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Dynamic mooring simulation with *Code_Aster* with application to a floating wind turbine

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A B S T R A C T

The design of reliable station-keeping systems for permanent floating structures such as offshore renewable energy devices is vital to their lifelong integrity. In highly dynamic and/or deep-water applications, including hydrodynamics and structural dynamics in the mooring analysis is paramount for the accurate prediction of the loading on the lines and hence their dimensioning. This article presents a new workflow based on EDF R&D's open-source, finite-element analysis tool *Code_Aster*, enabling the dynamic analysis of catenary mooring systems, with application to a floating wind turbine concept. The University of Maine DeepCwind-OC4 basin test campaign is used for validation, showing that *Code_Aster* can satisfactorily predict the fairlead tensions in both regular and irregular waves. In the latter case, all of the three main spectral components of tension observed in the experiments are found numerically. Also, the dynamic line tension is systematically compared with that provided by the classic quasi-static approach, thereby confirming its limitations. Robust dynamic simulation of catenary moorings is shown to be possible using this generalist finite-element software, provided that the inputs be organised consistently with the physics of offshore hydromechanics.

1. Introduction

Floating wind turbine (FWT) technology permits to access deep-water offshore wind resources up to depths of a few hundred metres. Whilst it has already been demonstrated at the MW scale through a handful of prototypes, its industrialisation is just beginning. Considerable challenges lie ahead due to the limited experience available in coupling a wind turbine generator to a floating structure. Producing cost-effective, integrated FWT designs will likely require a profound revision of engineering practices and quite possibly the adoption of radically innovative solutions before standardisation.

1.1. Mooring system

The station keeping of a FWT is achieved by transferring the mean horizontal loads, dominated by wind thrust, to the seabed. The mooring system, defined as the ensemble of components involved in the load path from the fairleads to the soil, must be designed to resist cyclical and extreme loads with adequate safety and, if required, redundancy. For a general introduction to offshore mooring systems and their functions, design, and certification, the reader may refer to Chakrabarti (2005).

Offshore mooring systems commonly use the catenary principle (Fig. 1a) to produce horizontal restoring forces, exploiting the gravitational potential of heavy suspended lines. On the contrary, the restoring power of taut mooring arrangements (Fig. 1b) relies primarily on their elasticity. In FWT applications, the choice of mooring solution is primarily linked to water depth and floater technology and deeply impacts system design, as well as marine operations and the risk structure of a project.

Whilst the MW-scale FWT prototypes installed to date (Hywind, WindFloat, and the units installed off Goto and Fukushima) employ slack chain moorings, semi-taut, taut or tensioned arrangements are also

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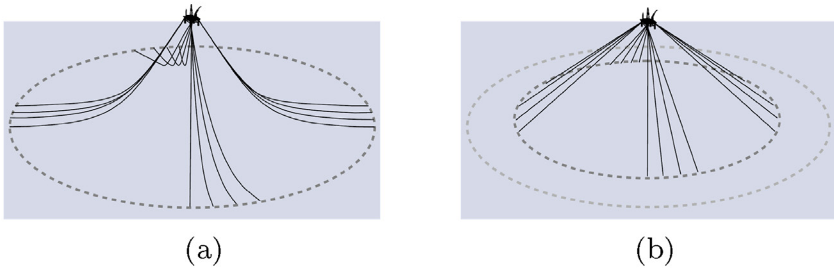

Fig. 1. Catenary (a) and taut (b) mooring arrangement a classic offshore platform, after Vryhof (2010).

considered for upcoming floating wind applications (Castro-Santos et al., 2013). Examples of taut mooring solutions using mainly fibre rope are found for instance within the early DCNS Sea Reed design and the IDEOL Floatgen demonstrator. In these cases nylon has been favoured over other fibres in order to insure sufficiently soft behaviour in very shallow water (30–40 m), where conventional arrangements become too stiff. Other configurations tailored for mid-shallow waters have been studied, such as catenary with clump weights (e.g. Vertiwind concept) or the multi-node GustoMSC patented system (de Boom, 2011). Turbine weathervaning by mooring design may eliminate the need for an active nacelle yawing system and/or attenuate loads on the floater; for this sake, single-point FWT mooring systems have been devised using a turret (e.g. Eolink and SAITEC concepts) or single anchor leg moorings. Finally, tensioned systems have been investigated in order to reduce stability demand on the floater, leading to the design of the SBM, Glosten PelaStar, and GICON tension-leg platform systems.

