Master's Thesis:
Aeroservoelastic Stability of Floating Offshore Reference Wind Turbine

Project Plan

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Contents

1 Learning objectives

The learning objectives of the MSc project comply with the shared academic goals for learning outcome of the MSc Eng programme and the programme specific goals of learning outcome of the Master of Science in Engineering (Wind Energy) that are suggested by DTU. The learning objectives are listed below:

- Identify and reflect on technical scientific issues of floating offshore wind turbines and understand the interaction between the various components of the issue, through aero-servo-elastic analysis;
- Apply elements of current international research in floating wind energy to develop ideas and solve the identified problems;
- Master technical scientific methodologies, theories and simulation tools relative to aero-servo-elasticity of wind turbines; develop the capacity to put a complex technical issue into a broader academic and societal perspective, and propose a variety of solutions;
- Develop, via analysis and modelling, relevant models, systems and processes for solving technological problems;
- Communicate and mediate research-based knowledge both orally (during weekly meetings with project stakeholders and collaborators and during the dissertation of the MSc Project) and in writing (when writing the Project Plan and the MSc Project Report);
- Develop the ability to work independently and reflect on own learning, academic development and specialization thanks to the high level of independence that characterises the project;
- Master technical problem-solving at a high level, and have the capacity to work with and manage all phases of a project - including preparation of timetables, design, solution and documentation;
- Discuss technological issues with various types of stakeholder thanks to the collaboration with specialized researchers in different fields from DTU Wind Energy department at Risø, the National Renewable Energy Laboratory (NREL) in Colorado (USA), and a peer-collaboration with an online MSc student.
- Develop an in-depth knowledge of the use of aerodynamics, structural dynamics, controls and hydrodynamics thanks to the interdisciplinary nature of the MSc project;
- Simulate and analyze the performance of a wind turbine in a floating offshore configuration;
- Combine knowledge from different technical interdisciplinary professional areas thanks to the topic nature and the collaboration with stakeholders specialized in different scientific areas;
- Establish the baseline behaviour of an offshore controller, identify weaknesses and issues, improve the controller logic, and evaluate the efficacy of the improvements.

2 Summary of the project

The IEA 15 MW [1] is a reference wind turbine model that was created to develop and test the next generation of technologies for wind turbines of the future. This master's project, which is a collaboration between DTU and NREL, evaluates the stability of the IEA 15 MW when mounted on the UMaine semisubmersible platform [2]. The platform model is implemented in HAWC2 [3], and the turbine is controlled using both NREL's ROSCO controller [4] and the DTU WEC controller [5]. The performance of the closed-loop system is evaluated in terms of stability and loads. Depending on the results of the analysis, the controller(s) will be updated to improve the performance of the turbine.

3 State of the art

3.1 Floating offshore wind turbines

In the current years, floating offshore wind turbines (FOWT) are becoming an attractive solution for offshore wind energy, as an alternative to fixed-bottom turbines. One of their major advantage is that FOWT can be installed at water depths larger than 50 m, where fixed-bottom solutions become economically unfeasible [6]. This makes it possible for FOWT to harness a very good wind resource, with high mean winds and low turbulent intensity. Furthermore, other advantages include low environmental and visual impact, more space availability, less sensitivity to site-specific constraints (such as water depth) [7].

One of the characterizing properties of floating platforms is static stability, which allows for the FOWT to counteract the overturning moments due to aerodynamic loads. The restoring moment can be expressed as the sum of three contributions [8]: the waterplane area contribution, the ballast contribution and the mooring system contribution, indicated respectively in red, blue and green in Equation 1.

$$\frac{\mathrm{M_R}}{\theta} = \rho \mathrm{g I_{WP}} + (\mathrm{F_B z_B} - \mathrm{mgz_G}) + \mathrm{F_{moor}} \tag{1}$$

where θ is the displacement caused by the overturning moment; ρ and g are respectively the water density and the gravitational constant; $\mathrm{I_{WP}}$ is the second moment of the waterplane area; $\mathrm{F_B}$ is the buoyancy force that is opposed to mg, the weight of the system; $\mathrm{z_B}$ and $\mathrm{z_G}$ are respectively the vertical coordinates of the center of buoyancy and of the center of gravity; finally the $\mathrm{F_{moor}}$ is the contribution of the mooring system, which is computed after imposing a minimum stiffness requirement on the support structure [9].

In Figure 1, the 6 degrees of freedom (DOFs) of a FOWT are represented. They consist of 3 translational motions and 3 rotations. The restoring force of Equation 1 can be written for both the roll and the pitch DOFs. As seen further in the section, the pitch motion is of particular interest for FOWT stability.

