The Influence of Flexible Towers on the Dynamics of Offshore Wind Turbine Gravity Base Structures

Kieran O'Leary[1]*, Vikram Pakrashi[2], and Denis Kelliher[1]

[1] Dept. of Civil and Environmental Engineering, University College Cork, Cork, Ireland
[2] School of Mechanical & Materials Engineering, University College Dublin, Dublin, Ireland
*Kieran_OLeary@umail.ucc.ie

Abstract. With offshore wind turbines increasing in size, there is increasing interest in non-traditional support structures. New concepts include lightweight and flexible fiberglass composite towers that have potential benefits over traditional stiff steel towers. The aim of this paper was to assess how the combination of a more flexible wind turbine tower with an offshore concrete gravity base foundation would affect the dynamic response of the structure. The results focus on how the dynamic amplification factors (DAFs) change with varying levels of foundation stiffness during an extreme event (50 year return period extreme event).

Keywords: Composite Tower, Gravity Base, Dynamic Amplification Factor.

1 Introduction

The offshore wind energy industry has grown successfully for the past two decades [1]. As the market continues to grow, water depth, turbine mass and tower height are also increasing which requires a re-evaluation of what type of support structure is most suitable. The increasing size of structures reduces the benefits of steel as self-weight becomes a design driver in the traditionally steel dominated offshore industry. Composite towers are being considered [2, 3] as alternatives for offshore wind turbines (OWT). Composites consisting of glass fibers in an epoxy resin matrix may provide benefits such as better fatigue performance and corrosion resistance. These material properties could offset the higher manufacturing cost by extending a structure's lifetime. It is not currently possible to perform, with confidence, a detailed levelized cost of energy (LCOE) comparison between steel offshore structures and composite alternatives due to a lack of available information on the long term behavior of large composite structures in extreme environments.

The focus of this study was the dynamic behaviour of the composite tower and how it influenced the overall structure's response to environmental loading. Previous work has discussed the ultimate strength of composite towers [2, 3]. The combination of a more flexible wind turbine tower and a concrete gravity base foundation (GBF) was chosen for this study as it has been noted [2] that such flexible composite towers may weigh less than stiff steel towers. If the tower had a lower mass the center of gravity of the superstructure would be lowered, which could be beneficial in reducing the over-turning moment of the structure and allowing the foundation size and mass to be reduced, saving on material and installation costs. The composite towers are also expected to be more flexible, which could potentially result in greater deflections of the turbine nacelle and increase the dynamic response of the entire structure. The dynamic amplification factors (DAFs) of both composite and steel towers were determined to allow a comparison between the dynamic behavior of both composite and steel tower concepts.

2 Methodology

2.1 Model

The analysis considered a time domain simulation of the structure's response to loads and included 6 different soil stiffnesses, three wave and six wind seeds (input for the pseudo-random number generator required for stochastic models) and two tower materials. The full aero-hydro-servo-elastic behavior of the structure was represented by two decoupled models. It has been noted [4] that this decoupled analysis method can adequately simulate the structure's response if the forcing frequencies of the loads do not approach the structure's natural frequency. The interface between the two models is the yaw bearing that connects the wind turbine to the tower.

National Renewable Energy Lab's (NREL's) OWT modelling software, FAST [5], was chosen to simulate the aerodynamic loading on the wind turbine and its blades above the yaw bearing. Once calculated, the wind turbine loads were included in a USFOS [6] model as a six component load set of forces and moments applied to the yaw bearing node. The USFOS model simulated the support structure from the yaw bearing to the foundation.

Wind loads were combined with stochastic wave and semi-static current loads and applied to the structure in 0.5 s time steps for a total simulation duration of 3600s (1hr). The total base shear (BS) and overturning moment (OTM) were calculated at the base of the structure for each time step.

