On the effects of basic platform design characteristics on floating offshore wind turbine control and their mitigation

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Abstract. Semi-submersible floating offshore wind turbines present significant advantages over other designs in terms of cost, deployment, maintenance and site-independence. However, these advantages are achieved by shifting a part of the burden of stabilising the platform pitch and roll motions to the turbine control system. A study is presented here of the effects of basic platform dimensions on the performance of a standard pitch controller and the possible methods for mitigating said effects.

1. Introduction
Floating offshore wind turbine (FOWT) platforms can be classified into three main types, i.e. spar-buoys, tension leg platforms and semi-submersibles [1]. They can all be stabilised by purely mechanical means, i.e. ballast [2], taut cables [3] and hydrodynamic design [4], respectively. However, said means present considerable disadvantages in terms of cost, which is driven by size and complexity [5], and flexibility, which is limited by dependence on site conditions and deployment methods [6].

Flexibility is scarcely an issue with semi-submersible-based FOWTs, because they can be built in shipyards and towed to site, while their cost varies strongly with their design. In general, platforms with larger hydrostatic restoring stiffness and hydrodynamic damping cost more to build and deploy, while less stable platforms can affect the FOWT’s performance. This paper investigates the relationship between fundamental semi-submersible design parameters and FOWT performance, specifically in terms of challenges posed to the turbine control system by less stable, more affordable and compact platforms, and presents different techniques by which the control system can overcome said challenges.

2. Turbine design
The scaled outlines of three different FOWTs based on two commercial designs and NREL’s 5MW baseline FOWT mounted on ITI Energy’s barge [7] are shown by figure 1, where the platforms are represented only below the waterline. Note the differences in draught and displacement, which are due to the spar buoy and semi-submersible designs using ballast for platform stabilisation, while the NREL design relies mostly on the lateral motion of its centre of buoyancy. Although the barge is a manifestly simpler, more compact platform, its benefits...
Figure 1. Spar buoy (Hywind), Semi-submersible (Windfloat) and NREL (baseline barge) floating offshore wind turbines dimensions

Figure 2. Barge floating platform dimensions

are reaped at the cost of making the turbine controller’s regulation objectives more difficult to achieve. This relationship between platform and controller design, which has been studied in works such as [7, 8, 9, 10, 11], suggests an incentive for advanced FOWT control techniques to seek tolerance to less stable, more compact platforms. Here, we seek to study the challenge said incentive poses in terms of controller design.

A variety of considerations, which are besides this paper’s focus, influence FOWT platform design. It is, therefore, challenging to systematically study the control needs of FOWTs in general via analysis of specific commercial designs, which may be differently influenced by said
considerations. Here, we try to isolate a single characteristic of FOWT platforms, i.e. their effect on controller design and performance, by seeking a family of platforms which are comparable in every other way. It is however desirable that said family have some relation to viable designs. To achieve this, we take overall dimensions and inertial properties from [NREL’s barge] as a reference for one member of said family. A shell of thickness $t$ and density $8000\text{kg/m}^3$ represents the hull and the structural elements near it, while internal structures are represented by a constant density of $275\text{kg/m}^3$ within the volume of the platform. The tower-platform interface is represented by the plate of thickness $1.5m$ shown in figure 1, which has a density of $8000\text{kg/m}^3$. Said simplified design presents approximately the same inertial properties as the original [7] when $b = 40m$, $c = 10m$, $d = 4m$ and $h = 6m$.

In order to produce other reasonable platform models for our family, which are different in terms of their influence on controller design and performance, the beam-draught ratio has been modified, while other parameters have been subjected to the following restrictions:

- Beam and draught have been chosen to achieve a given beam-draught ratio and, at the same time, make the displacement equal to the platform mass.
- The platform mass has been calculated by:
  - Keeping dimensions $c$ and $h$, the tower-platform interface and the internal structure density constant.
  - Choosing thickness $t$ so that the moment of area of section $A$, figure 1, around the horizontal axis, which is related to the platform’s stiffness, remains constant.

![Figure 3. Hydrodynamic coefficients for chosen barge beam-draught ratios](image-url)
Once the parameters of each platform have been chosen according to the criteria outlined above, hydrodynamic coefficients have been calculated via the Boundary Element Method code NEMOH, and are given by figure 3, where the values calculated via WAMIT in [7] are also shown for reference. Although some disagreement exists between NEMOH and WAMIT values, as was the case in [7] between WAMIT and NAME values, they are due to numerical issues which are besides the scope of this paper. NEMOH does however provide reasonable coefficients at no cost, which is needed here. Viscous damping and mooring lines are overlooked here for simplicity.

