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Influence of tower design on the dynamics of a 15MW floating offshore wind turbine

Francesco Papi [1], Giulio Ferri[2], Niccolò Bruschi[2], Enzo Marino[2], Alessandro Bianchini[1]

[1]*Deptartment of Industrial Engineering, University of Florence, Florence, Italy,* *fr.papi@unifi.it* *alessandro.bianchini@unifi.it*
[2]*Deptartment of Civil and Environmental Engineering, University of Florence, Florence, Italy,* *giulio.ferri@unifi.it* *niccolo.bruschi@unifi.it* *enzo.marino@unifi.it*

SUMMARY:
As research and industrial interests around Floating Offshore Wind Turbines (FOWTs) has grown, an aspect that has recently emerged is the fact that, in many instances, tower resonance frequencies are effectively shifted upwards. While onshore wind turbine towers are typically designed with a soft-stiff approach, to avoid controller-induced floater-pitch instabilities, FOWTs towers are often stiffened to shift first side-side and fore-aft natural frequencies above the 3P excitation. This may turn however into heavier towers, negatively influencing system stability and increasing tower base loads significantly.
The current study investigates the influence of careful tower design on FOWT dynamics and loads. In this context, the current study aims at exploring the potential influence of careful tower design on FOWT dynamics and loads. The IEA 15MW Reference Wind Turbine (RWT) is used as testcase, since in its floating configuration it features a stiff-stiff tower. Four different lightweight towers are proposed. The impact of these different design solutions is discussed in terms of performance and structural loads on the turbine and the floater. Results prove that improved and lighter tower designs may represent a key aspect to further improve FOWT design and operation. Moreover, alternative approaches to enhance the performances of the system are discussed.

Keywords: Wind Turbine, Offshore Wind Energy, Floating Platform

1. INTRODUCTION

The main source of loads on an onshore turbine is aerodynamic loading on the blades and, especially in parked conditions, on the tower itself. Considering a three-blade rotor, the ranges of the synchronous excitation (1P) and three times the synchronous excitation frequencies (3P) are relevant for the tower design to avoid resonance phenomena. For onshore wind turbines, these ranges are generally narrow, allowing for placing the first tower natural frequencies between the 1P-3P gap. When dealing with FOWTs, due to the presence of the floater, which can be 10 times heavier than the wind turbine, the mass of the system significantly increases, and therefore the first system eigenmodes are associated to the six platform rigid degrees of freedom (Papi, F., and Bianchini, A. 2022). This pushes the frequencies of the first flexible modes, typically the tower fore-aft and side-side bending modes, upwards (Koo et al. 2014). Additionally, as stated by Allen et al. 2020, the 1P-3P gap is often smaller in FOWTs due to different control strategies that need to be adopted. For these reasons, FOWT towers are often designed conservatively, allowing for increased resistance to peak loads and natural frequencies placed above the 3P frequency excitation band. This design choice results in heavier towers and, as a consequence, higher inertial and gravitational loads on the tower itself. This study aims at exploring the opportunity of employing lightweight towers on a FOWT. The possibility of placing the tower natural frequencies in the 1P-3P gap is explored, avoiding synchronous and super-synchronous excitation while reducing inertial and gravitational loads. The IEA 15MW Reference Wind Turbine (RWT) (Gaertner E. et al 2020) is used as a test case (Figure 1a). Starting from this reference floating WT, four alternative towers with different distribution of diameter, D, and thickness, t, (see Figure 1b) are designed and tested to assess the feasibility of lightweight solutions.

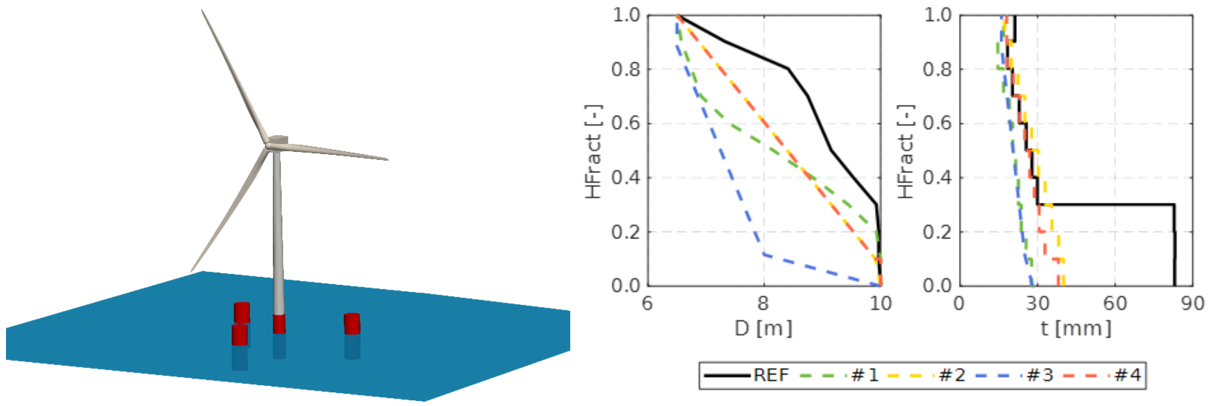

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Figure 1. OpenFAST model of the IEA 15MW RWT and the distributed towers properties of the proposed designs in terms of diameters and wall thickness. D tower diameter, t tower thickness.

