same BT profile produces the most benefits for both platforms. This was achieved when a BT was applied at a distance of 75% along the radius of the blade, as measured from the root, and which twisted back to -6° at the blade tip. These BT models are identified as the 'Spar VSVP-S BT 4' and 'Semi-sub VSVP-S BT 4' models, and achieved an increase in the tower axial fatigue life of 18.8% or 10.2% respectively, when compared to their respective feather base models.

A comparison of the platform and tower responses are presented in Figures 5-3 and 5-4, to show the difference in the responses due to platform type. As expected from previous literature (Thiagarajan and Dagher 2014; Bachynski et al 2014), the average surge responses of the spar platform were seen to be generally higher than those of a semi-submersible platform, and appear to correspond to increases in the average platform pitch angle (Figures 5-3(d-f, p-r)). The average surge response increases further with the VSVP-S BT 4 spar model at both 13 and 18 m/s winds, due to the increased rotor thrust. However, at the higher wind of 18 m/s the surge range was reduced by approximately 28% when compared to the spar feather model (Figures 5-3(d,f)). The overall effect of changes in both the sway and roll motion are minimal, as the variation is small.

However, the variation in the sway response is greater for both the spar configurations, when compared to both semi-submersible models (Figures 5-3(g-i)). The average heave response was below zero for both spar platform configurations with the VSVP-S BT 4 configuration creating an increased lowering of the turbine, which like the surge response, also seems to correspond with changes in the average platform pitch angle. One possible explanation for this is that the vertical (downward) component of the thrust is higher, due to the higher thrust (due to stall) and higher pitch angle, and therefore 'pushes' the platform down more. At 13 m/s this was around double that seen when operating in pitch-to-feather (Figure 5-3(k)). The average platform pitch response was higher with the spar platform than the semi-submersible regardless of the control system utilized. Both stall models also increased the platform pitch average at both 13 and 18 m/s mean winds. However, the ranges of the platform pitch were also reduced (Figures 5-3(q,r)). The yaw response variation was small at the lower wind speeds, however, an increase in the frequency of the response was seen for the spar platform coupled to the VSVP-S BT 4 turbine at 18 m/s mean winds (Figure 5-3(u)).

At 8 m/s mean winds, all the blade responses presented in Figure 5-4, for both platform types, were reduced by the introduction of the BT 4 blade, as the VSVP-S control has no effect for wind speed below rated (Figures 5-4(d,g,j)). At both 13 and 18 m/s, only the 'BFwBm' response range was reduced, as compared to their feather configurations (Figures 5-3(k,l)).

The 'TwrBsSSBm' range is reduced at all wind speeds for both VSVP-S BT 4 configurations with the semi-submersible benefiting from a 50% reduction at 18 m/s (Figures 5-4(m-o)). The 'TwrBsFABm' response is reduced in range by between 4 and 8% for both platforms with a VSVP-S BT 4 model at both 8 and 18 m/s (Figures 5-4(p,r)). Although a reduction in the response range of the 'TwrBsFABm' was not seen with either of the VSVP-S BT 4 models at 13 m/s, the tower axial fatigue life was increased the most at this wind speed due to the rise in rotor thrust seen with active stall control, which highlights the complexities in

predicting the nature of the random loading experienced by a wind turbine under turbulent wind conditions, from time signal data alone.

At 8 m/s mean turbulent wind speeds, the tower base axial fatigue life was increased (positive effect) with the introduction of both VSVP-S control and a back twisting blade with profile BT 4, for both the spar and semi-submersible platforms, by 18.7% (Table 5-2) and 6.5% (Table 5-3) respectively. The tower axial fatigue life increasing for both VSVP-S systems correlates with the reductions seen in the peak amplitudes of the tower base fore-aft bending moment spectrums at this mean turbulent wind speed (Figure 5-5(g)). The higher fatigue life increase achieved by the spar, with the VSVP-S control approach, as compared to feather control, could be due to the lower amplitude experienced when the frequency reaches 0.4 Hz. Therefore, although the spar has a higher amplitude initially at the lower frequency, when compared to the semi-submersible, the percentage reduction with the introduction of the VSVP-S BT4 is not greater for the spar platform (Figure 5-5(g)). Again, it is worth noting that all effects at this wind speed are down to the BT 4 profile change as the VSVP-S blade pitch control does not operate within the range of wind speeds experienced at this mean wind speed.

Both VSVP-S systems at 13 m/s mean winds experienced lower tower base axial fatigue, a 21.8% reduction or a 18.5% reduction for the spar and semi-submersible platforms respectively (Tables 5-2 & 5-3). This indicates that beneficial fatigue reductions are experienced in the 0.02 to 0.05 Hz range, where the platform damping is increased (Figure 5-5(e)). An increase in the platform damping around the rated wind speed, and hence a corresponding fatigue life increase, is a phenomenon mainly due to the introduction of the pitch-to-stall control system, as platform pitch damping is increased as the rotor thrust increases (Ward et al 2019). A further benefit is then seen from the back twisted blade profile. Both semi-submersible control methods also have a higher tower axial fatigue life compared to the corresponding spar control system at the 13 m/s mean wind speed, which correlates with the reduced amplitude experienced by

the semi-submersible's tower base fore-aft bending moment spectrum between 0.075 and 0.27 Hz (Figure 5-5(h)).

At 18 m/s mean wind speed the spar experiences an 8.4% increase in the tower axial fatigue life, due to the introduction of the VSVP-S BT4 configuration, whereas the semi-submersible VSVP-S system was seen to reduce the tower axial fatigue life by 1.8% compared to its corresponding feather system. One explanation for the reduction in the fatigue life of the semi-submersible VSVP-S system compared to the feather model could be due to a higher amplitude in both the rotor thrust and tower fore-aft bending moment at frequencies between 0.4 to 0.45 Hz, outside of the range seen in Figures 5-5(c,i). However, the fatigue life of the semi-submersible was nearly three times higher than the spar, regardless of the control method utilized, which corresponds with the much lower tower base fore-aft bending moment spectrum amplitudes seen at all frequencies (Figure 5-5(i)).

5.7 Conclusions

Previous studies have highlighted that FOWTs experience higher tower fatigue loads than the same turbines with a fixed base. Several studies have found that the tower axial fatigue associated with the tower fore-aft bending moment was the most negatively affected by the turbine being coupled to a floating platform (Robertson & Jonkman 2011; Li et al 2017; Bachynski et al 2014; Lackner 2013; Jonkman & Marth 2011). A spar platform was shown to experience increased tower fore-aft fatigue loads of x2.5 whilst those on a semi-submersible increased by x1.8 (Robertson & Jonkman 2011). Not controlling these increased loads will result in a reduced tower life unless the tower is strengthened, which would lead towards increased material costs and weight (Li et al 2017).

The present work's aim was to analyse whether the positive effects on tower axial fatigue life extension, seen by the introduction of a VSVP-S BT 5 MW HAWT coupled to the semi-submersible platform 'OC4-DeepCwind semi' (Ward et al 2020), was also of benefit to the spar 'OC3 Hywind' floating platform configuration. A weighted wind frequency analysis was conducted on the two

platform types, that compared a VSVP-S controlled turbine with a range of back twisted blades with their respective feather base models. This allowed a VSVP-S BT model to be selected, for further comparison between the responses and PSDs of both platform types (as compared to those seen with a pitch-to-feather configuration). The main conclusions from this research are:

- The same BT trends were seen for both the spar and semi-submersible platforms, with more fatigue life benefit being experienced with a 6° BT initiated close to the blade tip.
- Fatigue life increases seen in the BT VSVP-S models at a mean wind speed of 8 m/s can be directly attributed to the effect from the back twist, as the blade will not be pitching within this range of operation.
- The power spectral densities at 8 m/s mean wind showed a noticeable reduction in the peak amplitudes with the introduction of the BT VSVP-S models for both the spar and semi-submersible platforms, which correlated with an increase in tower axial fatigue life.
- At 13 m/s mean winds, the fatigue life increases are very high, which could indicate that large fatigue reductions are occurring in the 0.02 to 0.05 Hz range, where platform damping is higher.
- At 18 m/s mean winds, the spectral density of the spar was higher than the semi-submersible for most frequencies, hence an increase in fatigue life is more noticeable for the spar platform at these high mean winds.

This approach has shown that the introduction of a VSVP-S BT turbine achieves a noticeable and desirable increase in the tower axial fatigue life for the spar configuration. The tower axial fatigue life, both at each mean wind speed and with a total weighted with the frequency of the wind occurrence at each speed, have been presented as compared to the respective feather base models. The responses of the platform motions and a selection of turbine responses for both

platform types have also been presented and analysed, along with the most relevant PSDs for analysis of the tower axial fatigue life.

For both platform types, the same trends were seen with a weighted wind frequency analysis, such that when the BT angle increased and as the initiation point moved closer to the root, the tower axial fatigue life was extended. Thus, for a BT of -6° initiated 75% along the blade from the root, increases in tower axial fatigue life of 18.8% and 10.2% were achieved with the 'Spar VSVP-S BT 4' and 'Semi-sub VSVP-S BT 4' configurations respectively, compared to that experienced with a corresponding pitch-to-feather turbine (Tables 5-2 & 5-3).

Even though the semi-submersible VSVP-S suffered more fatigue overall at the 18 m/s wind speed than its feather model, it still achieved a fatigue life approximately 3 times higher than the spar, as would be expected by the much lower amplitudes on the tower fore-aft bending moment spectrum densities.

Further investigation into any additional system loads induced by the introduction of both the VSVP-S control and the BT blade are recommended. This would then make a full assessment of the VSVP-S BT configuration possible.

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6 VERIFICATION AND COMPARISON OF RESULTS

Verification and comparison of the results obtained in the three papers presented, on the initiation of a back twisted blade on a turbine that incorporates VSVP-S control when coupled to a floating platform, are difficult to achieve as there has been no previous research either in simulation or experimental form on this specific combination. However, verification of the models utilized without the back twist has been performed where possible. Verification of the original semi-submersible feather base model has been performed by correlation of a specific set of simulated outputs with simulated outputs presented as part of the OC4 phase II study (Robertson et al 2012) is presented in section 6.1. This also provides verification on the FAST simulation process as this aero-hydro-elastic-servo time-domain simulation code was utilized for both studies. Verification of the spar model when coupled to a turbine operating with the blades pitching towards feather and also with VSVP-S control has been carried out through comparison with results presented within the Larsen and Hanson (2007) study, as presented in section 6.2.

6.1 Verification and comparison of the semi-submersible model and FAST programming capabilities

To provide verification of both the user's understanding and programming ability in the FAST code, the requirements to match the environmental and FOWT parameters for the OC4 Phase II Load Case (LC) 2.6 were identified. These were then inserted into the relevant aerodynamic, hydrodynamic and FOWT control, mooring and dynamic sections of the FAST code. From time domain simulation results for the platform and tower motions and loads of interest, the Power Spectral Density (PSD) and Response Amplitude Operators (RAOs) were derived. The PSDs identify the distribution of the power of each signal (the squared of the response) over the frequency range and the RAOs illustrate the ratio of the system response to the wave amplitude. As this is a linear analysis, the OC4 Phase II LC 2.6 parameters, without wind was the most relevant, as with wind as in LC 3.7, it is not strictly linear (Robinson et al 2012). In particular, the

platform, tower and mooring are set as flexible whilst the rotor, nacelle and drivetrain are specified as rigid. The generator is also specified as locked, as there is no rotor rotation. Although FAST has a dynamic mooring code, the static code was used throughout the verification. The turbine and platform system was excited by implementing a banded white noise spectrum, used as it is a broadband frequency excitation, for $PSD=1 \text{ m}^2/\text{Hz}$ for 0.05 to 0.25 Hz without wind. Most of the energy in waves is within the specified wave period range of four (0.25 Hz) to 20 seconds (0.05 Hz). The responses of the semi-submersible platform in surge, heave and pitch, the tower base fore-aft bending moment and the mooring tension, to the wave elevation response were analysed. There are no noticeable platform responses in sway, roll and yaw as the wave direction was at zero degrees (in line with the direction of surge) and no wind was present. A comparison of the generated results was then made with the PSDs (Figure 6-1) and RAOs (Figure 6-2) result for the three companies that utilised the FAST simulation code as part of the OC4 phase II project: NREL, IST, and Goldwind.