As presented in [7], the main types of floaters are the barge, the tension-leg platform (TLP), the spar-buoy and the semisubmersible; a schematic representation is displayed in Figure 2. They are classified depending on which of the three terms of Equation 1 prevails when achieving static stability [10]. The barge is a buoyancy-stabilized support structure; it has a rectangular shape and a shallow draft that accounts for a large waterplane area. The spar buoy presents a long, slender cylinder that presents a heavy ballast at the bottom; in this way, the center of gravity is lowered and the distance between the center of gravity and the center of buoyancy is increased, making the

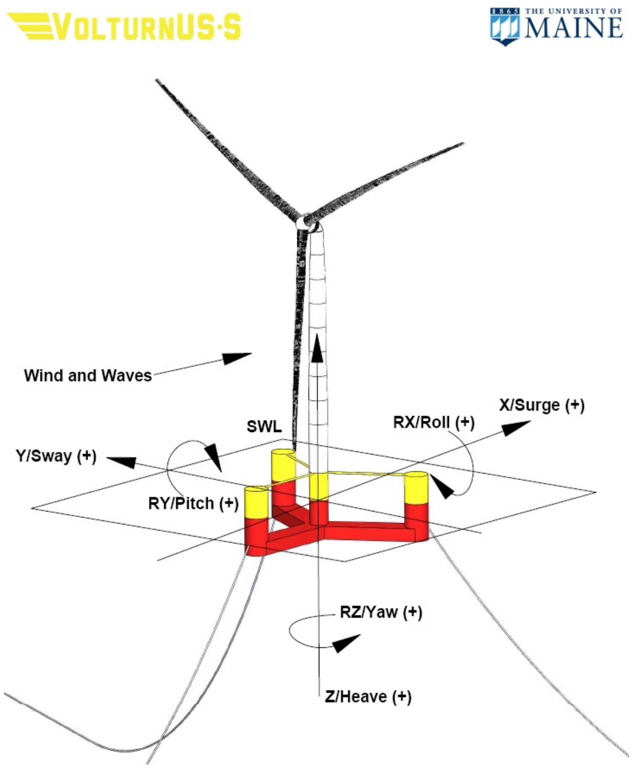


Figure 1. Coordinate system and degrees of freedom of a floating offshore wind turbine. Figure from [2].

spar-buoy a ballast-stabilized floater. The spar-buoy has the advantage of ease of manufacturing, but it has a water depth constraint, so it can only be installed in deeper waters [7]. The TLP is a mooring-stabilized structure; it is designed with an excess of buoyancy so that the mooring system is always in tension. Such system gives the design high rigidity and this support structure can be critical for stability [11]. The semisubmersible is a hybrid: it achieves stability through a large waterplane area, plus it has three or four cylinders (depending on the design) connected by struts that present ballast weights at their base [10], [2]. At the bottom of the columns, there are heave plates that increase damping and introduce added mass to the system, which modifies the system's natural frequency in the vertical direction [11]. The shallow structure of the barge and the semisubmersible allows them to be a versatile solution for a wide range of water depths.

Mooring system

The mooring system's primary function is to keep the floater in place, preventing it from floating away under external forcing. It is composed of mooring lines that connect the platform to the sea bed, on which they are fixed by anchors. Additional equipment might be installed on the mooring lines if necessary such as clump weights, whose aim is to reduce the vertical loads on the anchors as well as mooring line vibrations, while adding extra restoring force [13], and buoys, that are useful for lifting the mooring line from the sea bed if there is an obstacle to avoid [13].

There are different types of mooring lines [14]:

- The catenary line, which is typically in steel chain and provides restoring effect from lifting and resting a portion of line in the sea bed.