Figure 4 shows the eigenvalues of the linearised state matrix which correspond to platform pitch motion. Note that smaller beam-draught ratios result in lower frequency platform pitch motion, until static stability is lost due to reduction of metacentric height, as indicated by the positive real eigenvalue exhibited by the model with beam-draught ratio 4. This is consistent with figure 5, which shows how several turbine properties vary with beam and indicates the platform designs corresponding to arbitrarily chosen beam-draught ratios 10, 8, 6 and 4, respectively. Note that smaller beam-draught ratios result in smaller platform mass and inertia, at the cost of larger draught, a higher centre of mass, smaller metacentric height and larger static platform pitch.

Also note that the original platform, which corresponds to \( b = 40 \text{m} \), is near the minimum frontal area, which would suggest optimal design for drag, but also near the maximum hull thickness, which would suggest a compromise. Although such optimisation, based on the highly simplified design considered here, is rather speculative, the fundamental compromise necessary for platform design is evident - larger beam results in increased stability, as characterised by the height of the FOWT centre of mass, metacentric height and static platform pitch, at the cost of increased platform mass and size. It is possible to find optimal design parameters via a detailed cost model which includes the relationship between platform stability and controller performance [12]. Here, however, we seek a way to alter said relationship by enhancing controller tolerance to reduced platform stability.
3. Controller design

At wind speeds above rated, the blade pitch of modern wind turbines is governed by a generator speed feedback controller such as that represented by figure 6. An adequately tuned PI controller is typically sufficient [15]. Other controller design methods exist [16] [17], which reduce human intervention in the tuning process while taking into account model uncertainties and turbine non-linearities. However, the limits of what can be achieved by the controller are determined by the turbine characteristics and the controller topology, while the controller tuning method can only reach said limits. Here, we manually tune a PI controller for each platform model at the operation point corresponding to 13m/s wind, to achieve rejection of output disturbances up to the highest possible frequency, while respecting the following limits: 6 dB of maximum output disturbance amplification, 6 dB of gain margin and 30 degrees of phase margin. The resulting platform motion and rotor speed responses to wind speed changes are shown by figure 7. Note that smaller platform beam-draught ratios result in lower frequency, higher amplitude responses, as expected.

![Figure 6. Standard pitch feedback control loop](image)

**Figure 6. Standard pitch feedback control loop**
Although the performance represented by figure 7 is not necessarily optimal by any metric, it is in practice difficult to improve by means of generator speed feedback only. This is due to better generator speed regulation causing the excitation of the platform pitch motion. We therefore look to further feedback loops in order to aid the PI. For example, Aerodynamic platform stabilisation is possible via feedback of structural motion measurements [18]. Figure 8 shows one such stabilising feedback loop, in combination with the regular rotor speed regulation loop. The principle is that changes in wind speed which increase generator speed also increase thrust, which in turn causes the FOWT to pitch back. Responding to this by increasing the blade pitch angle contributes to generator speed regulation, as well as damping of the platform pitch motion.

Less stable floating platforms respond to changes in thrust faster and more vigorously, while turbine rotor response to changes in torque is largely platform independent. This results in the aerodynamic platform stabiliser blade pitch demand anticipating the rotor speed PI pitch demand, and therefore becoming the chief contributor to rotor speed disturbance rejection at frequencies near the platform pitch natural frequency.

There is currently no generally established procedure for tuning a controller such as the one represented by figure 8. Therefore, although work is ongoing at IK4-IKERLAN to develop advanced tuning methods, it is relevant to investigate what can be achieved via purely manual
Figure 8. Aerodynamic platform stabiliser

Figure 9. Platform and generator response to changes in wind speed with aerodynamic platform stabiliser and PI regulation

tuning. Some design level results are shown by figure 9, where platform motion has been fed back in the form of nacelle fore-aft acceleration. Note that, with said feedback, the authors have been able to significantly reduce generator speed sensitivity to wind speed variations, relative to what they could achieve with a traditional blade pitch controller, while also reducing platform motion.