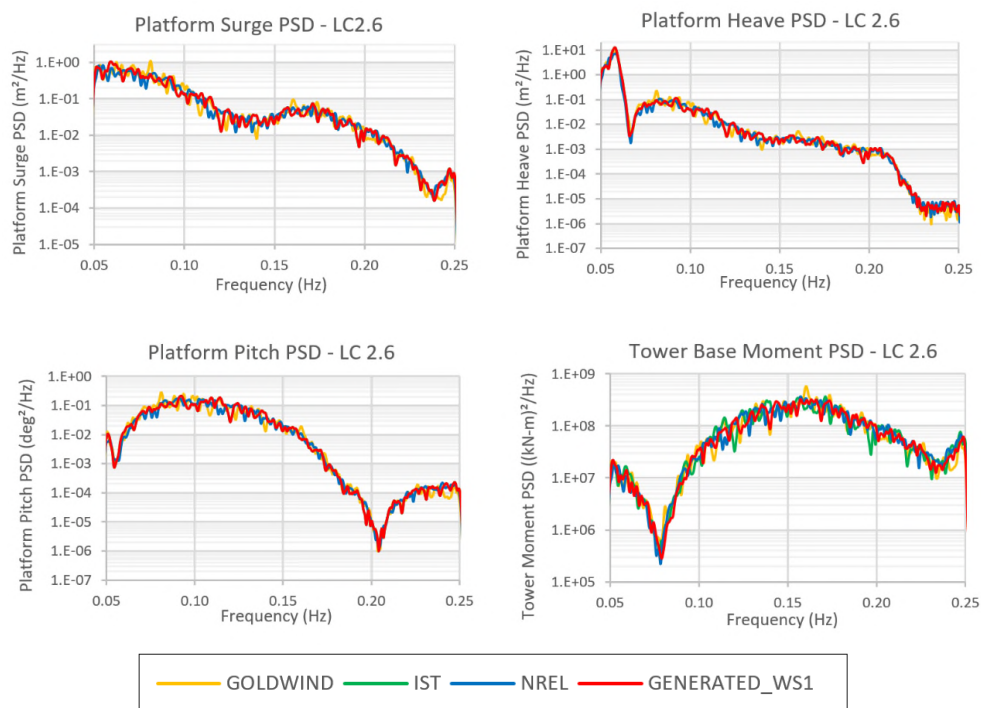


Figure 6-1. Comparison of PSD results with OC4 Phase II LC 2.6 to verify user programming capabilities and validate the semi-submersible model with no wind, $H_s=1.26 \text{ m}$, $T_p=10 \text{ s}$

The level of variation for the generated data depicted visually in Figures (6-1 & 6.2), was within the boundaries of the variations seen between the three OC4 phase II contributors presented. Therefore, the comparison of the raw responses, along with the PSDs and the RAOs, gave confidence in the ability to correctly define the load case and model parameters within FAST.

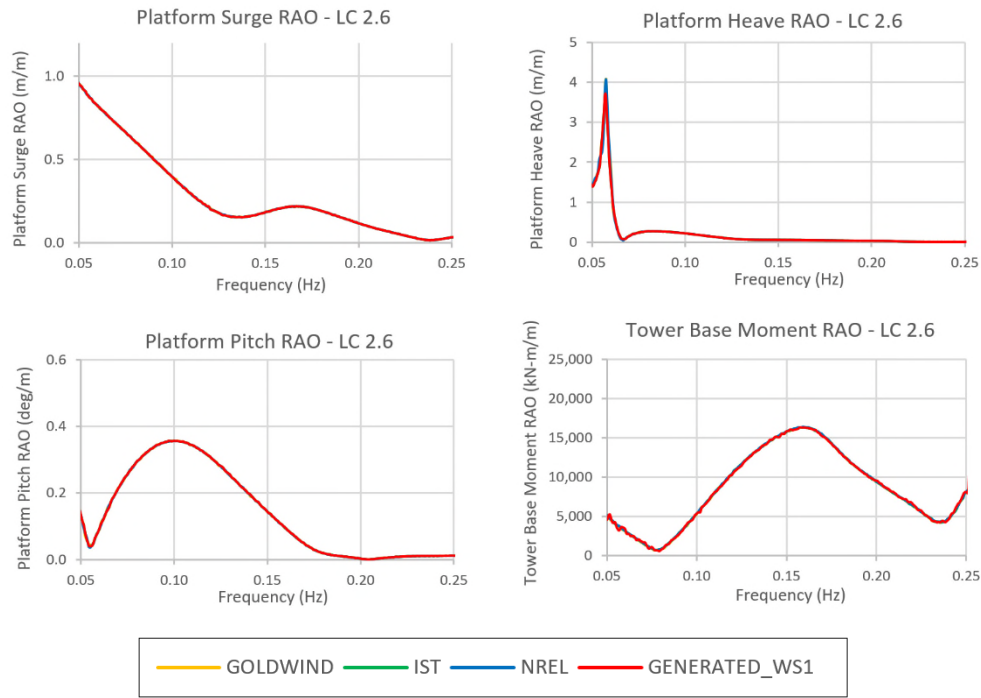


Figure 6-2. Comparison of RAO results with OC4 phase II results to validate user programming capabilities and semi-submersible model

6.2 Verification and comparison of the performance benefits due to VSVP-S control

In order to confirm the increased regulation of the generated power of a turbine controlled by VSVP-S when compared to the performance of the same turbine with pitch-to-feather control, a verification analysis was performed against the results obtained from the study presented by Larson and Hanson (2007). This study utilized the Hywind spar concept, designed for sea water depths between 200 and 700 m, coupled to an unspecified 5 MW turbine. The simulations were performed with coding developed utilizing both the SIMO/RIFLEX code designed by MARINTEK and the HAWC2 code designed by Risoe National Laboratory. The research does not specify what sea depth was used in the simulations.

Larson and Hanson's (2007) research aim was to increase the stability of turbine pitching-to-feather by altering the natural frequency of the controller. During their research however a sign error occurred causing the turbine to pitch-to-stall. The resulting responses were shown to be quite stable and have provided one of only two sets of results that examine VSVP-S control of a floating turbine. Figure 6-3 presents both the results derived by Larson and Hanson when the turbine was pitching to feather and corresponding results derived with the spar feather base model used within this study. The mean wind for both data sets is 12 m/s, with a turbulent intensity of 20% as this was the only wind speed conditions presented for the pitch-to-stall system. Figure 6-4 presents the results for the same turbines in the same environmental conditions, but now operating with VSVP-S control. No other changes were made to either the system presented by Larson and Hanson or the spar feather base model utilized by the current research.

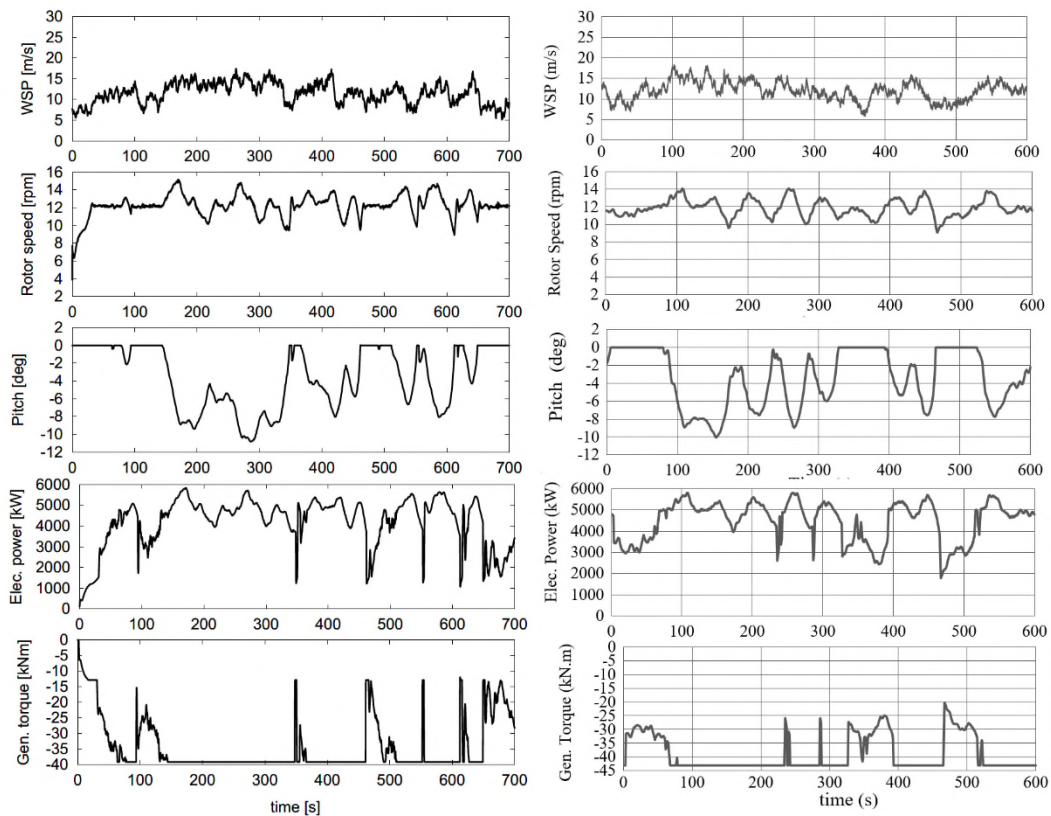


Figure 6-3. Turbine responses presented by Larson and Hanson (left) and the Spar Feather Base Model (right) when operating in 12 m/s mean turbulent winds with a turbulent intensity of 20% and pitching towards feather.

Considering the response results presented within Figure 6-3, a degree of correlation can be seen between the simulated rotor speed responses of the two systems when pitching-to-feather, such that the range of each rotor speed is between 9 and 15 rpm. A slight decrease in the variance of both the electrical power and the generator torque is experienced by the feather base model configuration, but this is likely to be due to the differences between the two 5 MW turbine systems, as well as other unknown differences between the two simulated environments.

