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A parameter study of the metacentric height role and limitations in minimizing the trim of the DTU 10-MW wind turbine mounted on moored spar-buoy floater

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Abstract: A primary design for a moderate size spar-buoy floater suitable for the 10 MW DTU wind turbine is introduced. Due to the high aerodynamic thrust acting on such large-rotor wind turbine, the tower pitching can become relatively high, which makes it a key point to be considered in the primary design stage. In addition, the floating platform is required to provide a sufficient dynamic stability to maintain stable energy production. However, it should stay cost-effective and limit the need to a complicated and expensive control system. The metacentric height plays a vital role in the dynamic stability, since it is related to the hydrodynamic stiffness of the floating system. Thus, in this study, minimizing the trim of the floating wind turbine was achieved through increasing the metacentric height by using ballast materials with different densities. The effect of increasing the platform stiffness on the spar-buoy pitch response was investigated with regard to the amplitude, natural frequency, damping ratio and energy production. The potentials and limitations of this approach were investigated analytically and numerically by using the aero-hydro-servo-elastic simulation tool OpenFAST. The simulations were performed at the rated wind velocity which is supposed to cause the maximal pitch inclination and with the blades pitch control system deactivated. The results showed that with a moderate substructure size for the large-rotor wind turbine “DTU 10-MW”, a satisfactory dynamic stability can be obtained only by using high density, commercially available, ballast materials.

Keywords: Offshore, Floating wind turbines, DTU 10-MW, spar-buoy, metacentric height

1. Introduction

Looking for better energy potentials and less legal restrictions, the market of wind energy is shifting more towards offshore industry. This promising transition is driven by the research and industrial achievements in this field. Several solutions for floating substructures have been introduced as concepts, prototypes or real scale floaters. The first floating platform to be in service on a scale of wind farm is the catenary-moored spar-type platform of Statoil company, which was used to support the Siemens SWT-6.0-154 (6 MW) wind turbine of Hywind Scotland project. The conference paper [1] refers to the advantages of the spar-type floaters. Design simplicity, onsite installation feasibility and the low sensitivity to waves make the spar an attractive choice for manufacturers. The emerging challenge when thinking about upscaling the harvested offshore energy is building an efficient large substructure to carry the large wind turbines. Enlarging the long drafted spars has manufacturing, transporting and installation limitations. Platforms aim to fulfil the hydrostatic and dynamic stability of the whole system. Hydrostatic stability is relatively easier to be satisfied whereas minimizing the pitch deflection without increasing the dynamic instability is more complicated. Less pitch angle needs more hydrostatic stiffness and therefore larger metacentric height. This can be achieved with limited platform size by modifying the floater inner structure geometry or nature. For a spar, its more efficient to change the nature of the ballast material. This study aims to show the potential of this method in obtaining a reasonably stable and moderate-size platform for the relatively large DTU 10-MW wind turbine [2]. A spar-buoy based on the Hywind-OC3 model is introduced in [3] as a floater for this wind turbine. It has a draft of 120 m, a maximum diameter of 12 m with a maximum heeling angle of 6.77°. While INNWEWIND.EU [4] project suggested a tripod platform to carry the DTU 10-MW. Both last floater concepts shortened the wind turbine tower, while it was kept complete in this study.

2. Methodology

A moderate-size spar-buoy suitable for the DTU 10-MW is introduced. Concrete of different densities as a ballast material was used. The effect of increasing the metacentric height due to ballast density increase on floating wind turbine hydrostatic and dynamic behaviour was investigated analytically and numerically with the open source code openFAST. The spar-buoy properties are shown in table [1].

Platform structural properties (Ballast density 4000 kg/m^3)	
Submerged length of the spar-buoy	100.35 m
Height of the tower base above SWL	15.00 m
Properties[1] of the cylinder under tower base	(2.00 m, 8.30 m, 0.06 m)
Properties[2] of the taper above SWL	(7.45 m, 0.06 m)
Properties[1] of the cylinder crossed by SWL	(10.00 m, 10.13 m, 0.07 m)
Properties[2] of the taper under SWL	(23.90 m, 0.08 m)
Properties[1] of the cylinder under SWL	(72.00 m, 16.00 m, 0.08 m)
Platform mass without ballast	4585.55 t
Ballast mass	12063.00 t
CM of the platform below SWL	-82.32 (Z = 0 at SWL)
Platform pitch moment of inertia around CM	9343553025.00 kg*m^2
Platform yaw moment of inertia around CM	642221381.00 kg*m^2

[1](Diameter, length, wall thickness), [2](Length, wall thickness)