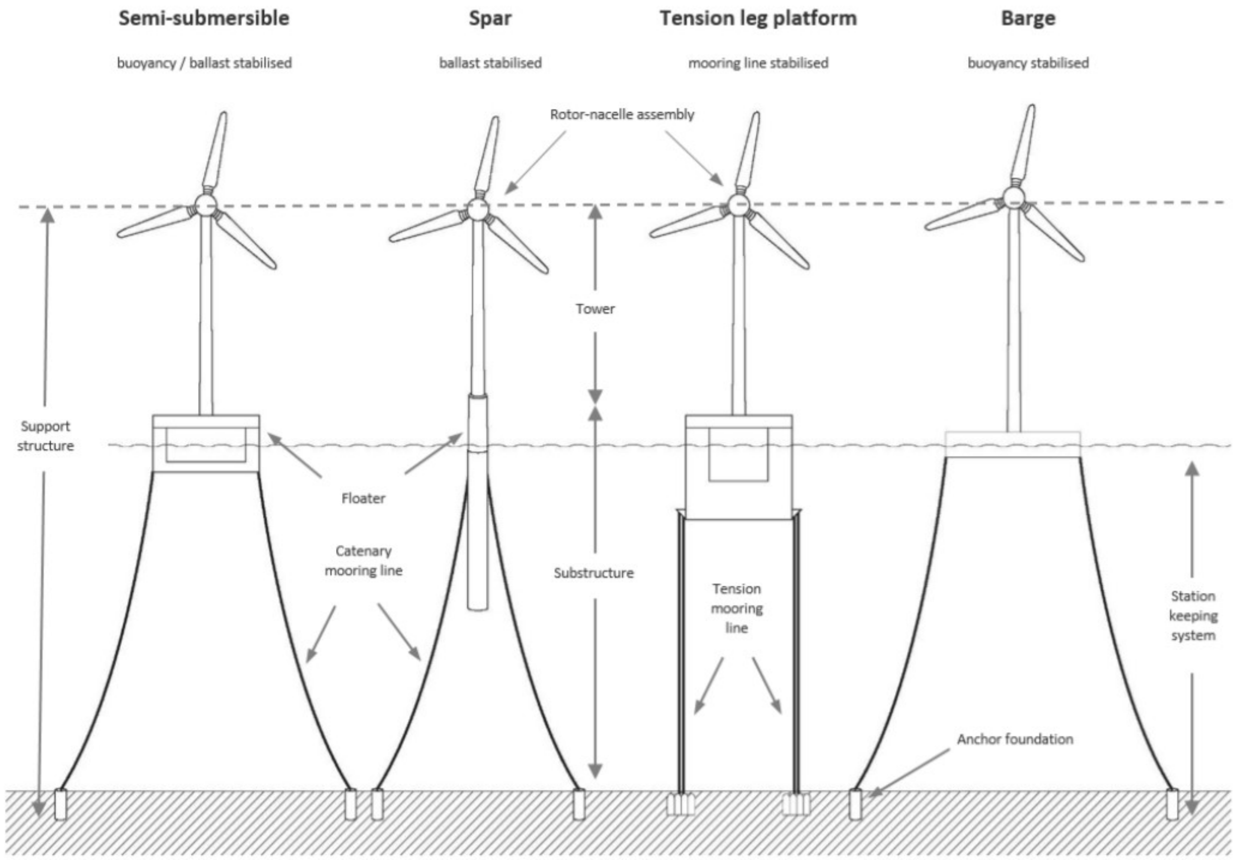


Figure 2. Types of floaters and nomenclature of the support structure. Figure from [12].

- The taut line is made of synthetic ropes and achieves restoring via elastic deformation of the ropes;
- The tension leg is typically in steel cables and is used in TLP, the restoring force comes from elastic deformation of the cables but it is critical for stability.

There are also different types of anchors depending on the type of soil and the water depth, and they are classified by how they anchor to the sea bed [14]:

- The dead weight is gravity based;
- The pile is a slender cylinder that is hammered into the sea bed;
- The drag-embedded anchor relies on the drag force between the sand and the anchor
- The suction anchor has a cylindrical shape and inside vacuum is generated
- The gravity-installed pile
- The vertical load anchor

The mooring dynamic model is usually inclusive of the inertial loads from its mass, hydrodynamic loads, seabed friction and buoyancy. It provides restoring forces to the FOWT and damping to surge, sway, and heave modes of the floater [15].

Aerodynamic loads

A wind turbine is able to produce energy extracting it from the incoming wind. The incoming wind produces aerodynamic torque on the blades, that make them turn and allow for energy generation, but it also generates thrust load on the rotor, which is the main trade-off to power production. The thrust has the steady-state characteristic curve displayed in Figure 3. Below rated wind speed, the thrust increases with the square of the wind velocity, until rated wind speed is reached and the pitch controller starts pitching the blade to limit power output; when the blades are pitched, the thrust also decreases. It is important to notice the change in sign of the slope of the thrust curve, from below to above rated, since it will be subject of discussion for the next section.