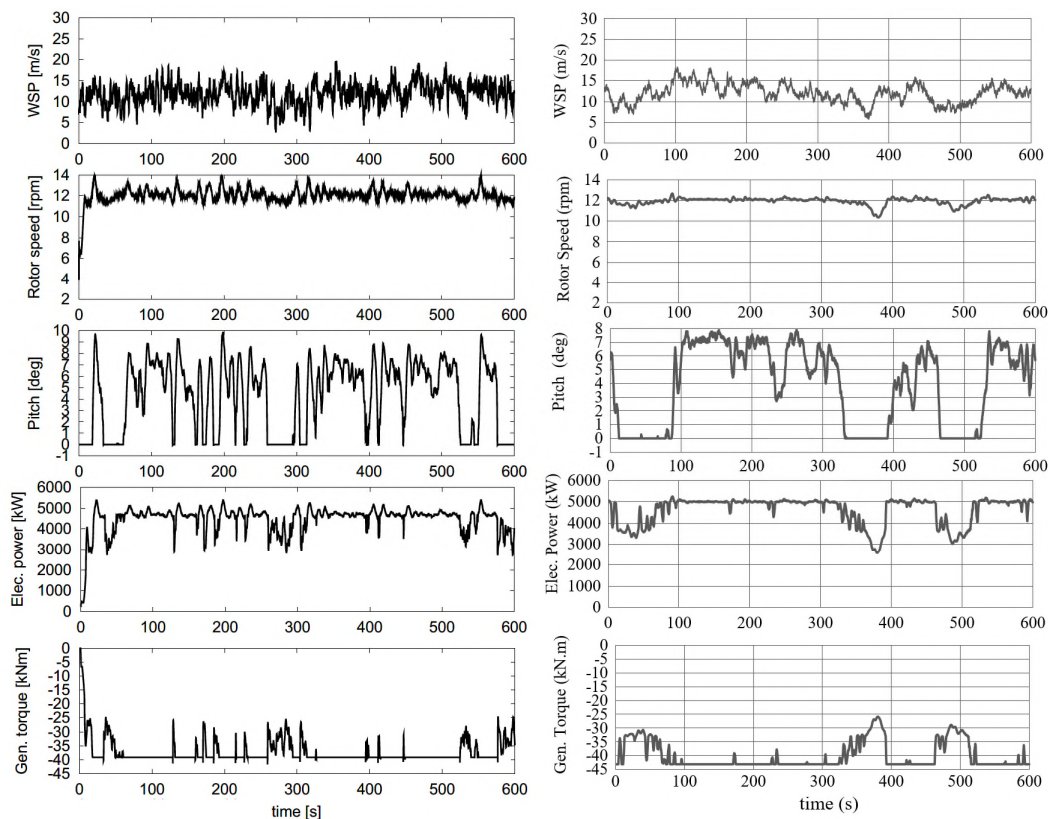


Figure 6-4. Turbine responses presented by Larson and Hanson (left) and the Spar Feather Base Model (right) when operating in 12 m/s mean turbulent winds with a turbulent intensity of 20% and pitching towards stall.

When examining the results presented in Figure 6-4, when both systems are operating with VSVP-S control, an anomaly is seen in the wind profile presented by Larsen and Hanson. Thus, the 12 m/s mean turbulent wind appears to have a turbulent intensity far exceeding the 20% specified within the study as seen in the results presented in Figure 6-3. Any comparisons made between the two sets of

simulated responses when pitching-to-stall would therefore be impossible to verify. However, even with the more intense wind profile, it can clearly be seen that the rotor speed and electrical power are both more regulated with VSVP-S control.

6.3 References

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7 GENERAL DISCUSSION

The main aim of this research was to investigate the potential of a VSVP-S controlled FOWT that incorporates a back twisted blade, to increase the tower axial fatigue life and present an optimum set of criteria, in terms of (1) the back twist magnitude at the blade tip and (2) the back twist initiation point along the blade radius. This has been achieved and a blade back twist design has been proposed that provides good mitigation of the increased undesirable tower fore-aft loads experienced when moving to floating platforms, as detailed within the following sub-sections.

7.1 Enhanced performance through VSVP-S control

Examination of the rotor thrust steady wind curves for both feather and stall control highlighted the issue of negative damping for a pitch-to-feather design (Figure 3-4). The rotor thrust reduction, seen with pitch-to-feather when operating in winds above rated, leads to the thrust vs windspeed having a negative derivative, which could lead to negative damping of the platform pitching mode.

In reality, negative damping must be avoided to prevent tower oscillations that would increase the tower fore-aft fatigue loads; this results in a low control frequency setting for pitch-to-feather control of a floating platform. Thus the main benefits in terms of rotor speed and power generation seen by a pitch-to-stall system actually arise from the higher control system frequency allowed. This higher setting is possible as negative damping is not an issue that needs avoiding in a pitch-to-stall system.

The enhanced performance that is seen with the higher controller gain setting is highlighted by the comparison of the two control systems in turbulent winds, shown in Figure (7-1). These are the responses of the 'Feather Base Model' and the 'Pitch-to-Stall Model', presented in section 3.3.1, which follow the same test conditions as detailed in section 3.4.3. The responses from both systems clearly highlighted that the energy produced by the VSVP-S control system was more regulated, with a variation of just 2% around the nominal generated power at

18 m/s when compared to a 40% variation seen with pitch-to feather control (Figure 7-1 (d)).

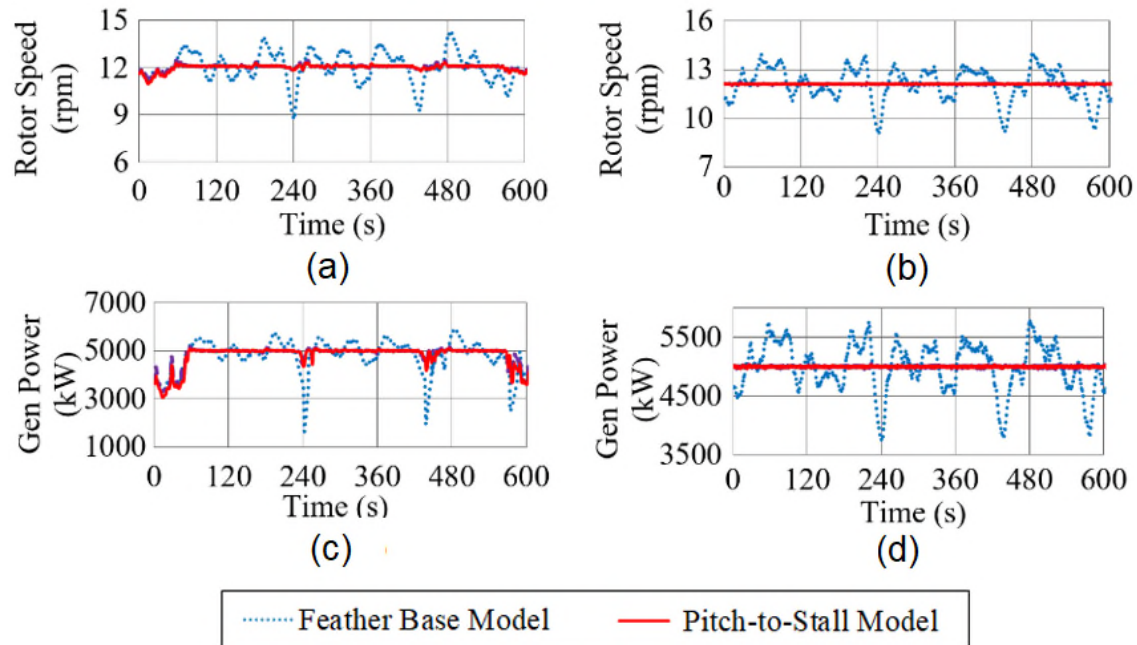


Figure 7-1 Rotor speed and generated power produced by a pitch-to-feather or a pitch-to-stall control method with mean turbulent winds and sea states of 13 m/s, $H_s=2.5$ m, $T_p=8.0$ s (left), and 18 m/s, $H_s=4.5$ m, $T_p=10.0$ s (right) when coupled to a semi-submersible floating platform.

Similar benefits were seen in the later study utilizing a spar floating platform with a VSVP-S control system, which also had a variance of 2% around the nominal at 18 m/s compared to 41% with pitch-to feather control (Figure 7-2 (d)). It can however also be seen that the semi-submersible suffered from more pronounced drops in power than seen by the spar when comparing both feather systems at 13 and 18 m/s winds (Figures 7-1 (c, d) & 7-2 (c, d)). The differences between the stability of the two floating platform systems is a likely cause but full identification of the effects would require a more in-depth analysis of the two feather systems which is beyond the scope of this study.

Comparison between the results seen for a barge with VSVP-S control within the study by Jonkman (2007) and the semi-submersible presented here highlights that the semi-submersible has much less variation in the range of rotor speed and generated power and hence provides an improved level of regulation. One

factor is that the semi-submersible experiences a much smaller range of platform oscillations when operating in stall (approximately 3°), compared to the 26° pitch range experienced by the barge. Hence the reduced platform pitching motion will ensure more consistent energy generation, and the rotor area will be more constant throughout the operational range, which is also beneficial in terms of lower accelerations at nacelle level. In general, the generated power of the turbine with a VSVP-S system coupled to a barge platform, as presented by Jonkman (2007), was comparable to that generated for the most part by the semi-submersible. However, the barge was also seen to suffer from intermittent large energy dips that can be seen to only occur when the blade pitch became zero. This was a response that the semi-submersible had also suffered from until the introduction of an anti-windup filter into the pitch-to-stall controller. It is also of some concern that the generated power, presented by Jonkman (2007), was seen to initially start at zero. This could indicate that transient effects were not removed from the presented results.

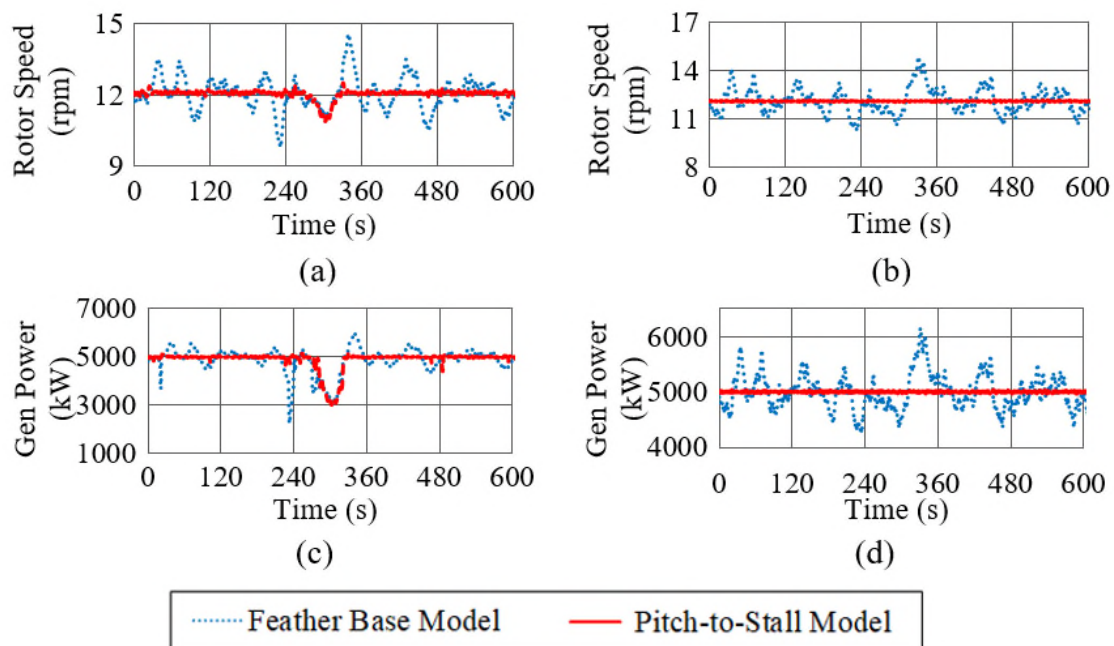


Figure 7-2 Rotor speed and generated power produced by a pitch-to-feather and a pitch-to-stall control method with mean turbulent winds and sea states of 13 m/s, $H_s=2.5$ m, $T_p=8.0$ s (left) and 18 m/s, $H_s=4.5$ m, $T_p=10.0$ s (right) when coupled to a spar floating platform.