2.2 Dynamic Amplification Factor

Dynamic amplification factors (DAFs) are a measure of how the dynamic response corresponds to the static response (no structural movement, inertial or relative velocity effects) of a flexible structure. The DAFs were determined from the statistical properties of the dynamic and static responses for both the global base shear (BS) and overturning moment (OTM). The "drag-inertia parameter" method [7] is used in this study and was developed by Shell to determine the effect of dynamics on offshore jack-up rigs. The method calculates the inertial loads by determining the difference between the quasi-static and dynamic responses. The statistical properties of the quasi-static, dynamic and inertial loads such as the kurtosis, standard deviation, and averages were used to determine the "most probable maximum extreme" (MPME) response for both the static and dynamic loads. The DAF is the ratio of dynamic MPME to quasi-static MPME.

2.3 Environmental Conditions

The IEC 61400-3 [8] design load-case DLC 6.1 represents an extreme event with the wind turbine parked and blades feathered. The extreme event consists of 50-year return period environmental conditions for both turbulent extreme wind and stochastic sea-state conditions with misalignment of wind and sea represented as a yaw error of ± 8°.

2.4 Foundation Rotational Stiffness

The interaction between the soil and GBF was modelled in accordance with DNVGL-ST-0126 [9]. The rotational stiffness (K_R) is determined in (1).

$$K_R = \frac{8*G*R^3}{3*(1-\nu)}\left(1+\frac{R}{6*H}\right)\left(1+2*\frac{Dp}{R}\right)\left(1+0.7\frac{Dp}{H}\right) \quad (1)$$

Where G : Equivalent Dynamic Shear modulus (MPa)
R : Radius of footing (m)
H : Depth to bedrock (m)
D_p: Depth of penetration to bottom of foundation (m)
ν : Poisson’s ratio (assumed to be 0.5)

3 Model Specifications

3.1 Structure

The NREL 5 MW reference wind turbine design [10] was chosen as a basis for the model with alterations to the foundation and tower to suit the study. The monopile foundation was replaced with a concrete GBF. The dimensions of the GBF are presented in Table 1.

The transition piece (TP) and the yaw bearing are located at 10 m and 97.6 m above mean sea level (MSL) respectively, which is consistent with the NREL 5MW reference design. The NREL 5MW steel tower dimensions varies linearly from a 6 m outer diameter with 35.1 mm thickness at the base of the tower to a 3.87 m outer diameter with 24.7 mm thickness at the top. The modulus of elasticity along the longitudinal axis of the tower is assumed to be 210 GPa for the steel tower and 40 GPa for the composite tower, which is near the upper limit of modulus of elasticity for mass produced commercial structural composites consisting of glass fibers.

The composite tower had a consistent outer diameter of 8.0 m and wall thickness of 44 mm. The composite tower maintained the required global stiffness by compensating for the lower modulus of elasticity of the composite laminate with a larger diameter and cross-sectional area. The sandwich laminate construction assumed for the composite tower consisted of a foam inner core surrounded symmetrically by axial unidirectional glass fiber plies and biaxial rovings in an epoxy matrix with material properties taken from Griffith T, & Johanns W [11].

Table 1. Concrete Gravity Base Foundation

Diameter Top (m)	Diameter Base (m)	Submerged Height (m)	Total Height (m)	Concrete mass (t)	Ballast mass (t)
8.0	20.0	20.0	30.0	13830	9920

3.2 Metocean Data and Soil Conditions

The metocean data [12] is presented in Table 2. The soil shear moduli (varying from soft to stiff [13]), corresponding rotational stiffnesses and the global natural frequencies of the whole structure (N_f) are presented in Table 3. The turbine, 1p (0.12-0.20 Hz), and blade passing, 3p (0.35-0.60 Hz), frequency constraints were omitted as the study assumes the turbine is parked with blades feathered in storm survival mode during the 50 year extreme event. If the 1p and 3p frequency restrictions were included, two of the steel natural frequencies and four of the composite frequencies would be unacceptable. The 50 year extreme event was considered as there is minimal aerodynamic damping provided by the non-rotating feathered blades. The low damping in the system during storm survival mode produces higher DAFs.