Table.1 Platform structural properties

2.1 Analytically

The relation between the metacentric height GM and the platform pitch angle θ can be derived at the static equilibrium from the formula: $M_{heel} = \theta * K_{55}$, where K_{55} is the hydrostatic stiffness coefficient of the floating system in pitch direction. The following assumptions were adopted: Mooring lines stiffness is neglected, platform pitch θ <15°, the nonlinearity in the metacentric height is neglected and the highest thrust 1500 KN according to [2] is applied. Eq. (1) gives the platform pitch angle.

$$\theta = \frac{M_{heel}}{\rho * g * V_0 * \left(GM - \frac{I_{yy}}{V_0}\right) + \rho * g * I_{yy}} \quad (1)$$

Where V_0 is the displaced water volume and I_{yy} is the second moment of inertia of the cross section at the water level. The natural pitch period is obtained by Eq. (2). [5]

$$T_{eig} = 2\pi/(K_{55}/(I_{55} + A_{55}))^{0.5} \quad (2)$$

Where I_{55} is the pitch moment of inertia of the whole system around the centre of mass and A_{55} is the pitch added mass. Pitch Added mass of the submerged part of the spar-buoy can be obtained according to strip theory by integrating the 2D added mass expression of the cross section along the submerged body. The 2D Added mass of a circle moving in the plane of its surface is given by Eq. (3).

$$a_{11}^{2D} = \pi\rho r^2 \quad (3)$$

The 3D added mass of a cylinder in pitch direction is calculated by Eq. (4).

$$A_{55} = \int_{-draft}^{0} \pi\rho r^2 (Z - Z_g)^2 \, dz \quad (4)$$

Where Z_g is the gravity centre vertical coordinate. The integration was applied on every part of the spar independently so that the sum of all integrations gave the total added mass. The added mass was fixed for all ballast densities.

2.2 Numerically

The open source software OpenFAST was used to estimate the pitch angles, natural pitch periods , damping ratios and produced power at rated wind speed for different ballast densities with the blades pitch control deactivated. OpenFAST is an aero-hydro-servo-elastic simulation tool developed by the American National Renewable Energy Laboratory (NREL).

3. Results and discussion

With high density concrete 4000 kg/m^3 , the spar has a pitch angle less than 6°. However, increasing the stiffness led to shorter natural periods. The ballast with the density 7500 kg/m^3 (Steel) caused a pitch period of 29 sec when considering the mooring lines. This value lays within the waves periods spectrum and might cause resonance. Fig. 1 shows the relationship between the metacentric height and the pitch angle. As can be seen, increasing GM decreases the pitch angle but also the natural period. In general, heeling reduces the generated energy and at 10.67° of inclination the energy drop is more than 16% of the rated energy. By minimizing the pitch to 5.79°, this drop becomes around 6.6%. In addition, the metacentric height was found to be in an inverse relationship with the pitch damping ratio. This relationship was almost linear when ignoring the mooring lines damping in the simulations.

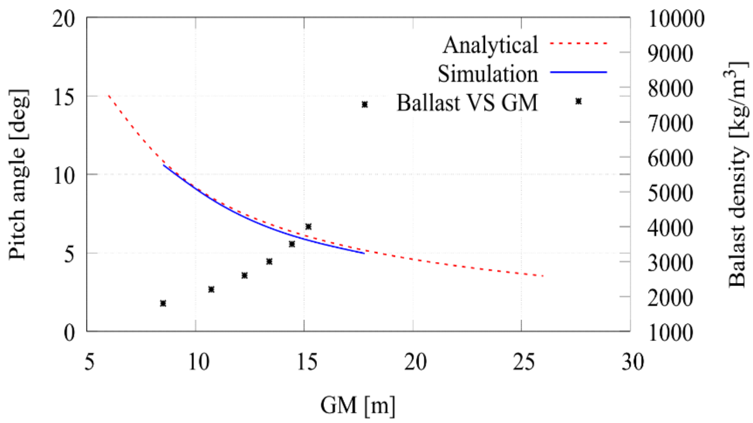

Fig.1 The relation between the metacentric height and the pitch angle

4. Conclusion

The metacentric height has an essential role in the floating spar-buoys hydrostatic and dynamic behaviour. Increasing it will minimize the trim of the floating structure and subsequently increase the extracted wind energy. At the same time, it increases the natural frequencies which must be kept out of the critical range of waves frequencies. An analytical approach can be used for a primary estimation of the required metacentric height for a specific spar-buoy system and later the required ballast density. The available high density concrete in the market, up to 4000 kg/m^3, provides more flexibility regarding increasing the stiffness of the floating spar-buoy systems without the need to increase the size of the substructure.

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