The simulated responses of the rotor speed and power regulation for both the spar feather base model, used within this study, and the pitch-to-feather spar configuration, presented by Larsen and Hanson (2007), were shown to compare favourably as seen in Figure 6-3. This was when both were operating in a mean turbulent wind of 12 m/s with a turbulent intensity of 20%. However, verification between the results presented by Larsen and Hanson when pitching-to-stall with the increased regulation achieved by the spar feather base model turbine operating with VSVP-S control was not achieved. This was due to anomalies seen within the wind profile (Figure 6-4) presented by Larsen and Hanson which appears to have a turbulent intensity much higher than the 20% shown in Figure 6-3.

From the results presented in section 3.4.4 it can be concluded that the improved regulation is achieved solely by the pitch-to-stall configuration and the higher control system frequency setting the pitch-to-stall control method allows, and not by the back twisted blades. Due to the higher gain setting, the more regulated responses would come at the expense of an increased pitch actuation rate, which could increase operational and maintenance costs. It is also worth noting that the gains used for each stall model investigated were constant regardless of changes in the wind speed. Hence, the gain setting was the same whether the turbines were operating at 13 m/s mean winds or at 18 m/s. This is because most gain schedulers rely upon the actual change in blade pitch angle to predict the required gain, which is not easily achievable with an active pitch-to-stall configuration due to the double-valued nature of the stall controlled pitch angle. However, wind measurements using LIDAR systems could see gain scheduling for stall operated turbines becoming more possible, if accurate real time wind measurements can be used instead of the blade pitch angles.

7.2 Platform load damping

The thrust to wind speed sensitivity of the semi-submersible floating platform was investigated through the calculation of the open loop and ideal closed loop platform pitch damping ratios, for both rotor speed control methods (Appendix A-

3). From Figure A-2 it was seen that the control systems are identical below rated as the pitch angle of the blades are constant. However, once the rated wind is exceeded, the blades start to pitch to shed power and the predictions of the two control systems now vary greatly. The ideal closed loop system more closely resembles what might be expected from the rotor thrust curves (Figure 3-4(b)), such that as the rotor thrust initially increases for stall so does the platform pitch damping ratio and vice versa for feather control. The actual platform damping would be expected to fall somewhere within the open and ideal close loop boundaries, but it would be reasonable to predict that the stall system could produce enhanced damping in the wind speed region from 11 to 14 m/s and that the feather could provide better damping than stall between 15 and 19 m/s. This indicated that a stall configuration may experience an increase in useful platform pitch damping compared to a feather model, as the wind frequency will be higher at the lower winds where stall sees more possible benefits. However, although platform pitch damping can be a good indicator, it is also important to recognise that the design criteria was to reduce the tower base fore-aft response and hence increase tower fatigue life directly.

7.3 Wind and wave seeds and simulation time selection

Verification of the selection of three simulations each three-hours in length, for the analysis of the tower fore-aft fatigue seen with different configurations, has been presented within Appendix A.4. This found close correlation with the responses seen using the more standard six simulations with a length of one-hour each. Three-hour simulations for the analysis of tower base fore-aft fatigue could be more appropriate for FOWTs, as more variation is seen in the structural responses of turbines on floating platforms with time, compared to fixed base turbines. The analysis examined both pitch-to-feather and pitch-to-stall control (as presented in Tables A-4 and A-5 respectively for one-hour simulations, and Tables A-6 and A-7 respectively for three-hour simulations). The pitch-to-feather combined results of the six one-hour simulations, compared to the combined three three-hour simulations, were within 0.35% of each other and the pitch-to-stall control results were within 0.91% of each other.

7.4 Rotor blade manipulation

The literature had indicated that reducing the blade bending moment through changes to the blade geometry could result in a reduction in the tower motion and hence could aid in the aim of increasing the tower fore-aft fatigue life (Stäblein et al 2017; Merz 2011; Méndez and Greiner 2009). Initial results for a back twisted blade, for the VSVP-S semi-submersible design, showed that reductions in the range of the blade deflection and the flapwise bending moment were seen by implementing a back twist (Figure 3-6). These reductions were also observed with a corresponding reduction in the rotor thrust variance and an increase in tower axial fatigue life (Figure 4-2). However, at different mean turbulent wind speeds, different back twist profiles were seen to be the most beneficial.

Recognising that different factors play an increased or decreased role in different environmental conditions made the idea of examining the tower axial fatigue experienced by different blade twists at one specific wind speed, as suggested by Ostachowicz et al (2016), less viable. A weighted analysis that takes account of the distribution of probability of occurrence of the different wind speeds could give a better indication of the overall performance of a back twisted VSVP-S turbine over its full operational range. This study however, only took account of three different mean turbulent wind speeds as this was sufficient to indicate possible benefits but would not be sufficient for a full fatigue life analysis to be made.

From examination of the combined weighted tower base fatigue life increases available with VSVP-S control, interestingly the trends seen were the same for both floating platform types, even though the responses of each system at each wind speed was different. Thus the back twist profile was seen to be the most effective when it started higher up the blade at 75% radius from the root and when the back twist angle was 6° at the tip. This corresponded to the BT 4 profile, as seen for the spar in Table 5-2 and the semi-submersible in Table 5-3.

When examining any of the results presented, it is also important to understand when the turbine blade pitch control system will not be operating. This particularly

applies to the lower wind speed simulations (at a mean of 8 m/s), since the pitch angle will be constant during these times, and therefore the VSVP-S control systems, (or pitch-to-feather systems), will not be a factor in any of the FOWT response changes seen. This understanding, allows for a more informed analysis of the effects seen at the different mean turbulent wind speeds. Range reductions were seen at 8 m/s in 'blade out-of-plane deflection' (BOoPDef), 'blade out of plane bending moment at the blade root' (BOoPBmBr), 'blade flapwise bending moment' (BFWBm), 'tower base side-to-side bending moment' (TwrBsSSBm) and 'tower base fore-aft bending moment' (TwrBsFABm) for both the spar and semi-submersible VSVP-S configurations (Figure 5-4), which resulted in a beneficial increase in the tower base axial fatigue life for both floating systems. With the profile defined as BT 4 this increase was 18.7% for the spar (Table 5-2) and 6.5% for the semi-submersible (Table 5-3). This correlates with the decrease seen in peak amplitude for the tower fore-aft bending moment spectrums at 8 m/s, when VSVP-S BT4 control was implemented (Figure 5-5(g)). The spar VSVP-S BT4 configuration achieves a higher increase in tower fatigue life at this wind speed, which may be due to the lower amplitudes seen after 0.4 Hz. These beneficial changes must be mainly due to the back twist profile utilized, as the control system is not operating at wind speeds below rated.

At 13 m/s mean winds, benefits in terms of reduced tower axial fatigue came from both the VSVP-S control action and was also dependent upon the specific blade back twist profile. With the BT 4 blade profile reductions in tower fatigue of 21.8% and 18.5% were seen by both the spar (Table 5-2) and semi-submersible (Table 5-3) respectively. From the power spectrums, this indicates that sizable reductions in the fatigue must be gained when operating in the 0.02 to 0.05 Hz range, as the platform can be seen to be more damped in this region with the VSVP-S BT4 configurations. Less fatigue is experienced by both the feather and stall semi-submersible configurations at 13 m/s when compared to the corresponding spar control design. This correlates with the reduction in amplitude seen by the semi-submersibles between 0.075 and 0.27 Hz (Figure 5-5(h)).

At 18 m/s mean winds the back twist profiles had a major influence on both systems, with more benefit seen when the back twist was initiated higher up the blade, and when the twist angle was increased to 6°. However, the response of the platform pitch was not seen to be influenced by reductions in the rotor thrust, even though it could be seen in Figure (4-3 (i & l)) that they translated into a more regulated tower fore-aft motion and fatigue life increase. These results therefore align with the analysis presented by Lackner (2013), who reiterated the importance of examining changes in tower motion, rather than platform pitch, as reductions in the latter are not always directly transferable to the tower. With the BT4 blade profile, the spar gained an increase of 8.4% in the tower fatigue life whereas the semi-submersible experienced a reduction in the fatigue life of nearly 2%. This increase in fatigue for the semi-submersible could be seen to be quite surprising when examining the reductions in the amplitude below 0.05 Hz. As although below 0.05 Hz corresponds to wave periods of 20 seconds or above where the wave loads tend to be low, the platform pitch natural frequency is within this frequency range. Hence, more benefits could be expected from the VSVP-S control system. However, it may be that the higher fatigue is due to a higher amplitude that was seen at frequencies higher than those depicted in Figure 5-5(i).

Overall more benefit was seen by the spar platform with an increased axial tower life of 18.8% when compared to its feather base model, compared to 10.2% for the semi-submersible. However the semi-submersible tower base axial fatigue life was higher overall. In reality it is not appropriate to compare the two systems with each other as the environmental scenarios were not identical. The spar was situated in water at a depth of 320 m and the semi-submersible was in water at a depth of 200 m. Also, although they both incorporated a similar 3-line catenary mooring system, their pre-tension and elastic stiffness requirements were different. The semi-submersible platform also has a mass that is approaching double that of the spar, which would increase manufacturing costs especially for a steel construction. It should also be noted that the increases in fatigue life came

at the expense of a weighted power reduction of 0.8% and 1.1% for the spar and semi-submersible VSVP-S systems, respectively.

7.5 References

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8 CONCLUSIONS AND FURTHER WORK

8.1 Main conclusions

The expected move from fixed base to floating offshore wind turbines comes with several challenges, such as those due to the increased turbine tower loads experienced. To make floating platforms financially viable, these loads need to be reduced. The induced tower base bending moments are negatively affected when a turbine is coupled to a floating platform, with bending moment increases of up to 1.6 times higher than those that a tower on a fixed base may experience (Robertson & Jonkman 2011). This specific tower fore-aft motion is also associated with the phenomenon known as 'negative damping', which can occur when a turbine is pitching to feather, due to the reduction in the rotor thrust that occurs when wind speeds exceed rated. Generally negative damping is avoided by reducing the frequency of the blade pitch controller. However, when this method is applied to a FOWT, the actuation frequency must be made low enough to avoid the frequencies of the platform's motions in surge, sway, roll, and pitch, as well as the natural frequency of the turbine tower vibration Eigen frequencies (Fleming et al 2019). As such, much lower control frequencies must be chosen. Furthermore, the lower control frequency setting creates an undesirable increase in fluctuations in rotor speed and generated power, and hence leads to a reduced performance (Larsen & Hanson 2007).

This thesis has examined the possible benefits to both the performance, by improving the energy regulation, and to the reduction of tower fore-aft loads, through the implementation of a back twisted blade that actively pitches towards stall to control the rotor speed at higher winds. The following novel contributions to knowledge have also been fulfilled:

- Provide further information on tower axial fatigue propagation relative to platform, tower and blade profiles when operating with VSVP-S control.

- Increase the data on the effects of a VSVP-S control strategy for different FOWT platform types, and the benefits of avoiding negative damping in terms of a more regulated rotor speed and power output.
- Determine if tower axial fatigue reductions can be achieved utilising a back twist towards feather blade on a VSVP-S blade pitch control system.
- Present the most appropriate blade back twist configuration in terms of magnitude and initiation point along the blade radius, through a weighted wind frequency analysis for a specific set of environmental conditions, for both a semi-submersible and a spar FOWT platform.

Useful data has been provided on the increased energy regulation achievable through VSVP-S control on two types of floating platform, a semi-submersible and a spar. This data has allowed a comparison to be made between the regulation of energy generated by a VSVP-S controlled FOWT and that achieved by a similar FOWT with a standard pitch-to-feather control configuration.