Table 2. Hollandse Kust Zuid – 50 Yr Return Period Extreme Event

Water Depth (m)	Sig Wave Height Hs (m)	Peak Period (s)	Wave Direction (°)	Current Speed (m/s)	Hub Wind Speed (m/s)
20	7.0	12.1	000	1.5	40.4

Table 3. Shear Moduli, Foundation Rotational Stiffness K_R, and Natural Frequencies N_f

Shear Modulus (MPa)	5	15	25	35	45	55	65
K_R (10e4 MN m)	3.35	10.06	16.77	23.47	30.18	36.88	43.59
N_f – Composite (Hz)	0.25	0.33	0.35	0.36	0.37	0.37	0.38
N_f – Steel (Hz)	0.34	0.51	0.57	0.60	0.62	0.63	0.63

4 Results and Discussion

While not a full structural analysis or design, the DAFs were indicative of the relative differences in loads and displacements between the composite tower and the steel tower and can provide a trend on how the dynamic responses change with varying foundation stiffnesses. The results of the analysis are presented in Fig. 1.

The only sources of excitation are wave and wind loads as the turbine was assumed to be parked. As the foundation stiffness decreases, the DAFs increase as the natural frequency moves closer to the wave and wind forcing frequencies. It can be seen from Fig. 1 that the composite tower results in a significantly larger DAF than the steel tower design. The increased DAF indicates an increase in both displacements of the superstructure and loads on the foundation. The DAF of the composite tower concept could be brought in line with the steel tower by increasing the global stiffness of the structure. This could be achieved through either a larger base diameter or the use of a composite laminate with higher modulus of elasticity via the addition of carbon fibers to the laminate.

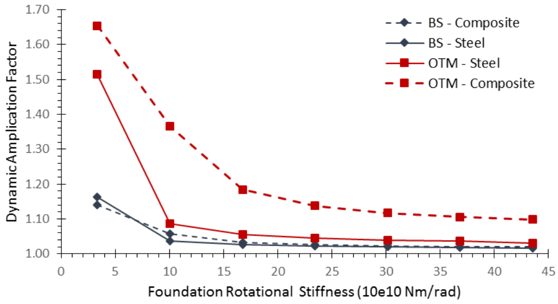

Fig. 1. Base Shear and Over-Turning Moment DAFs for Foundation Rotational Stiffness

If the use of a composite tower leads to higher overturning moments, the safety margin of the concrete foundation would decrease. To maintain the same safety factor for higher loads, an increase in foundation ultimate capacity would be required via a larger base diameter and higher concrete and ballast mass. This increase in size and mass would increase the cost of the foundation due to increased volume of materials, higher labour requirement, longer fabrication time, and the use of larger installation vessels operating in smaller weather windows.

There is not sufficient information about the potential taxes, profit margins, logistics transportation, supply chain, equipment/plant costs and secondary effects (changes to foundation) to compare the LCOE between steel and composite towers.

Limiting the cost comparison to material and labour costs, the composite tower would cost a total of $885,890 to manufacture assuming the fabricating process is based on the VARTM process used for similarly sized wind turbine blades [14]. A comparable 5MW steel tower would cost in the range of $430,000 - $670,000 [1].

As the LCOE is the primary driver in offshore construction, any increase in costs (due to the addition of carbon fiber or increased foundation size) would decrease the economic viability in comparison with the steel tower. The concept may remain viable for high soil stiffness locations where such measures would not be required.

Therefore the composite tower is unlikely to be suitable as a straight replacement for the traditional steel tower for gravity base structures without significant re-design as the cost of both the concrete foundation and the tower would be higher for the composite option.

5 Conclusion

The results suggest that it would not be beneficial to simply replace steel towers with composite towers in offshore wind turbine structures as composite towers have higher initial manufacturing costs than steel towers. It is possible that even with additional optimization composites may remain an unsuitable for the tower of a standardized “soft-stiff’ OWT design due to secondary effects on the foundation.

Composite tower concepts that mitigate the flexible behavior, such as the C-Tower’s “soft-soft” design [3], concepts that use active-pitch control to minimize displacement via blade drag, or concepts that use the lower mass of a tower to reduce foundation size and cost such as VolturnUS [2] remain viable.

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