Proceedings of 9th PhD Seminar on Wind Energy in Europe
September 18-20, 2013, Uppsala University Campus Gotland, Sweden

CONCEPTUAL DESIGN OF FLOATING WIND TURBINES

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ABSTRACT

The need for different numerical models with varying degrees of simplification for the conceptual design of a floating offshore wind turbine is the focus of this paper. While parts on the component level can be designed apart from the others the overall dynamics on the system level have to be assessed from the beginning. Starting with very simple models and identifying the significant contributions to the system behavior while going step by step to more detailed ones makes a successful dimensioning possible. The significant effect of the blade pitch controller on the system dynamics is analysed and preliminarily designed with a simple 1-degree of freedom (dof) model. Further on the section forces at tower base and the distributed platform loads are calculated with a 9-dof multibody system with simplified aerodynamics and Morison equation allowing a pre-dimensioning of the structure.

INTRODUCTION

Along with the intensified construction of offshore wind parks worldwide research seeks solutions for seas with a depth beyond the limits of bottom mounted foundations. Several technologies for floating offshore wind turbines (FOWTs) have already been applied in the oil & gas industry. The concepts differ in the way how stability and a reduction of wave excitation is achieved. Tension-leg platforms, for example, achieve stability through a taut mooring, whereas others, like the barge and spar-buoy, rely on high mass and inertia. These concepts have been repeatedly improved so that abundant experience in their conceptual design exists. There are basic, mostly empirical rules for, e.g., the spacing of the columns of a semi-submersible, the eigenfrequency of a spar or the additions to minimize vortex induced vibrations, see [1]. In the field of wind energy, however, demands and standards are different: Due to the technology that is still very young the readiness to invest is limited and the cost of energy needs to be close to the one of conventional power plants. Thus, it is a main target to conceptual design to keep the material cost low. With the resulting floating geometries that are much lighter as their oil & gas counterparts new challenges are arising that have not been known before. While a common practice is to increase the inertia of a floating structure in order to shift the RAOs to frequencies lower than the wave spectral peak this is not feasible in the same way for FOWTs. It is necessary to ensure a high hydrostatic restoring stiffness in order to decrease the static wind misalignment of the rotor. On the other hand the reduction of costs requires a reduction of used wall and ballast material so that a FOWT platform easily reaches RAOs at higher frequencies, close to the wave spectrum. When looking at the dynamic behavior of FOWTs compared to oil & gas structures it is obvious that the aerodynamic forces play a major role. The turbulent wind field introduces stochastic forces and moments in all directions on the rotor hub. Out of this reason the wind turbine controller is crucial to the design of a floating wind turbine system. It has been observed that conventional controllers that do not take into account the tower or platform motion yield an unstable behavior for wind speeds closely above rated wind speed. This phenomenon is even enhanced for platforms with high eigenperiods resulting from a small metacentric height and a high structural inertia. When designing a new concept of a floating wind turbine the interconnectedness of the mentioned facts has to be considered and therefore numerical models with increasing degree of detail need to be applied.

In the following an exemplary process of conceptioning a FOWT on system level with regard to its dynamics is outlined.

HYDROSTATIC CALCULATIONS

For a new platform the hydrostatic restoring stiffness C_{55} can be calculated as

$$C_{55} = \sum_{i=1}^{n} z_i F_g + \rho g (I_{wtrpln} - V_{subm} z_{cob}), \tag{1}$$

giving an important departing point for all further calculations, see also [3]. The gravitational contribution F_g depends on the location of the center of mass at z_i over mean sea level (MSL) of body i. The influence of the buoyancy force exerted at the center of the submerged volume V_{subm} at z_{cob} is always destabilising when taking the MSL as reference point unlike the waterplane contribution. It depends on the second moment of area of the body cross-section at MSL, I_{wtrpln}. For the sample preliminary calculations of the hydrostatic properties of a FOWT platform a spar-type cylinder with a slightly reduced cylinder diameter around MSL is assumed. Fig. 1 shows how the mass varies quadratically over spar radii for all selected drafts and how the hydrostatic restoring stiffness C_{55} increases for bigger radii and decreases with the cylinder height. As mentioned above a minimum restoring is required for FOWTs to ensure a small wind misalignment. The black dashed line shows the restoring stiffness of the spar defined by the OC3 study, see [4].