This research has achieved its aim and has shown that a VSVP-S control turbine with a BT blade can both increase the regulation of the energy and reduce tower base fore-aft induced fatigue when coupled to either a spar or semi-submersible floating platform type. The proposed design, that provides good mitigation of undesirable loads without undue power loss, has a BT magnitude at the tip of -6° and a twist initiation at 75% from the blade root. With a weighted wind frequency analysis at three mean turbulent wind speeds, this configuration has been shown to provide possible increases in the tower axial fatigue life of up to 18.8% for the spar type and 10.2% for the semi-submersible, when compared to their respective feather base models.

The findings from the two studies on different floating platform types has also enabled a comparison of the effects on tower fatigue due to both VSVP-S control and has also enabled trends in the back twist profiles at different wind speeds to be identified. This data therefore provides increased knowledge that could help provide further potential solutions and make VSVP-S a more viable, techno-

economically solution for future FOWT designs. Reducing the increased tower loads could also result in decreased costs and weight rather than increased fatigue life, depending upon the specific requirements of a FOWT configuration.

8.2 Meeting the objectives

The initial investigation into the possible benefits of a VSVP-S control system, in terms of avoiding negative damping by design, was conducted on the semi-submersible floating platform used in the OC4 Phase II project, as outlined in section 3.3.1. The semi-submersible platform type was chosen partially due to possible benefits in assembly and maintenance. The main selection criteria however, was the increased fore-aft tower loads that both semi-submersibles and spars were seen to experience as detailed in section 2.3 and seen in Figure 2.5. Thus, semi-submersibles and spars would both benefit from a reduction in the tower fatigue loads experienced. The choice of the open source OC3 phase IV spar and OC4 phase II semi-submersible floating platform configurations, coupled to the NREL 5 MW turbine, further allowed the research to concentrate on tower fatigue load reduction, rather than model development. Thus the first objective of this thesis, to 'select a suitable floating platform type and configuration', was achieved.

The second objective, to 'evaluate and compare the state-of-the-art methodologies utilised for the simulation, analysis and control of loads as they propagate on a wind turbine tower fixed to a floating platform', was achieved through the extended literature review in section 2.2. From further analysis in section 2.4, the FAST v-8 aero-hydro-servo-elastic code was chosen to simulate both the turbine and platform responses in the time domain.

A site in the Northern North Sea off the Scottish coast and relatively close to the first commercial floating wind farm 'Hywind Scotland', was chosen to accomplish objective three 'a reference site with appropriate environmental conditions, and hence define the load case for the aerodynamic and hydrodynamic models'. The selected site, as specified in section 3.3.1, had data collected on the mean wind speeds and significant wave heights at hourly intervals over several years (Geos

2001) allowing an informed decision when defining the load cases for the aerodynamic and hydrodynamic models’.

The selection of two fully open source floating platform models, compiled within FAST, benefited this research by providing fully developed aerodynamic, hydrodynamic, structural dynamic and control models for the analysis of both the semi-submersible and spar FOWT systems when operating in pitch-to-feather. Details of the verification of those models and also the programming capabilities within FAST, can be seen within section 6.1, thus completing objective four.

Objective five was achieved utilising Simulink within MATLAB to develop a variable speed, variable pitch-to-stall control model, with constant gains between the rated and cut-out wind speeds, as detailed in section 3.3.1. This was linked into the FAST v8 aero-hydro-servo-elastic model utilizing the FAST S-Function, as provided by the simulation code.

The first part of objective six, to identify blade models to reduce tower fore-aft responses, was realised through the extended literature review, specifically within section 2.3.5. This allowed suitable blade manipulations, in the form of a back twist, to be defined and implemented. Simulations confirmed that the model was capable of positively reducing tower fore-aft responses, under the different environmental and operational conditions specified, as detailed in the first paper, presented in section 3.

The second paper, presented in section 4, fulfils objectives seven and eight by both analysing and presenting the findings in terms of the effects of back twist angle, initiation point and constant pitch angle below rated and also by identifying the most appropriate active-stall blade profile modifications for fatigue reduction at the tower.

The final ninth objective, to ‘determine if the wind turbine with blade modifications would provide benefit to another floating platform type’, was achieved within the third paper, presented in section 5, which analysed the effects on a spar type platform.

8.3 Further work

This initial study, through a numerical investigation of the potential advantages arising from the implementation of a back twisted blade, imposed a parametric sweep of the twist distance along the blade length. This was applied to a blade with characteristics that were mainly relevant to a pitch-to-feather control system, rather than the variable speed, variable pitch-to-stall control system imposed. Further analysis on a back twisting blade, aerodynamically designed for active pitch-to-stall control and that could provide a smoother transition in the thrust-speed curve would be beneficial. Investigation of three-dimensional flows in back twist turbine blades employing Computational Fluid Dynamics techniques would provide further knowledge and may also highlight more appropriate back twist profiles to achieve not only tower axial fatigue reduction, but also increased power generation.

Further research would also need to analyse the structural loads imposed on the blades by the incorporation of a back twisting blade, both individually and upon the rotor as a whole. Full system load analysis, including loads on the nacelle, gearbox and drive train would also be recommended. A future study should also include the effects of shear stress due to torsion, on the overall tower fatigue life. It may also prove useful if the two components of this study, the VSVP-S control and the back twist blade, were separately analysed.

A study of possible energy loss over the turbine life would also provide useful additional information for wind turbine developers and would be an essential component towards the possible selection of the most preferable back twist design for a specific environmental scenario and floating turbine type.

A more complete analysis, initially through simulation, of the effects of both VSVP-S and BT on a specific FOWT type, that covered all operational mean wind speeds, each analysed with 10 variable wind and wave seeds would also be advisable. This would ensure that all possible variations in the motions of a FOWT are more adequately captured.

From this more thorough investigation of a VSVP-S BT configuration, a scaled experimental FOWT could provide validation of the simulated responses. Experimental testing would also provide real time results that would further indicate the pros and cons of the proposed VSVP-S BT FOWT configuration.

8.4 References

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APPENDICES

Appendix A Supplementary Material - Paper 1

Appendix A contains supplementary data relating to the first paper, 'Reducing Tower Fatigue through Blade Back Twist and Active Pitch-to-Stall Control Strategy for a Semi-Submersible Floating Offshore Wind Turbine'. This includes additional detail on the semi-submersible platform (section A.1); the blade twists (section A.2); the platform damping ratios (section A.3) and wind and wave seeds and simulation time (section A.4).

A.1 Semi-submersible platform

Paper 1, makes reference to a semi-submersible platform; more detail on this platform is provided here. A depiction of the semi-submersible platform utilized within the paper can be found in Figure A-1 (adapted from Robertson et al 2014). The total height of the 'offset columns' is 30 m. This comprises of 10 m above the SWL and 20 m below it. The platform has a mass of 13,473,000 kg, which is the total mass that includes ballast. The CM is at a depth below SWL of 13.46m. Mooring is provided by three catenary lines. Figure A-2 illustrates the semi-submersible floating platform coupled to the 5 MW NREL HAWT (Robertson et al 2015).

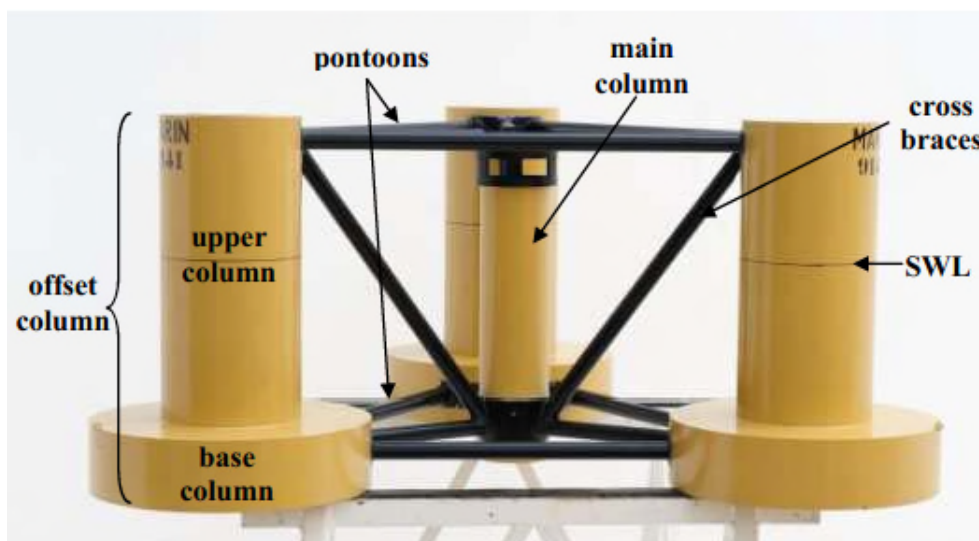


Figure A-1 Semi-submersible platform. (Adapted from Robertson et al 2014).

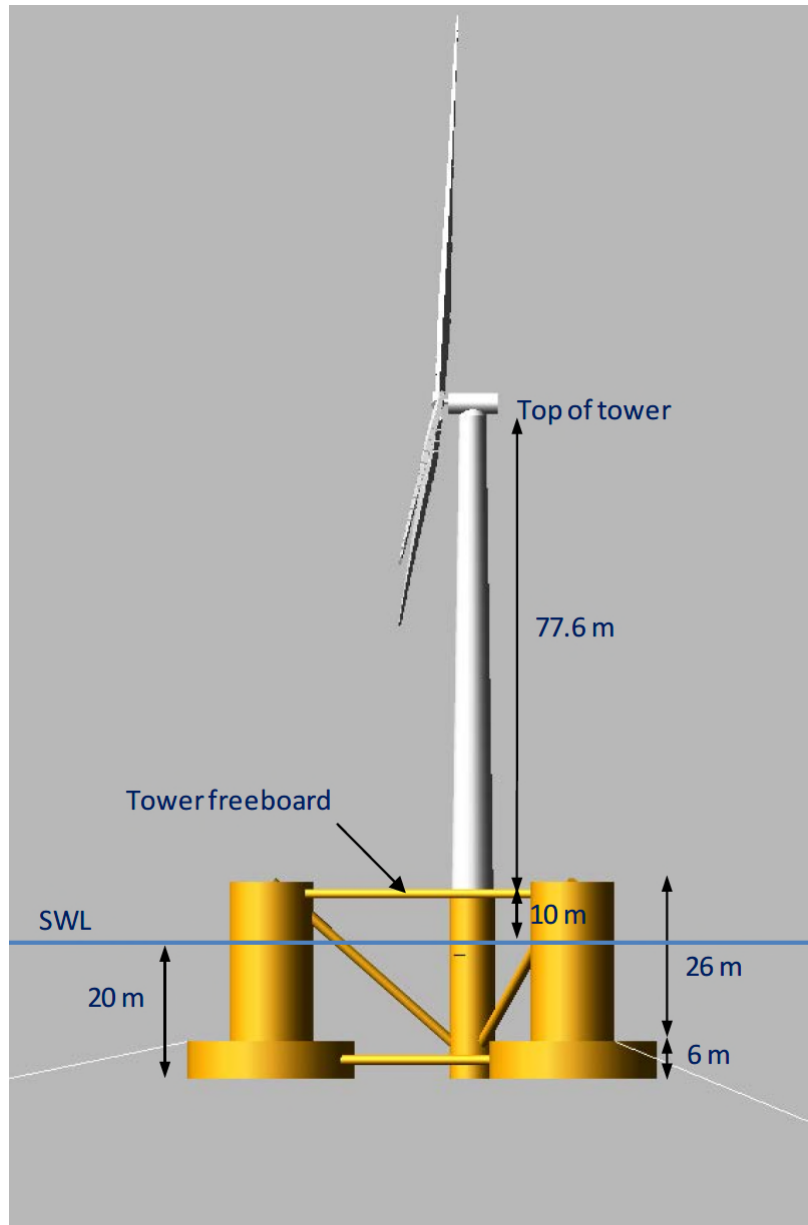


Figure A-2. Semi-submersible platform couple to the 5 MW NREL HAWT (Robertson et al 2015).