As imaginable, the properties of the mooring system define the dynamic response features of the whole system. Appropriately stiff or compliant behaviour in different degrees of freedom, as well as the avoidance of resonance, can be obtained by intervening on the mooring arrangement. The design of a floating wind farm mooring system that is low-maintenance, sufficiently reliable, and optimised for cost challenges the existing practices and holds large potential for improvement by R&D. Considering that a permanent floating structure's very survivability depends on the integrity of its moorings, a thorough understanding of their mechanical behaviour in the highly dynamic conditions found offshore is fundamental.

1.2. *Numerical modelling of floating wind turbine moorings*

In the floating offshore structure industry both frequency- and time-domain numerical tools are used for the estimate of platform and (mostly platform-driven) mooring response. The less computationally intensive frequency-domain methods treat wave-frequency and low-frequency wave loads and responses separately, typically employing linear and quadratic wave force transfer functions (QTF) to define the excitation term of the platform's rigid-body EoM (equations of motion). This approach, valid when non-linearities other than those treated with QTF are modest, is commonly applied to conventional offshore structures, especially in early design stages and for large design load case (DLC) sets (notably fatigue).

In floating wind, the addition of wind and turbine-related excitation at its own range of frequencies as well as the non-linearities caused by the reduced size of structures calls for time-domain solvers at earlier design stages. In this case all physics can be treated at once in coupled fashion albeit at higher computational cost. Concerning the effect of the mooring system on platform motions, in frequency versus time-domain (dynamic mooring) model comparisons it is common to observe relative conservatism in frequency domain results, due to absence of mooring damping (cf. for example Stendal (2015)). Conversely, mooring tensions may be underestimated by frequency-domain solvers as they typically miss line-bound inertial and hydrodynamic effects, as discussed below.

After half a century of offshore engineering experience, the role of dynamics in the mechanical behaviour of mooring systems is vastly documented. It is commonly accepted that the quasi-static representation of mooring lines becomes too inaccurate for the sake of engineering design when the motions of the structure are highly dynamic, when drag-intensive components are used (for instance, a mooring chain), when water depth exceeds about 150 m, or with any combination of the above (Matha et al., 2011). In such cases the inertial, hydrodynamic, and seabed contact loads can govern the extreme and cyclical tension regimes on the lines. Dynamic effects can dominate the tension variance especially in domains where high energy and high compliance coexist. This typically applies to conventional deep-water offshore platforms (Mavrakos et al., 1996) and to highly dynamic applications such as marine renewable energy installations (Johanning et al., 2007). As a consequence, the current state-of-the-art time-domain software for the design and analysis of offshore mooring systems (e.g. OrcaFlex, aNySIM, Flexcom, FASTlink,[1] etc.) typically include dynamic simulation capabilities.

The above guidelines are readily transposed to the floating wind context and dictate the use of dynamic simulation tools, especially when focussing on the mechanical response of the mooring system. Past research (see for example Karimirad, 2013) has shown that the dynamic mooring effects tend to bear a limited impact on FWT motion, due to the economical limitations to the practicable water depth – presently a few hundred metres at the most. Yet even in these conditions the impact on platform motion may become observable in extreme sea states, as pointed out by Masciola et al. (2013). Increasing the water depth rapidly augments the sensitivity of platform motion to the mooring dynamics, as reported by Matha et al. (2011). For instance, a lumped-mass model is used by Lin (2015) to simulate the dynamics of a spar FWT with catenary chains, for increasing water depths (320, 600, and 900 m), confirming the growing importance of dynamic line tension in determining the global response. A different picture can be drawn for the dynamic effects on mooring line tension: among others, Coulling et al. (2013) and Masciola et al. (2013) demonstrate that the quasi-static tensions severely underestimate experimental measurements even at the limited depth of 200 m and for operational met-ocean conditions.

A recent review of the available dynamic mooring line theories is provided by Masciola et al. (2014), distinguishing three main categories: lumped-mass, finite-difference, and finite-element. Literature shows that both the popular finite-element and lumped-mass theories can provide accurate tension predictions, although with more stringent resolution requirements by the latter approach (Lin, 2015; Masciola et al., 2014).

The finite-element (FE) method has been chosen by numerous authors in the FWT modelling field. A study by Jeon et al. (2013) evaluates the response of a spar-type FWT using a catenary system, evidencing the extensional vibrations of the mooring lines. The dynamics of large multi-turbine platforms are analysed by Kallesoe et al. (2011) and by Kim et al. (2015) incorporating a FE moorings model. Finite bar-type elements are used in the coupled simulations of Cheng et al. (2015) to assess different VAWT arrangements, and by Bachynski et al. (2013) to determine the severity of transient, fault-related events on mooring tension. Coupled motion response and dynamic mooring tensions are obtained by Zhang et al. (2013) for a MW-sized HAWT on a small semi-submersible

[1] A simulator coupling NREL's code FAST and OrcaFlex.