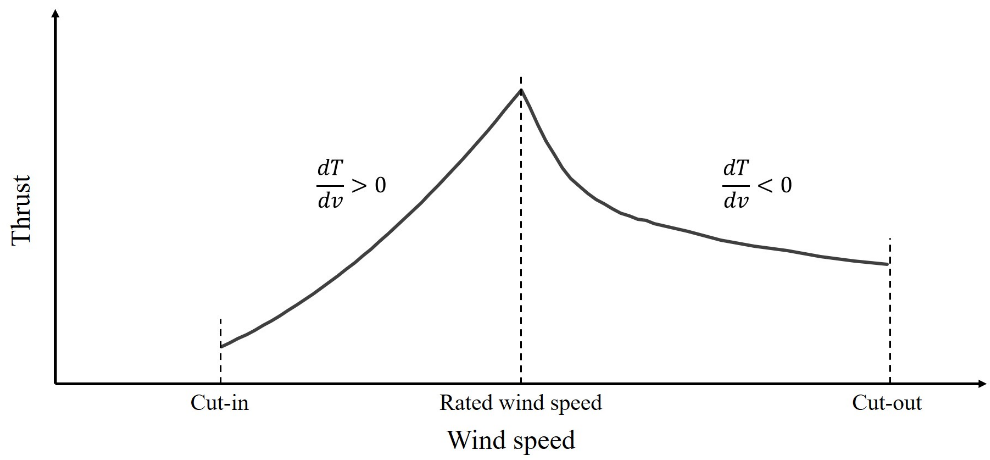


Figure 3. Thrust versus wind speed; the slope of the thrust curve changes from positive below-rated to negative above-rated.

To model a realistic wind field is necessary to include, beside the mean wind speed, turbulence intensity, wind shear and the tower effect as well. All these effects affect the asymmetric loads on the rotor, and have a significant impact on fatigue damage as well.

The aerodynamic loads on the turbine can be calculated based on the local aerodynamics forces acting on the blade. The first aerodynamic model for a wind turbine is attributed to Betz [16], then further developed with the integration of Glauert [17] blade element theory (BEM), that correlates the aerodynamics of the rotor with the local aerodynamics of single blade elements and their geometry. These models have been only a starting point, and further models have been implemented to correctly predict aerodynamics of a turbine such as dynamic stall, tip and hub losses, dynamic inflow and wake corrections [3].

Hydrodynamics loads

The hydrodynamic loads affecting the wind turbine come from waves, buoyancy forces, viscous forces and sea currents. There are two types of wave excitation forces: the diffraction forces and radiation forces. The former are the result of the contribution of incident waves on the structure and scattering (when the floater cannot be considered a slender body); the latter, are a consequence of the radiation waves emitted by the floater as it oscillates in the water, and are actually a loss of energy to the floater, hence providing damping [18]. Furthermore, a component of the hydrostatic forces affecting the floating structure are buoyancy forces, that originate from the displacement of water by the floater. Since the buoyancy is a force always acting in the vertical direction, it affects only heave, roll and pitch DOFs [18]. Viscous forces have an important contribution, since they provide part of the damping to the system. Finally, floaters are also subject to sea currents, that are highly site-dependent and might have seasonal or yearly variations. As suggested by [18], appropriate velocity profiles should be considered to properly estimate the loads substructures have to sustain.

The most basic theory to model waves is the linear wave theory, that identifies two types of waves: regular waves and irregular waves. Regular waves are characterized by a wave height, a wave period and a wave length, and have a Gaussian probability density function (PDF). Irregular waves are formed superimposing several regular waves with different heights, frequencies, and wave lengths, and determine the sea state [18]; they are characterized by a significant wave height, that is the average height of 1/3 of the highest waves in a certain sea state, a wave peak period, that is the frequency at which the waves spectrum has the largest energy content, and a parameter gamma, that represents the shape of the Gaussian PDF of the irregular waves [11]. From the spectrum of irregular waves, the time series of a sea state can be derived, in particular, the free-surface elevation, the wave particle velocity and wave particle acceleration can be computed.

To model the hydrodynamics of a floating substructure, two theories are proposed, based on the shape of the body: the Morison equation is used for slender bodies, when the wave scattering and radiation damping can be neglected; the radiation-diffraction theory is used for more geometrically complex body structures that cause scattering of waves.

The Morison equation (Equation 2) models the hydrodynamic load as the contribution of three terms: the Froude-Krylov term, which accounts for the wave particle acceleration, the hydrodynamic added mass, which is related to the difference between the wave particle acceleration and the structural acceleration of the floater, and the viscous drag, which takes into account the viscous effects on the floater. The three terms are colored in red, blue, green respectively in Equation 2:

$$\mathrm{F_{hydro}} = \int_{\mathrm{z}} \left(\rho \mathrm{A} \dot{\mathrm{u}} + \rho \mathrm{A} \mathrm{C_a} (\dot{\mathrm{u}} - \ddot{\mathrm{x}}) + \frac{1}{2} \rho \mathrm{D} \mathrm{C_d} (\mathrm{u} - \dot{\mathrm{x}}) |\mathrm{u} - \dot{\mathrm{x}}| \right) \mathrm{dz} \tag{2}$$

Where z is the coordinate along the length of the floater; ρ is the water density; $\mathrm{C_a}$ and $\mathrm{C_d}$ are the added mass and drag coefficient respectively; A is the cross-sectional area of the floater and D its diameter; u, $\dot{\mathrm{u}}$, $\dot{\mathrm{x}}$ and $\ddot{\mathrm{x}}$ are the wave particle and structural velocity and acceleration.