A.2 Blade twists

Details of the blade twists analysed in Paper 1, are provided here. The original blade twist of the NREL 5 MW HAWT, as used for both the 'Feather Base Model' and 'Pitch-to-Stall Model', has been defined as the 'original blade twist' in Table A-1 (Jonkman 2007). How this twist has been altered, in terms of an imposed back twist that starts at 75% along the blade span, can be seen by the further

three back twist models (for 3°, 6° and 9°) relative to the specific twist angle at a given blade span (as measured from the root).

Table A-1. Blade twist profiles presented in section 3

Blade span from the root (m)	Original blade twist (deg)	3° back twist (deg)	6° back twist (deg)	9° back twist (deg)
0.00	13.31	13.31	13.31	13.31
1.37	13.31	13.31	13.31	13.31
4.10	13.31	13.31	13.31	13.31
6.83	13.31	13.31	13.31	13.31
10.25	13.31	13.31	13.31	13.31
14.35	11.48	11.48	11.48	11.48
18.45	10.16	10.16	10.16	10.16
22.55	9.01	9.01	9.01	9.01
26.65	7.80	7.80	7.80	7.80
30.75	6.54	6.54	6.54	6.54
34.85	5.36	5.36	5.36	5.36
38.95	4.19	4.19	4.19	4.19
43.05	3.13	3.13	3.13	3.13
47.15	2.32	2.55	2.75	2.95
51.25	1.53	2.68	3.68	4.68
54.67	0.86	2.79	4.45	6.12
57.40	0.37	2.87	5.07	7.27
60.13	0.11	2.96	5.69	8.42
61.50	0.11	3.00	6.00	9.00

A.3 Platform damping ratios

Background research relevant to section 3 and the possible benefits to the semi-submersible with a VSVP-S control system are presented here. To initially analyse the difference in the platform pitch damping of the semi-submersible platform, the damping ratios of the semi-submersible platform coupled to turbines with pitch-to-feather and pitch-to stall control were derived using equations A-1 to A-4 (Jonkman 2007).

$$\zeta_x = C_x / (2\sqrt{K_x M_x}) \quad [\text{Eq A-1}]$$

where, ζ_x is the platform pitch damping ratio, C_x is the damping coefficient (N/(m/s)), K_x is the stiffness coefficient (N/m), and M_x is the effective mass coefficient (kg).

$$C_x = ((B_R + B_{55})/L_{HH}^2) + (dT/dv) \quad [\text{Eq A-2}]$$

where, B_R represents the damping with respect to the pitch hydrodynamic radiation ($\text{kg.m}^2/\text{s}^2$), B_{55} represents the linearized damping with respect to the pitch hydrodynamic viscous drag ($\text{kg.m}^2/\text{s}^2$), L_{HH} is the hub height (m) and dT/dv is the change in thrust with change in wind speed (N/m/s).

NOTE: B_R has been approximated as the amount of linear radiation damping at the platform pitch natural frequency of $\omega_{xn} = 0.037$ Hz as suggested by Jonkman (2007).

$$K_x = (C_{55} + C_{lines})/L_{HH}^2 \quad [\text{Eq A-3}]$$

where, C_{55} is the pitch hydrostatic restoring (Nm/rad) and C_{lines} is the linearized hydrostatic restoring of the mooring lines in pitch (Nm/rad).

$$M_x = (I_{55} + A_{55})/L_{HH}^2 \quad [\text{Eq A-4}]$$

I_{55} is the pitch inertia with respect to the combined turbine and platform masses (kg.m^2), and A_{55} is the added mass with respect to the pitch hydrodynamic radiation (kg.m^2).

The thrust sensitive to changes in wind speed has been derived by two methods as detailed by Jonkman (2007). The method identified as the ‘ideal closed loop’ in Tables A-1 and A-2, derives the change in thrust seen with steady winds at 1 m/s incremental steps. Hence, no value are derived at either the initial cut-in wind speed of 3 m/s or the cut-out speed of 25 m/s. The term ‘ideal’ is used as the blade pitch controller actually uses the rotor speed change rather than the wind speed change used in the platform pitch damping ratio analysis. The ‘open loop’ values have been derived from linearization in FAST v8 with AeroDyn 15, performed with a steady wind speed for each incremental wind speed change. The linearization method requires the specific pitch angle and rotor speed to be provided for each wind speed, which was derived from the steady wind

simulations used to obtain the 'ideal closed loop' values. Further details of both the open and closed loop methods are presented in Jonkman (2007). More information on the other specific elements required to obtain the platform pitch damping ratios can be found in the definition of the OC4 Phase II semi-submersible system (Robertson et al 2014).

Table A-2. Damping ratios with respect to the thrust sensitivity to wind changes for both open loop and ideal closed loop blade pitch controllers as applied to the 'Feather Base Model'.

X-direction wind velocity	Feather dT/dv Open Loop	Feather - Open Loop	Feather dT/dv Ideal Closed Loop	Feather - Ideal Closed Loop
(m/s)	(N/m/s)	ζ_x	(N/m/s)	ζ_x
3	5.62E+04	1.32E-01		
4	5.76E+04	1.35E-01	4.79E+04	1.17E-01
5	5.96E+04	1.39E-01	5.67E+04	1.33E-01
6	6.24E+04	1.44E-01	6.52E+04	1.49E-01
7	6.60E+04	1.51E-01	7.45E+04	1.67E-01
8	6.95E+04	1.58E-01	8.94E+04	1.95E-01
9	7.80E+04	1.74E-01	1.04E+05	2.24E-01
10	8.64E+04	1.90E-01	1.03E+05	2.22E-01
11	8.48E+04	1.87E-01	5.26E+03	3.53E-02
12	9.37E+04	2.04E-01	-8.53E+04	-1.37E-01
13	9.38E+04	2.04E-01	-6.78E+04	-1.04E-01
14	9.33E+04	2.03E-01	-4.48E+04	-6.00E-02
15	9.29E+04	2.02E-01	-3.36E+04	-3.87E-02
16	9.21E+04	2.01E-01	-2.67E+04	-2.55E-02
17	9.14E+04	1.99E-01	-2.17E+04	-1.60E-02
18	9.23E+04	2.01E-01	-1.79E+04	-8.79E-03
19	9.24E+04	2.01E-01	-1.50E+04	-3.26E-03
20	9.06E+04	1.98E-01	-1.28E+04	9.10E-04
21	8.89E+04	1.95E-01	-1.11E+04	4.21E-03
22	8.84E+04	1.94E-01	-9.62E+03	6.99E-03
23	8.86E+04	1.94E-01	-8.36E+03	9.39E-03
24	8.87E+04	1.94E-01	-7.29E+03	1.14E-02
25	8.83E+04	1.93E-01		

The semi-submersible platform pitch damping ratios for both feather and stall are presented in Figure A-3. Below rated the open loop predictions (shown in blue as a solid line for feather and a broken line for stall) are identical, regardless of the control type. This is as no pitch control is implemented at these lower wind speeds. When the blade is pitched to feather to shed power as the wind

increases, the open loop damping ratio remains fairly constant at approximately 0.2. However, with active pitch-to-stall control, there is an initial drop directly after the rated wind speed is exceeded. This takes the open loop damping ratio down to 0.05 at 13 m/s. It then remains steady until cut out at a wind speed of 25 m/s.

Table A-3. Damping ratios with respect to the thrust sensitivity to wind changes for both open loop and ideal closed loop blade pitch controllers as applied to the 'Pitch-to-Stall Model'.

X-direction wind velocity	Stall dT/dv Open Loop	Stall - Open Loop	Stall dT/dv Ideal Closed Loop	Stall - Ideal Closed Loop
(m/s)	(N/m/s)	ζ_x	(N/m/s)	ζ_x
3	5.62E+01	1.32E-01		
4	5.76E+01	1.35E-01	4.79E+04	1.17E-01
5	5.96E+01	1.39E-01	5.67E+04	1.33E-01
6	6.24E+01	1.44E-01	6.52E+04	1.49E-01
7	6.60E+01	1.51E-01	7.45E+04	1.67E-01
8	6.95E+01	1.58E-01	8.94E+04	1.95E-01
9	7.80E+01	1.74E-01	1.04E+05	2.24E-01
10	8.64E+01	1.90E-01	1.03E+05	2.22E-01
11	8.48E+01	1.87E-01	1.96E+05	3.99E-01
12	3.51E+01	9.21E-02	1.73E+05	3.54E-01
13	1.42E+01	5.23E-02	3.57E+04	9.32E-02
14	1.34E+01	5.08E-02	1.29E+04	4.99E-02
15	1.29E+01	4.98E-02	-3.85E+03	1.80E-02
16	1.37E+01	5.13E-02	-2.02E+04	-1.31E-02
17	1.53E+01	5.44E-02	-2.53E+04	-2.29E-02
18	1.69E+01	5.74E-02	-8.89E+03	8.38E-03
19	1.77E+01	5.90E-02	1.50E+04	5.39E-02
20	1.62E+01	5.62E-02	2.63E+04	7.53E-02
21	1.51E+01	5.41E-02	3.26E+04	8.74E-02
22	1.36E+01	5.13E-02	3.97E+04	1.01E-01
23	1.22E+01	4.85E-02	4.32E+04	1.07E-01
24	1.14E+01	4.69E-02	4.50E+04	1.11E-01
25	1.01E+01	4.46E-02		

The ideal open loop predictions are also identical for both feather and stall control at the lower winds. However, at higher winds the two damping ratio prediction methods vary greatly. For the feather system an initial drop occurs, resulting in a negative damping of nearly -0.15. This then slowly rises to become positive again

at a wind speed of 20 m/s and then remains just above zero until 24 m/s. The stall configuration has an opposite effect initially, due to the increased rotor thrust seen in this region as shown in Figure 3.4(b) within section 3.4.1. This then drops gradually until it falls just below zero between 16 and 18 m/s wind speeds, then rises again to just above 0.1 by the time 24 m/s winds are reached. The actual damping ratios for both systems can be expected to be somewhere in between those found from both the open and ideal closed loops, however this contains a large range of possible values.