The significance of these results is considerable, since they suggest it may be possible to design wind turbine controllers which are less demanding in terms of platform stability. Note, from figure 9, that not only has generator speed regulation improved for each platform individually, but also the deterioration caused by reducing the platform beam-draught ratio has been compensated. This is indicated by all the dashed lines on the lower Bode plot being below the continuous line corresponding to beam-draught ratio 10. If generator speed regulation is considered acceptable with the larger, more stable platform, it may also be considered acceptable with the smaller, less stable platforms and the aerodynamic platform stabiliser.
4. Conclusions
This paper has discussed what the authors consider to be one of advanced control engineering’s fundamental *raisons d’être* in the context of offshore wind energy, i.e. the relaxation of stability requirements for platform design, with the ultimate objective of cost reduction.

With an open, simplified FOWT model as a basis, this paper has quantified the relationship between some basic platform design characteristics and their effects on controller performance. The results show that a strong incentive for improvement of controller tolerance to reduced platform stability is intrinsic to FOWT design. Furthermore, said improvement is possible via aerodynamic platform stabilisation based on additional sensor data, such as nacelle fore-aft acceleration. The process of tuning these additional feedback loops is non-trivial and will require formalisation in dedicated, dedicated publications, which analyse controller performance in realistic wind and waves conditions. However, the magnitude of the potential cost reduction derived from making the use of more compact platforms viable is considerable, as shown by figure 5, and justifies the added complexity.

Efforts are currently being carried out at IK4-IKERLAN to develop robust, practical methods for aerodynamic platform stabiliser tuning, test them via full aero-elastic simulation campaigns and implement them on commercial wind turbines. Furthermore, it is essential to analyse the impact of the additional sensors required by aerodynamic platform stabilisers on system reliability, and design fault tolerant control algorithms which mitigate said impact.

References
[1] Jonkman J M and Matha D 2011 *Dynamics of offshore floating wind turbines-analysis of three concepts* (Wind Energy)
[2] Yongoon O, Kwansu K, Hyungyu K and Insu P 2015 *Control algorithm of a floating wind turbine for reduction of tower loads and power fluctuation* (International Journal of Precision Engineering and Manufacturing)
[3] Betti G, Farina M, Guagliardi G, Marzorati A and Scattolini R 2014 *Development of a control-oriented model of floating wind turbine* (IEEE, Transactions on Control Systems Technology)
[4] Bagherieh O and Nagamune R 2014 *Utilization of blade pitch control in low wind speed for floating offshore wind turbines* (ACC, American Control Conference)
[5] Fingersh L, Hand M and Laxson A 2006 *Wind turbine design cost and scaling model* (NREL)
[6] Rhodri J and Costa Ros M 2015 *Floating offshore wind: market and technology review* (The Carbon Trust)
[7] Jonkman J M 2007 *Dynamics modeling and loads analysis of an offshore floating wind turbine* (NREL)
[8] Savenije F and Peeringa J 2014 *Control development for floating wind* (The Science of Making Torque from Wind 2014)
[9] Antonutti R, Peyrard C, Johanning L, Incecik A and Ingram D 2016 *The effects of wind-induced inclination on the dynamics of semi-submersible floating wind turbines in the time domain* (Renewable Energy)
[10] Tran T and Kim D 2015 *The platform pitching motion of floating offshore wind turbine: A preliminary unsteady aerodynamic analysis* (Journal of Wind Engineering and Industrial Aerodynamics)
[11] Fleming P, Pineda I, Rossetti M, Wright A and Arora D 2014 *Evaluating methods for control of an offshore floating turbine* (OMAE2014)
[12] Sandner F, Schlipf D, Matha D and Cheng P W 2014 *Integrated optimization of floating wind turbine systems* (OMAE 2014)
[13] Jonkman J M, Butterfield S, Musial W and Scott G 2009 *Definition of a 5-MW reference wind turbine for offshore system development* (NREL)
[14] McKook Field, Engineering Division 2005 *Structural analysis and design of airplanes* (Dayton, OH: Wexford College Press)
[15] Bagherieh O and Nagamune R 2015 *Gain-scheduling control of floating offshore wind turbines above rated wind speed* (Control Theory and Technology)
[16] Neeraj A, Manikandan R and Nilanjan S 2014 *Dynamic analysis and control support structures for offshore wind turbines* (ICONCE, International Conference on Non Conventional Energy)
[17] Lackner M and Rotea M 2011 *Structural control of floating wind turbines* (Elsevier)
[18] Jonkman J M 2008 *Influence of control on the pitch damping of a floating wind turbine* (NREL)