For floaters that cannot be considered slender, the linear radiation-diffraction theory is used to compute the hydrodynamic loads. This theory faces the problem splitting it in two contributions, diffraction and radiation, and superimposing their solutions. The diffraction part considers the body as fixed and exposed to the incoming waves with a certain frequency; the radiation part considers the body oscillating with that same frequency in calm water, therefore is the body itself that produces the waves that radiate away from it and provide forcing and damping [18]. Linear radiation-diffraction theory is formulated in frequency domain and assumes potential flow, therefore, viscous effects are commonly added through the Morison viscous drag term [11]. Its final mathematical expression in frequency domain and vector form is:

$$-\omega^2(\mathbf{M} + \mathbf{A}(\omega))\xi + \mathrm{i}\omega\mathbf{B}(\omega)\xi + \mathbf{C}\xi = \mathbf{X}(\omega) \tag{3}$$

Where ω is the wave and body oscillation frequency while ξ is the floating body displacement; $\mathbf{X}$ is the matrix containing diffraction contribution which adds like an external load; $\mathbf{A}$ and $\mathbf{B}$ are the matrices containing radiation contribution, respectively emulating added mass and damping; $\mathbf{C}$ is the hydrostatic term which gives a stiffness contribution.

Once all the external loads have been modelled accordingly to the design of the FOWT, the dynamics of the FOWT are described by the equation of motion (EOM):

$$(\mathbf{M} + \mathbf{A})\ddot{\mathbf{x}} + \mathbf{B}\dot{\mathbf{x}} + \mathbf{C}\mathbf{x} = \mathbf{F}_{\text{hydro}} + \mathbf{F}_{\text{moor}} + \mathbf{F}_{\text{wind}} \tag{4}$$

Where $\mathbf{x}$ is the 6x1 vector formed by the displacements in the 6 DOFs in Figure 1, and $\dot{\mathbf{x}}$, $\ddot{\mathbf{x}}$ its velocity and acceleration.

3.2 Control of floating offshore wind turbines

The control of a wind turbine is primarily oriented to two objectives: maximize the power output below rated wind speed and limit the power production above rated wind speed due to turbine design constraints. The operation of a variable-speed-variable-pitch (VSVP) wind turbine can be divided into three main regions [19] with different control objectives, represented in Figure 4.

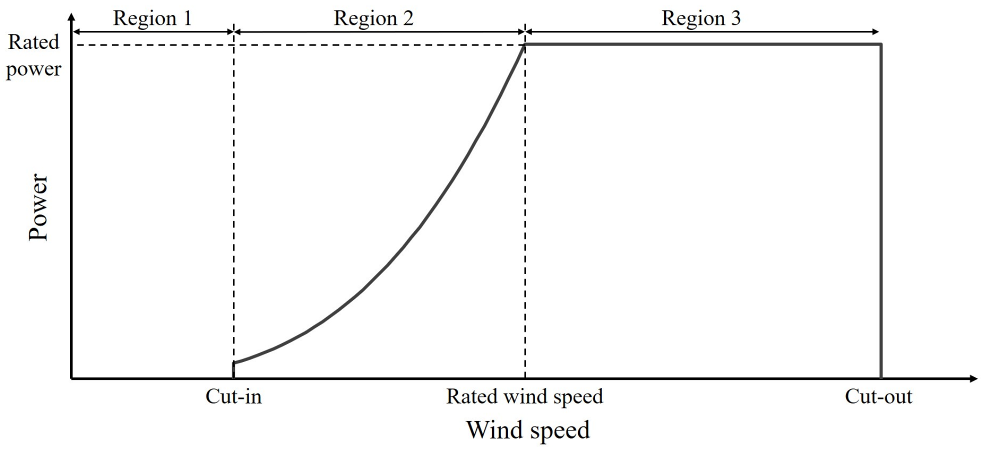


Figure 4. Control regions on power curve of a generic VSVP win turbine.

Region 1 is the operational region below cut-in wind speed, where the turbines are not run because the power available in the wind is low compared to the losses in the turbine.

Region 2 spans from cut-in wind speed to rated wind speed; this is the region where the power output has to be maximized or, more precisely, the power coefficient. The maximum power coefficient $C_{P,max}$ is design-dependant of the turbine and it occurs at a specific tip-speed ratio (λ_{opt}) and pitch angle (θ_{opt}). Hence, in this control region, the pitch angle of the blades is fixed at its optimal value and the rotor speed is regulated in order to achieve optimal tip-speed ratio. The rotor speed in region 2 is regulated by a generator torque controller, which is designed expressing the generator torque τ_g as:

$$\tau_g = K\omega_r^2 \tag{5}$$

where ω_r is the measured rotor speed, that is input in the controller, and the generator constant K is expressed as [20]:

$$K = \frac{1}{2}\rho\pi R^5 \frac{C_{P,max}}{\lambda_{opt}^3} \tag{6}$$

The generator constant is dependent on $C_{P,max}$ and on λ_{opt} and therefore ensures that the maximum power is tracked at all wind speeds below rated. To allow for a better tracking of the maximum C_P, in [21] a proportional-integral (PI) controller is implemented also for the generator torque controller.