2. METHODOLOGY

2.1. Modal analysis

A modal analysis is performed to obtain the mode shapes of the investigated towers, and to assess the possibility of placing the first FA tower natural frequencies in the 1P-3P gap.
To do so, BModes (Bir, G., 2005) simulations are carried out, considering the contributions coming from the platform and the mooring system, in terms of floater mass matrix, zero-frequency hydrodynamic added mass, hydrostatic stiffness matrix, and moorings stiffness matrix. Such inputs are fundamental to properly model the tower-base constraint which has a large influence on the modeshapes of the tower. The floater geometry is kept fixed as the reference one (Allen et al. 2020). The ballast is consistently updated in order to satisfy the buoyancy vertical equilibrium for all the tower solutions. This requires also to update the hydrostatic stiffness matrix. Concerning the contribution of the mooring lines, a quasi-static model (Ferri et al. 2022) is employed to obtain the mooring stiffness matrix with respect to the rigid-body platform DoFs.

2.2. Time-domain simulations

Loads on the selected test cases are evaluated through time-domain aero-hydro-servo-elastic simulations in OpenFAST, an open-source wind turbine simulation tool developed by NREL. simulations are performed for a variety of IEC 61400-3 Design Load Cases (DLCs). The load cases that are simulated are the same that were used in the design of the IEA 15MW RWT and allow for a quick and reliable estimation of ultimate loads. Met-ocean conditions corresponding to mean

Atlantic environmental conditions, used in the design of the IEA 15MW RWT (Allen et al. 2020, Gaertner E. et al 2020) are adopted.

3. RESULTS

A summary of the main characteristics of the proposed towers is shown in Table 1. The mass of the proposed towers ranges from approximately 37% lower than the reference in the case of Tower 2 to 60% lower in the case of Tower 3. All the proposed towers feature centers of mass that are higher above mean sea water level than the reference tower. In fact, the reference tower features higher wall thicknesses near the tower base, that lower the centre of gravity. The most severe condition for the proposed designs is DLC 1.6. Compared to the reference tower, both mean and maximum pitch recorded during operation (DLC 1.6) decrease. Nacelle acceleration however increases significantly for the new designs, up to approximately 40% for Towers 3 and 4.

Table 1. Main properties of the proposed towers and maximum rotation and accelerations under DLCs simulated.

	REF	Tower 1	Tower 2	Tower 3	Tower 4
fn [Hz]	0.43	0.28	0.35	0.248	0.33
CoM [m]	-	73.96	51.05	67.27	51.91
Mass [t]	1262.9	562.68	796.72	498.42	720.56
CoM FOWT [m]	-	-11.95	-11.54	-11.85	-11.72
Θmean DLC1.6 [°]	4.00	3.53	3.68	3.60	3.60
Θmax DLC1.6 [°]	6.83	6.05	6.39	6.02	6.02
Θmax DLC6.1 [°]	6.21	6.33	6.38	6.24	6.24
TT Axmax DLC1.6 [m/s^2]	2.03	2.83	2.62	2.85	2.85
TT Axmax DLC6.1 [m/s^2]	1.68	1.85	1.78	1.81	1.81

Furthermore, results will show that fore-aft tower base shear forces decrease 10-15% depending on the specific tower design. However, tower base bending moments decrease only slightly, up to approximately 7%. Due to the increase in the flexibility of the proposed towers, maximum deflections tend to increase.

4.CONCLUSIONS

In this study the possibility of designing a lightweight tower for the IEA 15MW RWT is evaluated. In this regard, four new tower designs are proposed, with a range of masses that vary from approximately 37% to 60% lighter than the reference tower design. FOWT towers are in fact usually conservatively designed. In offshore industry it is common to use stiffened tower with respect to onshore designs, in order to assure that their natural frequencies are fixed above the 3P excitation band, while in onshore structures the range tends to be between 1P and 3P. This procedure leads to heavier designs, which result in an increase of inertial loads and cost of the structure. A subset of DLCs is simulated to evaluate design loads on the proposed designs. Results show that, despite the lighter towers, the ultimate design loads do not decrease as much as it was expected. In particular, for the tower base bending moment a very little reduction is observed, due to the fact that the proposed designs are characterized by a higher position of the CoG and a more flexible structure. For that reason, Tower #3, which is the most flexible design, is not affordable from a structural point of view, while Tower#2 and #4 are statically verified and able to resist to the ultimate design load. Those solutions are thus feasible, and they achieve a reduction in mass up to 43% in comparison to the reference design. However, a proper assessments of fatigue loads has not been performed, as it would require the evaluation of multiple sea states and operating conditions. In conclusion, from this study it is possible to identify two different routes for designing lighter FOWTs. First, the possibility to build a frequency-avoidance controller would allow the turbine to avoid the rotor speed that cause the 3P excitation. Second, the possibility to reduce peak loads thanks to a peak-shaving strategy, opening the potential use to structures very flexible like Tower #3. Both these possibilities would obviously affect the Annual Energy Production (AEP) thus require further analysis and could be the subject of further work on this topic. An alternative solution which does not affect the AEP and allows to shift tower natural frequencies is to modify the floating foundation. In particular, future works will be dedicated to exploit the capabilities of different moorings layouts to shift tower natural frequencies above the 3P range for the designed towers.

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