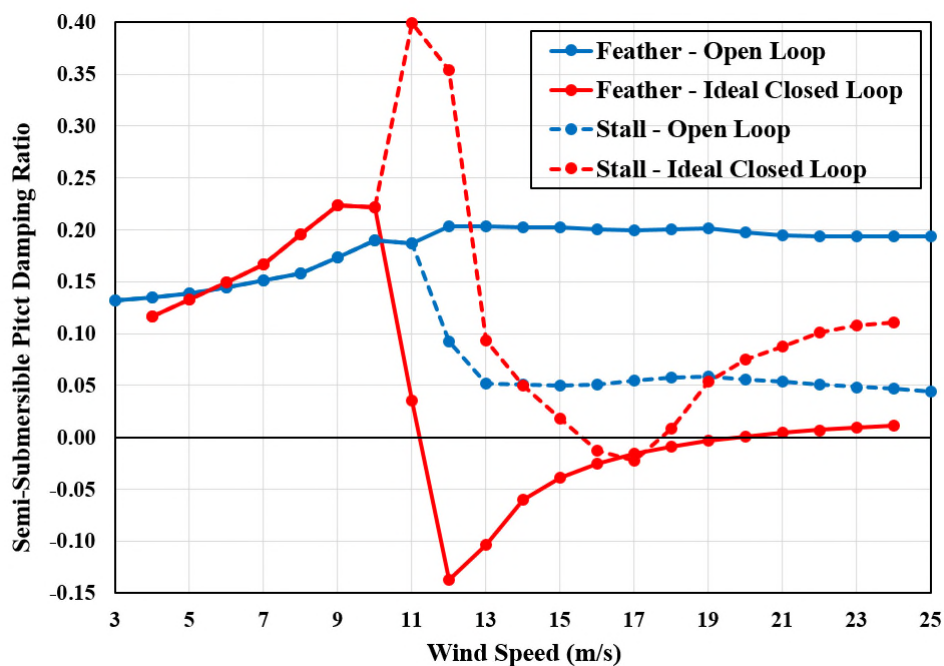


Figure A-3 Platform pitch damping ratios for the semi-submersible floating platform relative to the 'Feather Base Model' and Pitch-to-Stall Model', where the solid line is the damping for the feather system and the broken line is the damping of the stall system

Jonkman (2007) found that the stall configuration for a barge floating platform, as shown in Figure A-4 for easy comparison, gave a lower damping ratio at winds above 15 m/s than when feather control was initialized. This was confirmed by the increased response of the barge platform pitch at a mean turbulent wind of 18 m/s. However, for the semi-submersible, this is likely to only be applicable for a small range of wind speeds around 16 to 18 m/s. Therefore, as the frequency

of occurrence is much lower for winds around 18 m/s than for those around rated and below; an overall fatigue reduction is expected.

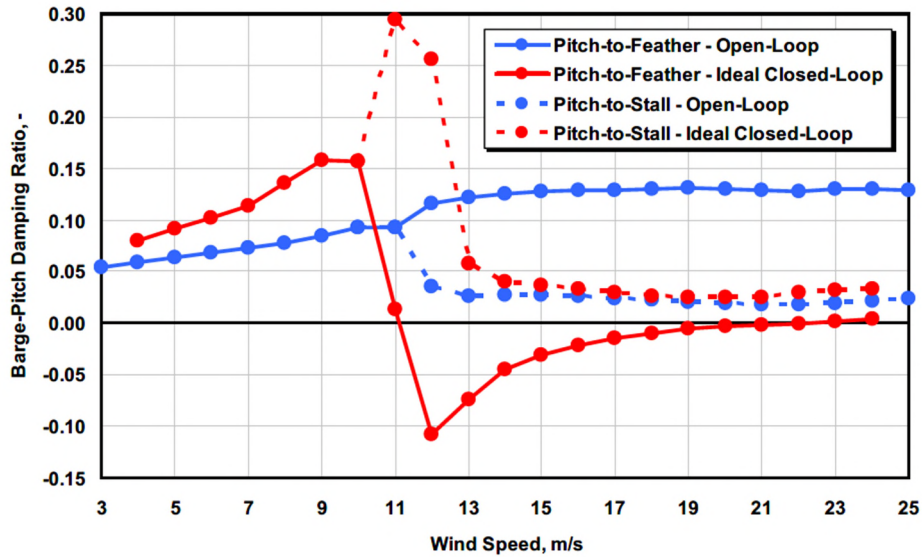


Figure A-4 Platform pitch damping ratios with pitch-to-feather and pitch-to-stall active blade pitch control for the barge FOWT (Jonkman J 2007).

A.4 Wind and wave seeds and simulation time

Simulation lengths and wind and wave seed number analysis prior to the selection utilized within section 3 are presented here. To validate the selection of three individual simulations in terms of varying random wind and wave seeds (while retaining three hours in lengths for each) a comparison study was conducted against the more standard use of six times one-hour simulations. The use of three hour simulations for the fatigue analysis of FOWTs was seen to be preferable, due to more variation in the responses of FOWTs with time, compared to fixed base turbines. Each of the simulations presented had a mean turbulent wind of 18 m/s, a significant wave height of 4.5 m and a spectral peak period of 10 s. To ensure transient responses were avoided, the first 300 s of each simulation was also discarded. Tables A-4 and A-5 present the results of six simulations, each one hour in length and each with a different set of random wind and wave seeds. The values within Table A-4 are with feather control and those presented in Table A-5 are for stall control. The average tower base axial fatigue

life from all the simulations for each control type were then compared against their respective averages from three times three-hour simulations, as presented in Table A-6 for feather and Table A-7 for stall. The results from both methods were within 0.35% for feather control, and 0.91% for stall control. Therefore, the use of three times three-hour simulations was validated.

Table A-4. Variability in the tower axial fatigue life of the pitch-to-feather with 1 hr wind and wave seed simulations

	Feather T0 v18 1hr WS1	Feather T0 v18 1hr WS2	Feather T0 v18 1hr WS3	Feather T0 v18 1hr WS4	Feather T0 v18 1hr WS5	Feather T0 v18 1hr WS6	Average of 6 x 1hr sims
Tower Base Axial Fatigue Life (days)	10584	10744	11174	10282	11984	11246	11003
Tower Base Axial Fatigue Life (years)	29.0	29.4	30.6	28.2	32.8	30.8	30.14
Variable from the Averaged Fatigue Life	-3.80	-2.35	1.56	-6.55	8.92	2.22	

Table A-5. Variability in the tower axial fatigue life of the pitch-to-stall with 1 hr wind and wave seed simulations

	Stall T0 v18 1hr WS1	Stall T0 v18 1hr WS2	Stall T0 v18 1hr WS3	Stall T0 v18 1hr WS4	Stall T0 v18 1hr WS5	Stall T0 v18 1hr WS6	Average of 6 x 1hr sims
Tower Base Axial Fatigue Life (days)	6193	7081	6529	6569	6855	5859	6514
Tower Base Axial Fatigue Life (years)	17.0	19.4	17.9	18.0	18.8	16.1	17.85
Variable from the Averaged Fatigue Life	-4.93	8.69	0.22	0.84	5.23	-10.06	

Table A-6 Variability in the tower axial fatigue life of the pitch-to-feather with 3 hr wind and wave seed simulations

	Feather T0 v18 3hr WS1	Feather T0 v18 3hr WS2	Feather T0 v18 3hr WS3	Average of 3 x 3hr sims
Tower Base Axial Fatigue Life (days)	10593	11227	11071	10964
Tower Base Axial Fatigue Life (years)	29.02	30.76	30.33	30.04
Variable from the Averaged Fatigue Life	-3.39	2.40	0.98	

Table A-7. Variability in the tower axial fatigue life of the pitch-to-stall with 3 hr wind and wave seed simulations.

	Stall T0 v18 3hr WS1	Stall T0 v18 3hr WS2	Stall T0 v18 3hr WS3	Average of 3 x 3hr sims
Tower Base Axial Fatigue Life (days)	6384	6823	6160	6455
Tower Base Axial Fatigue Life (years)	17.5	18.7	16.9	17.69
Variable from the Averaged Fatigue Life	-1.10	5.69	-4.58	

A.5 References

Jonkman J (2007) Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine; Technical Report: NREL/TP-500-41958, National Renewable Energy Laboratory, USA.

Robertson A, Jonkman J, Masciola M, Song H, Goupee A, Coulling A, Luan C (2014) Definition of the Semisubmersible Floating System for Phase II of OC4. Technical Report: NREL/TP-5000-60601, National Renewable Energy Laboratory, USA.

Ward D, Collu M, Sumner J (2019) Reducing Tower Fatigue through Blade Back Twist and Active Pitch-to-Stall Control Strategy for a Semi-Submersible Floating Offshore Wind Turbine. *Energies* 2019, 12, 1897, Switzerland. doi: 10.3390/en12101897

Appendix B Supplementary Material - Paper 2

Appendix B contains supplementary data relating to the second paper, 'Analysis of the effect of a series of back twist blade configurations for an active pitch-to-stall floating offshore wind turbine'. This includes additional detail on the blade twists (section B.1) and the tower axial fatigue life at each wind speed (section B.2).

B.1 Blade twists

Details of the blade twists analysed in Paper 2, are provided here. Table B-1 presents the 'original blade twist' of the feather configuration (Jonkman 2007) and the 12 back twists imposed on the stall controlled turbine.

Table B-1. Semi-submersible blade twist profiles presented in section 4

Blade Span from the Root	Original Blade Twist	Stall Back Twist Model 1	Stall Back Twist Model 2	Stall Back Twist Model 3	Stall Back Twist Model 4	Stall Back Twist Model 5	Stall Back Twist Model 6	Stall Back Twist Model 7	Stall Back Twist Model 8	Stall Back Twist Model 9	Stall Back Twist Model 10	Stall Back Twist Model 11	Stall Back Twist Model 12
(m)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)
0.00	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31
1.37	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31
4.10	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31
6.83	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31
10.25	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31	13.31
14.35	11.48	11.48	11.48	11.48	11.48	11.48	11.48	11.48	11.48	11.48	11.48	11.48	11.48
18.45	10.16	10.16	10.16	10.16	10.16	10.16	10.16	10.16	10.16	10.16	10.16	10.16	10.16
22.55	9.01	9.01	9.01	9.01	9.01	9.01	9.01	9.01	9.01	9.01	9.01	9.01	9.01
26.65	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80
30.75	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54	6.54
34.85	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36	5.36
38.95	4.19	4.19	4.19	4.19	4.19	4.19	4.19	4.19	4.19	4.19	4.19	4.19	4.19
43.05	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13
47.15	2.32	2.55	2.32	2.32	2.75	2.32	2.32	2.95	2.32	2.32	3.15	2.32	2.32
51.25	1.53	2.68	1.53	1.53	3.68	1.53	1.53	4.68	1.53	1.53	5.68	1.53	1.53
54.67	0.86	2.79	1.25	0.86	4.45	1.58	0.86	6.12	1.91	0.86	7.79	2.25	0.86
57.40	0.37	2.87	1.95	0.64	5.07	3.35	0.88	7.27	4.75	1.12	9.47	6.15	1.37
60.13	0.11	2.96	2.65	2.21	5.69	5.12	4.29	8.42	7.58	6.37	11.16	10.05	8.46
61.50	0.11	3.00	3.00	3.00	6.00	6.00	6.00	9.00	9.00	9.00	12.00	12.00	12.00

B.2 Tower axial fatigue life at each wind speed

The average tower axial fatigue life utilised within Paper 2, are provided here. Table B-2 presents the tower axial fatigue life seen at each mean turbulent wind speed for each of the 12 back twist models analysed within section 4. This data along with the wind frequencies presented in Table 4-2 of section 4 was used to derive the weighted values seen in Table 4-3.

Table B-2. Tower axial fatigue life for each back twist model at mean turbulent wind speeds of 8, 13 and 18 m/s.