Region 3 goes from rated wind speed until cut-off wind speed; in this region, the power production of the wind turbine has to be limited to rated power, and this is achieved by regulating the rotational speed of the rotor with a controller on the pitch angle of the blades. The pitch controller is most commonly a proportional-integral-derivative (PID) collective pitch controller [22], [19], that calculates the desired pitch angle based on the error between the measured rotor speed and the set-point. There are two possible control strategies for this region: the rotor speed can be regulated while maintaining either constant power or constant torque. Both control strategies are valid and have advantages and drawbacks; as seen later in the section, it is more common to opt for constant power strategy for onshore or fixed-bottom wind turbines, while for floating wind turbines the constant torque strategy is recommended.

Many works [23], [15], [24] describe the dynamics of the pitch controller with a second-order differential equation, for a system with only one degree of freedom (DOF), that is the rigid body rotation of the rotor; the resulting equation is:

$$\left[\mathrm{I_{DT}} - \frac{\partial \tau_{\mathrm{aero}}}{\partial \theta}\mathrm{K_D}\right]\ddot{\phi} + \left[\frac{\partial \tau_{\mathrm{g}}}{\partial \omega} - \frac{\partial \tau_{\mathrm{aero}}}{\partial \theta}\mathrm{K_P}\right]\dot{\phi} + \left[-\frac{\partial \tau_{\mathrm{aero}}}{\partial \theta}\mathrm{K_I}\right]\phi = 0 \tag{7}$$

where ϕ, $\dot{\phi}$ and $\ddot{\phi}$ are respectively, the rotor position, velocity and acceleration, $\mathrm{K_P}$, $\mathrm{K_D}$ and $\mathrm{K_I}$ are respectively the proportional, derivative and integral gains, $\mathrm{I_{DT}}$ is the inertia of the drive train of the turbine and τ_{aero} is the aerodynamic torque. The pitch controller is therefore characterized by an inertia, a damping and a stiffness and can be described by a natural frequency and a damping ratio, which both depend on the PID gains of the controller. This design allows to decide the systems' behaviour only by selecting the desired frequency and damping of the controller and this tuning method is called pole-placement [25].

The controller gains play a fundamental role in the control of the wind turbine and the tuning of the PI controller is not trivial. If the controller tuning produces too low gains, it results in a sluggish controller that is not able to react promptly to a change in inputs; on the contrary, tuning a controller aggressively can result in instabilities, with the controller frequency interfering with other natural frequencies of the system. Furthermore, due to the sensitivity of the torque to a change in pitch angle, and the wind turbine not being a linear system, the PID controller gains change with wind speed. To account for this change, gain scheduling is widely performed [22], [25].

Further control strategies are implemented in additional control regions, identified in correspondence of the transition from one region to the other. To avoid systems frequencies overlapping, such us the 1P (rotor rotation frequency) and the first tower fore-aft, sometimes turbines are operated with a minimum rotational speed at low winds; this defines region 1.5, where, even if in below-rated conditions, the rotor is not operated at maximum C_P. Region 2.5 is the transition between region 2 and region 3 and it can be delicate in a sense that it is the region where the controller switches between generator torque and pitch; many strategies can be implemented [22], [5], [21] to make the switch as smooth as possible, and avoid over-speed of the rotor. Furthermore, a last region 3.5 can be present, where different strategies are implemented in industry for a smooth stop of the turbine and to mitigate shut-down loads [26].

Besides controlling the power output, the pitch controller has an important impact also on the loads experienced by the turbine. Avoiding excessive loading is essential to ensure the safe operation of the turbine, while average reduction of loads would lead to lower operation and maintenance costs [27] and reduce material weight for structural parts that have to sustain those loads [28]. Advance and modern controllers can be explicitly designed to reduce certain loads or enhance modes damping, by including additional feedback signals, filters and models, as reviewed in [22].

3.3 Challenges of floating offshore wind turbines

As stated in [22], the torque control in below rated-region is usually not as critical as the pitch control above rated: this is due to the fact that the aerodynamics and the structural dynamics of the turbine may interact significantly and produce undesired effects. In particular, it is of interest the interaction between the thrust and the tower motion of the turbine, especially for floating wind turbines.