Not only the static restoring stiffness is crucial to the behavior of the FOWT but also the natural frequency. The rigid body natural frequency of the system should be out of the wave spectrum in order to avoid excitation from the waves. For these preliminary calculations the eigenperiod $T_{eig,55}$ of the rigid body oscillation about y-axis, see fig. 2, can be approximated as

$$T_{eig,55} \approx \frac{2\pi}{\sqrt{\frac{C_{55}}{I_{22,FOWT}+I_{22,addedmass}}}}. \tag{2}$$

The mass moment of inertia of the added fluid mass $I_{22,addedmass}$ can be calculated as

$$I_{22,addedmass} \approx C_A \frac{1}{12} m_{FOWT} (3r_{spar}^2 + l_{spar}^2) \tag{3}$$

with the added mass constant C_A that is set to 1 in this study according to [5]. Although this approximation assumes an oscillation about the fixed reference point, which is not always true, it gives a good qualitative estimate of the eigenperiod in still water. Thus, the frequency of rotational motion about y can be compared to other geometries and already optimised during the first assessments. The value of $T_{eig,55}$ is plotted over spar radii r_{spar} for all platform drafts l_{spar} at the bottom of fig. 1.

With these first platform properties a simplified model can be set up to investigate the behavior of a controlled wind turbine.

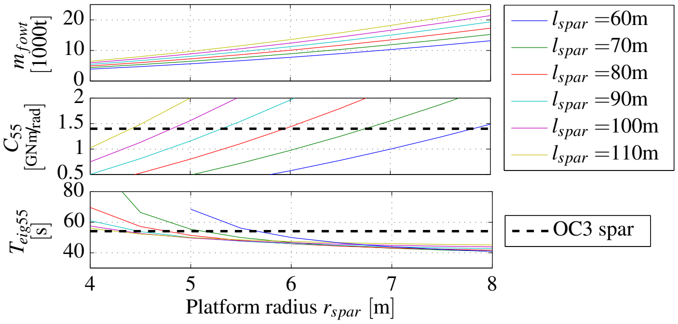

FIGURE 1. Restoring stiffness and approximate eigenperiod over spar radius and length.

WIND TURBINE CONTROLLER

As reported by [2] and [6] a conventional collective blade pitch controller (CPC) can cause instabilities in the above-rated wind speed region. This happens according to [4] when the bandwidth of the controller is higher than the one of the whole plant rotating about y. Thus, it is reasonable to use the so far calculated dimensions to set up a simplified model for controller design.

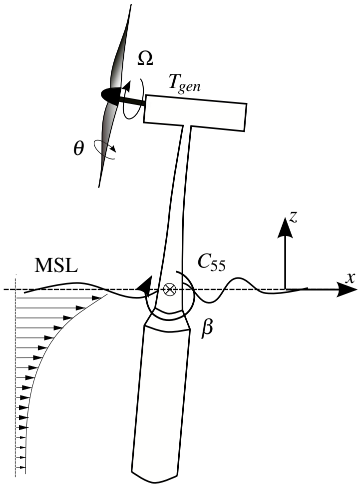

FIGURE 2. Simplified model for controller design.