Test ID for semi-submersible variable-speed variable-pitch-to-stall models	BT 1	BT 2	BT 3	BT 4	BT 5	BT 6	BT 7	BT 8	BT 9	BT 10	BT 11	BT 12
Initiation point along the blade, measured from the root (%)	75.0	87.5	92.8	75.0	87.5	92.8	75.0	87.5	92.8	75.0	87.5	92.8
Back twist angle at the tip (°)	-3	-3	-3	-6	-6	-6	-9	-9	-9	-12	-12	-12
Total weighted tower axial fatigue life for each scenario (years)	27.6	26.8	26.3	28.1	27.2	26.6	28.3	27.4	26.8	28.6	27.8	27.0
Tower axial fatigue life change from 'Semi-sub Feather Base Model' (%)	8.3	5.1	3.1	10.2	6.5	4.1	11.0	7.5	4.9	12.1	8.8	5.9
Total generator power average for each scenario (kW)	1901	1907	1899	1888	1894	1895	1865	1884	1888	1836	1871	1880
Average generated power change from 'Feather Base Model' (%)	-0.5	-0.1	-0.5	-1.1	-0.8	-0.8	-2.4	-1.4	-1.2	-3.9	-2.0	-1.6

* (+ve number means a longer tower life)

B.3 References

Jonkman J (2007) Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine; Technical Report: NREL/TP-500-41958, National Renewable Energy Laboratory, USA.

Ward D, Collu M, Sumner J (2020) Analysis of the effect of a series of back twist blade configurations for an active pitch-to-stall floating offshore wind turbine. J. Offshore. Mech. Arct. Eng. 2020, USA. doi: 10.1115/1.4046567

Appendix C Supplementary material - Paper 3

Appendix C contains supplementary data relating to the third paper, 'Back twisted, active pitch-to-stall blade for floating offshore wind turbine tower damping'. This includes additional detail on the spar platform (section C.1) and the blade twists (section C2).

C.1 Spar platform

Paper 3, makes reference to a spar platform; more detail on this platform is provided here. Figure C-1 depicts the OC3 Hywind spar when coupled to the 5 MW NREL HAWT (Xu & Srinil 2015).

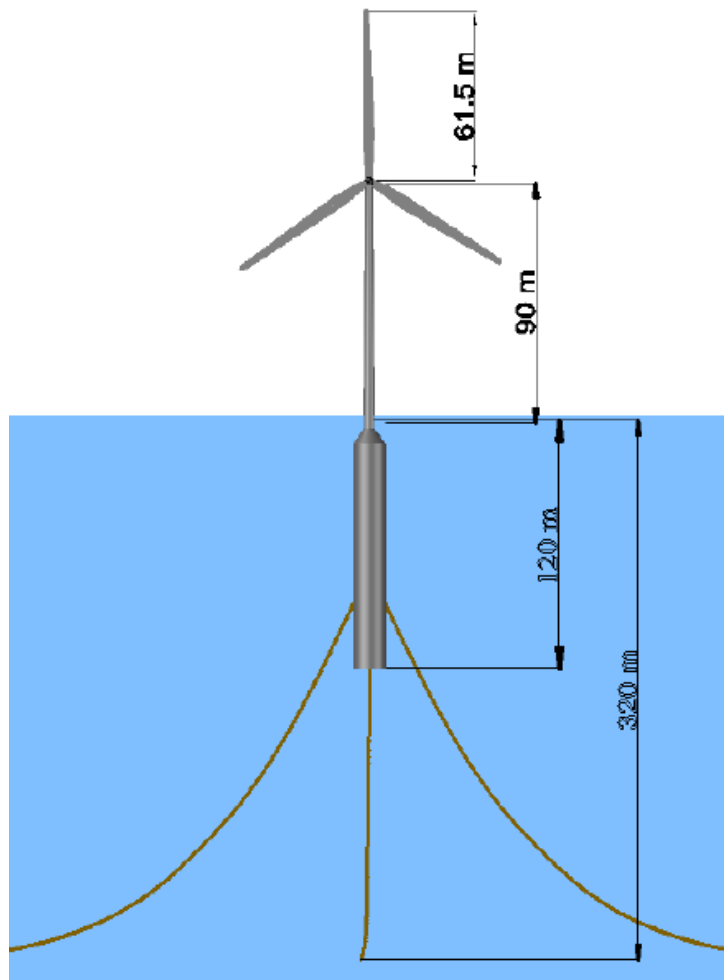


Figure C-1. Spar platform couple to the 5 MW NREL HAWT (Xu & Srinil 2015).

C.2 Blade twists

The blade twists analysed in Paper 3, are presented here. The blade twist profiles used within the study presented in section 5 can be found in Table C-1. The six back twisted blades are the same for both the spar and the semi-submersible platforms. The 'original blade twist' is that utilized by the feather configuration (Jonkman 2007). These back twist profiles also correspond to the stall back twist models one to six seen in Table B-1 of Appendix B, as part of the supplementary material for the study presented in Paper 2, as laid out in section 4.

Table C-1. Blade twist profiles for both the spar and semi-submersible floating platform configurations presented in section 5.

Blade Span from the Root	Original Blade Twist	Back Twist 1	Back Twist 2	Back Twist 3	Back Twist 4	Back Twist 5	Back Twist 6
(m)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)	(deg)
0.00	13.31	13.31	13.31	13.31	13.31	13.31	13.31
1.37	13.31	13.31	13.31	13.31	13.31	13.31	13.31
4.10	13.31	13.31	13.31	13.31	13.31	13.31	13.31
6.83	13.31	13.31	13.31	13.31	13.31	13.31	13.31
10.25	13.31	13.31	13.31	13.31	13.31	13.31	13.31
14.35	11.48	11.48	11.48	11.48	11.48	11.48	11.48
18.45	10.16	10.16	10.16	10.16	10.16	10.16	10.16
22.55	9.01	9.01	9.01	9.01	9.01	9.01	9.01
26.65	7.80	7.80	7.80	7.80	7.80	7.80	7.80
30.75	6.54	6.54	6.54	6.54	6.54	6.54	6.54
34.85	5.36	5.36	5.36	5.36	5.36	5.36	5.36
38.95	4.19	4.19	4.19	4.19	4.19	4.19	4.19
43.05	3.13	3.13	3.13	3.13	3.13	3.13	3.13
47.15	2.32	2.55	2.32	2.32	2.75	2.32	2.32
51.25	1.53	2.68	1.53	1.53	3.68	1.53	1.53
54.67	0.86	2.79	1.25	0.86	4.45	1.58	0.86
57.40	0.37	2.87	1.95	0.64	5.07	3.35	0.88
60.13	0.11	2.96	2.65	2.21	5.69	5.12	4.29
61.50	0.11	3.00	3.00	3.00	6.00	6.00	6.00

C.3 Performance characteristics in turbulent winds

Turbine responses to highlight the performance differences between the 'Spar Feather Base Model' and the 'Pitch-to-Stall BT4 Model' are presented in Figure C-2. These were generated when all the DOF were enabled.

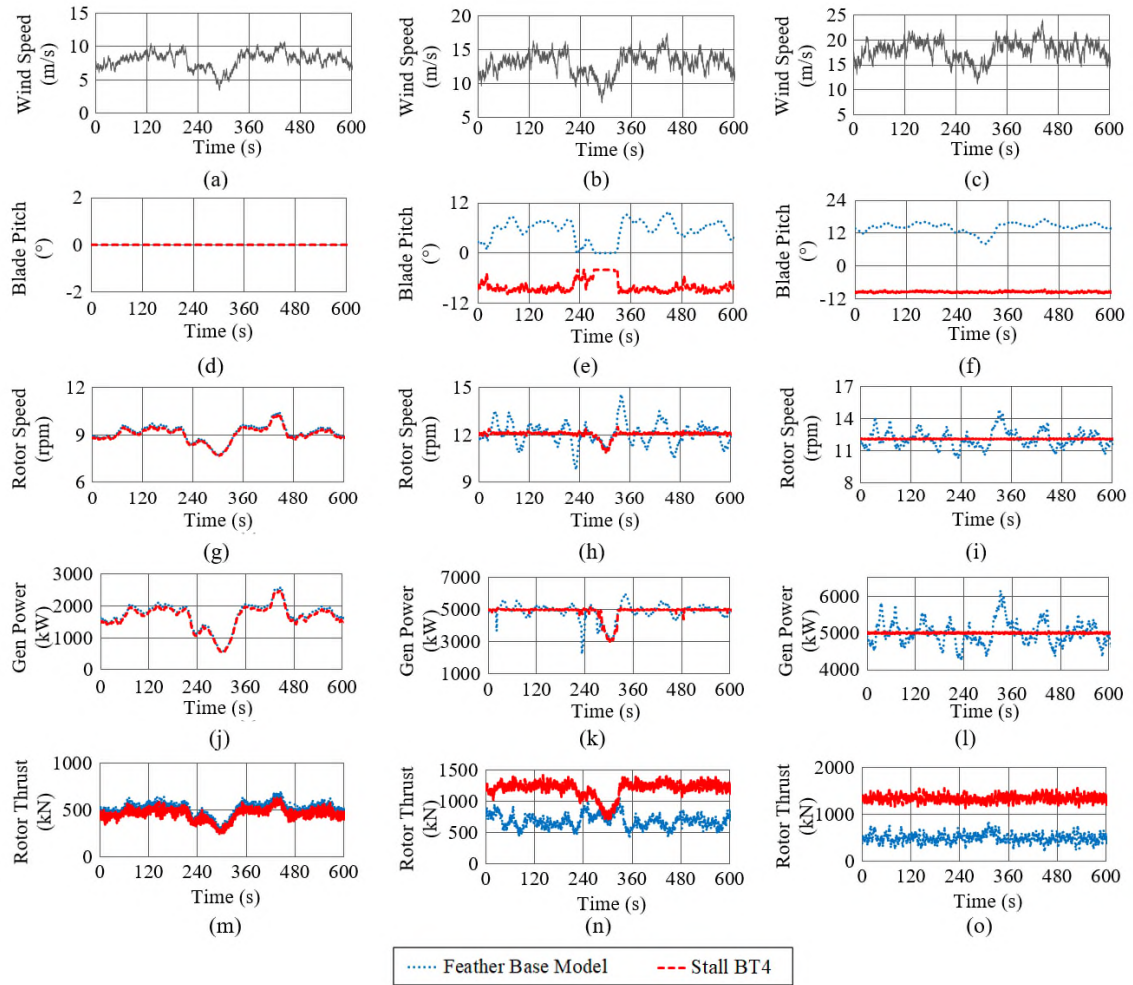


Figure C-2. Simulation outputs for pitch-to-feather and pitch-to-stall blade with back twist at 8 (left), 13 (centre), and 18 m/s (right) mean turbulent winds.

For the pitch-to-feather system, utilizing the spar platform, the maximum rotor speed is over 23% higher than the nominal rotor speed, when operating in mean turbulent winds of 18 m/s (Figure C-2(i)). At the same mean turbulent wind the rotor speed variance was reduced to just 1% higher than the nominal by the introduction of the stall back twist model. A similar pattern was also seen in the power generated at 18 m/s winds, with the stall providing a very smooth output within 1% of the nominal at all times, compared to a maximum nearly 24% higher than the nominal when the spar is under pitch-to-feather control (Figure C-2(l)).

C.4 References

Jonkman J (2007) Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine; Technical Report: NREL/TP-500-41958, National Renewable Energy Laboratory, USA.

Ward D, Collu M, Sumner J (2020a) Analysis of the effect of a series of back twist blade configurations for an active pitch-to-stall floating offshore wind turbine. J. Offshore. Mech. Arct. Eng. 2020, USA. doi: 10.1115/1.4046567

Ward D, Collu M, Sumner J (2020b) Back twisted, active pitch-to-stall blade for floating offshore wind turbine tower damping. Submitted on the 8th March 2020 to the J. Offshore. Mech. Arct. Eng. USA

Xu X, Srinil N (2015) Dynamic response analysis of spar-type floating wind turbines and mooring lines with uncoupled vs coupled models. In ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering, USA. doi: 10.1115/OMAE2015-41512