The tower during operation of the turbine, oscillates backwards and forwards subject to external loads; this motion changes the relative wind velocity seen by the rotor so that, when the tower is moving forwards, the relative wind velocity increases, while the opposite is true when the tower moves backwards. Above rated wind speed, the pitch controller is regulating the generator speed and reacts to the change in relative wind velocity due to tower motion; in particular, when the tower moves forwards, the relative velocity increases and the pitch controller pitches the blades to limit the generator speed while also decreasing the thrust (see Figure 3: the slope of the thrust curve above rated wind speed is negative, meaning that for an increase in wind speed, the thrust decreases). Because the thrust decreases, the aerodynamic damping provided by the thrust also decreases, which enhances the forward tower motion; the opposite happens when the tower moves backwards, and the pitch controller reacts to a decreased wind speed causing the thrust to increase, which enhances the backwards tower motion. This effect is known as negative damping [28], [15], and can cause serious problems to the turbine stability if not properly addressed.

The negative damping problem is a phenomenon that is present in both fixed-bottom and floating wind turbines. For fixed-bottom turbines, the negative damping is solved by decreasing the reaction time of the controller, and setting a natural frequency lower than the first natural frequency of the system (which is commonly the tower first fore-aft) [28]; tuned this way, the pitch controller performance is still satisfactory. However, applying a classic onshore pitch controller on a floating wind turbine, instabilities occur as observed in [15]. In a wind ramp simulation, [15] observed that the FOWT, after reaching rated wind speed, was having severe instability issues, for which the tower started to move back and forth with increasing displacement amplitude; the rotor speed was also having big oscillations as well as the pitch angle, which the controller was trying to adjust. The negative damping problem was enhanced by the controller frequency interfering with platform modes, in particular, with the tilt motion. In fact, FOWT are designed so that the platform natural frequencies do not interfere with the waves frequency range, and are therefore designed with very low natural frequencies (in the order of 10 times lower [15]). While other low frequencies, such as the ones of translational modes and heave mode, are highly damped by the catenary lines of the mooring system [15].

Multiple solutions to the negative damping problem of the tilt mode have been suggested. In [15] and [29], the frequency of the pitch controller is set lower than that of the platform; however, this resulted in a pitch controller that is too slow to react to changes in wind speed, causing big variations in the rotational speed of the rotor. [29] also studied the integration of the nacelle velocity feedback in the controller, described in [28] as well, an approach called "parallel compensation"; it succeeded in achieving stability and load reduction in the tower, but also showed over-speed and large rotor speed variations. [30] and [15] investigated active stall control as a solution to negative damping, but did not lead to a satisfactory improvement. Individual blade pitch control for reducing pitch motions has been investigated by [31], which showed promising results. Finally, a non-control solution is suggested in [32], where a tuned mass damper (TMD) is included in the nacelle of the turbine; however, such solution would imply the addition of the TMD on the nacelle, which could increase costs.

Control strategy also plays an important role in the negative damping instability. While for onshore wind turbines it is preferred to regulate the generator speed above rated maintaining constant power, such strategy results in high over-speeding of the rotor for FOWT. In case of FOWT, it is more common to use the constant torque strategy, which seems to limit the variation in rotor speed [15].

4 Research questions

RQ 1: What are the natural frequencies of the IEA-15-240-RWT mounted on the UMaine semisub?

One of the challenges for FOWT design and operation is to avoid resonance issues between the different components of the system (structural, environmental and control) that have specific natural frequency ranges. Even though the natural frequencies of the IEA-15-240-RWT in a fixed-bottom configuration have been determined [1], when the turbine is mounted on a floating substructure its natural frequencies change [11]. Furthermore, the UMaine semisub has been designed so that its natural frequencies do not overlap with the waves frequency range. To be able to characterize the system and tune the controller appropriately, it is relevant to know what are the natural frequencies of the IEA-15-240-RWT when mounted on the UMaine semisub.

RQ 2: How does peak shaving affect the stability of the IEA-15 MW?

Peak shaving is a widely used strategy to reduce the thrust load on the rotor at rated wind speed by pitching the blades before rated wind speed is reached, and above rated wind speed by increasing the pitch of the blades. The negative damping effect is enhanced when the slope of the thrust curve is higher [29], which is around rated wind speed; therefore, peak shaving is applied to the IEA-15-240-RWT mounted on the UMaine semisub in order to evaluate if reducing the thrust curve slope around rated wind speed can reduce the negative damping effect and improve the performance of the turbine in terms of loads and stability. A drawback of peak shaving is a loss in power production, as early blade pitching delays when rated power is reached. An assessment on power production loss will be carried out as well, which will lead to an assessment of the turbine's performance in terms of loads, stability and AEP. A stability measure will be determined, based on the standard deviation of the outputs and/or the derivative of the thrust curve with respect to wind speed.