Fig. 2 shows the principle set up of a 1-dof model of the FOWT. The equation of motion remains with the hydrostatic restoring stiffness C_{55}, eqn. (1) and the mass moment of inertia $I_{22,FOWT}$ and $I_{22,addedmass}$ of equations (2) and (3) as

$$F_{aero} h_{hub} = (I_{22,FOWT} + I_{22,addedmass})\ddot{\beta} + C_{55}\beta. \tag{4}$$

Knowing the thrust coefficient of the rotor at the rotor effective wind speed v_{eff}, the blade pitch angle θ and the rotor speed Ω the aerodynamic force $F_{aero} = f(v_{eff}, \theta, \Omega)$, acting on the hub at h_{hub} above MSL, can be calculated. For conservativeness no damping except for the aerodynamic one is assumed. The performance of a baseline PI-CPC is evaluated for typical onshore and offshore gains in fig. 3. Additionally, the behavior of the platform pitch angle β is shown for a tower feedback control as proposed by [2]. This controller reduces significantly the platform motion which is not possible by only adjusting the gains of the baseline controller. After this evaluation of the controller performance a more detailed model is used to get an estimate of the external forces on the platform.

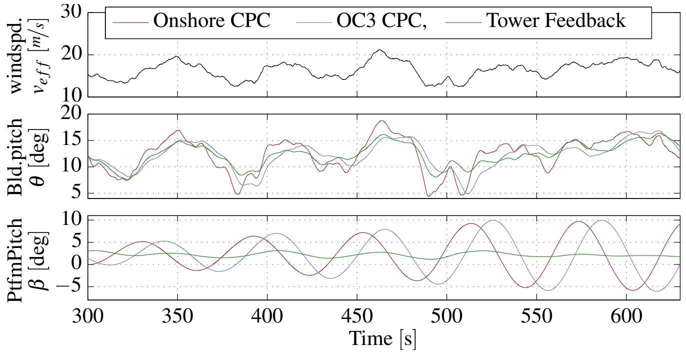

FIGURE 3. Tower feedback controller performance.

DISTRIBUTED PLATFORM LOADS

For this calculation a 9-dof model is applied that uses Morison equation to compute the hydrodynamic and wave loading on the platform and a quasi-static model for the catenary lines as proposed by [7]. Fig. 4 shows the distributed wave loads on the structure without the contribution from hydrostatic pressure. Such a computation of external forces on the submerged part of the platform is important for the structural dimensioning. Although this estimation has a lower fidelity than, for example, FEM and linear hydrodynamic solutions, it couples all forces and motions on-line and not consecutively as it is mostly necessary when using a separate software for each problem.

CONCLUSIONS

The application of a range of computational models for the different phases of the conceptual design of a FOWT has been presented. Whereas simple spreadsheet calculations allow for an assessment of hydrostatic properties in the overall design space a more detailed dynamic model gives insight into coupled dynamic effects and structural load estimations. Within the design of a floating wind turbine system the proposed methods are, on one hand, related to a very early conceptional stage. On the other hand, the proposed model includes aerodynamic, hydrodynamic and the effects from the controller and the mooring system in the same way as high-fidelity tools. Thus, reliable results can be obtained with a low computational effort at an early stage allowing for numerous iterations of the geometry and the controller. Consequently, less computational time will be required during the design phase and the detailed load case simulations.

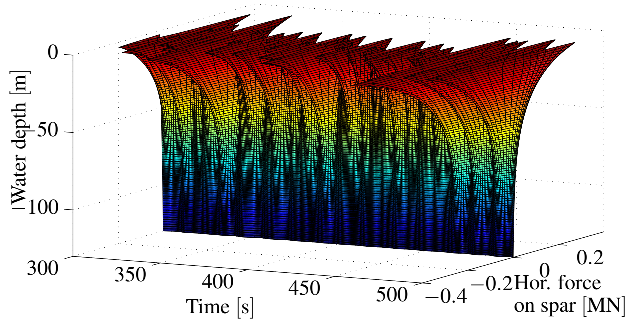

FIGURE 4. Timeseries of distributed loads.

ACKNOWLEDGEMENTS

This work has been partly fulfilled within the KIC-AFOSP (Alternative Floating Offshore Support Platform) project by Gas Natural Fenosa (GNF), Universitat Politècnica de Catalunya (UPC) and Endowed Chair of Wind Energy (SWE).

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