RQ 3: What controller design do we recommend for a FOWT?

Stability can be assessed in different ways. Since oscillations in the rotor speed, power, and other signals are expected, if these oscillations are confined within a specific range for the whole turbine operation, the system can be said to be stable. A controller design is recommended for floating offshore applications and assessed in terms of standard deviation of the output signals, loads and AEP, also based on the results from RQ 2.

If time allows, the following research questions are also going to be addressed.

RQ 4: What gain scheduling do we recommend for a FOWT?

Gain scheduling is performed in order to account for the change of the torque sensitivity to a change in pitch angle. A gain scheduling strategy above rated wind speed is designed based on the controller design recommended in RQ 3.

RQ 5: How can constant-power torque control be improved for FOWT control?

Constant-power strategy of the torque controller above rated can help reduce the oscillations of the power output. However, this strategy seems not to properly work for FOWT, causing large variation in the rotor speed. By understanding why this happens, additional filters or feedback terms in the closed-loop control can be implemented in order to improve the performance of the torque control in constant-power mode and therefore, the overall performance of the FOWT.

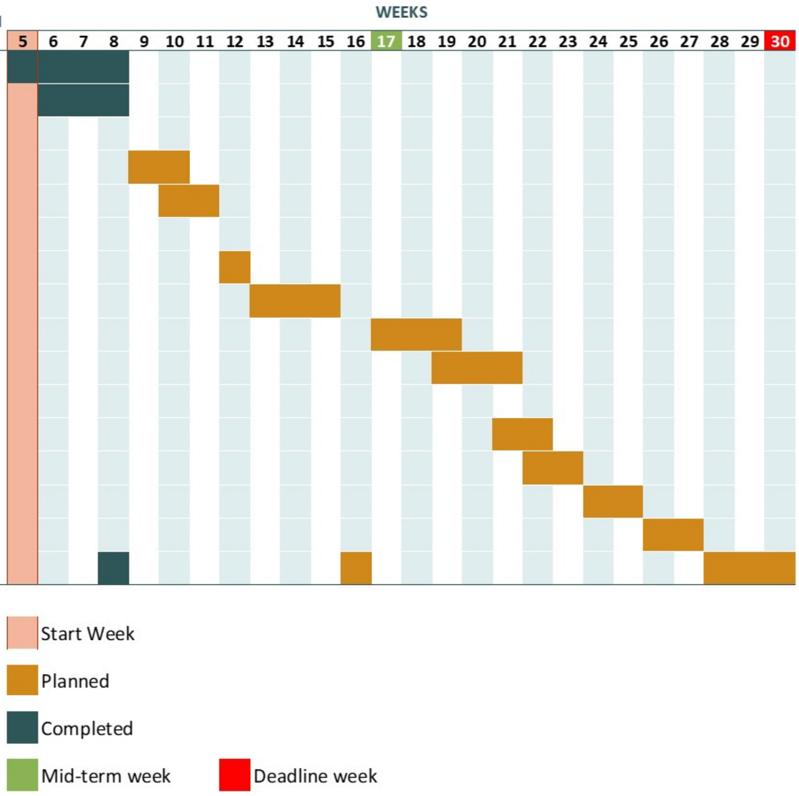
5 Project management

To answer the research questions, the following timeline is suggested, presented in the form of a Gantt chart. For each research question, sub-tasks have been identified and appropriate period of time has been assigned. The project period has been divided in a weekly basis, with week numbers corresponding to the calendar. Task duration is also estimated in number of weeks.

The activities planned for the project have been divided in project plan, literature review, the research questions and the thesis writing. For the project plan, literature review has been carry out in order to identify significant research questions. This has allowed to prepare the background of the project, which will be inserted in the thesis as well. The research questions presented in the previous section have been slip into sub-tasks. RQ 2 is divided into stages. This is because this research question is expected to be an iterative process; stage number 1 is planned to be finished by the mid-term week, in order to start the second part of the term with a peak shaving strategy set. Furthermore, by the mid-term week, the methodology section of the thesis is planned to be finished. RQ 4 and 5 are inserted in the project plan as supplementary interesting research questions that will be addressed if the suggested timeline is respected.

MSc Thesis Project Plan

ACTIVITY	START	DURATION
Project Plan	5	4
Literature review	6	3
RQ 1: Natural frequencies		
Simulations	9	2
Results' post-process/analysis	11	2
RQ 2: Peak shaving		
Preparation	12	1
Stage 1	13	3
Stage 2	17	3
Stage 3	19	3
RQ 3: Controller tuning		
Simulations	21	2
Results' post-process/analysis	23	2
RQ 4: Gain scheduling	24	2
RQ 5: Torque controller strategy	26	2
Thesis writing	28	3



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