



Title	An integrated dynamic analysis of a 5MW monopile-supported offshore wind turbine under environmental loads
Authors(s)	Jawalageri, Satish, Jalilvand, Soroosh, Malekjafarian, Abdollah
Publication date	2022-08-26
Publication information	Jawalageri, Satish, Soroosh Jalilvand, and Abdollah Malekjafarian. "An Integrated Dynamic Analysis of a 5MW Monopile-Supported Offshore Wind Turbine under Environmental Loads." CERAI, August 26, 2022.
Conference details	The 2022 Civil Engineering Research in Ireland (CERI) and Irish Transportation Research Network (ITRN) Conference, Dublin, Ireland, 25-26th August 2022
Publisher	CERAI
Item record/more information	http://hdl.handle.net/10197/26019

Downloaded 2026-04-30 03:39:54

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

An integrated dynamic analysis of a 5MW monopile-supported offshore wind turbine under environmental loads

Satish Jawalageri^{1,2*}, Soroosh Jalilvand², Abdollah Malekjafarian¹

¹Structural Dynamics and Assessment Laboratory, School of Civil Engineering, University College Dublin, Dublin, Ireland.

²Gavin and Doherty Geosolutions, Dublin, Ireland.

* Corresponding author, Email address: satish.jawalageri@ucdconnect.ie

ABSTRACT: This paper investigates the dynamic behaviour of an offshore wind turbine (OWT) supported on medium dense sand using an integrated load assessment. An integrated modelling approach is introduced to allow for considering aerodynamic and hydrodynamic loading and also soil-structure interaction. A numerical model of the NREL 5MW monopile-supported OWT is initially developed in OpenFAST software. The foundation of the structure is modelled using SESAM software where soil-structure interaction is adopted using API curves and integrated to the OpenFAST model using the stiffness values at mudline level. The integrated model provides a better understanding of the structural behaviour of OWT under various environmental conditions.

KEY WORDS: Offshore wind turbines, Waves, Wind, Load assessment, Integrated model, Monopile, Soil-structure interaction.

1 INTRODUCTION

A large amount of carbon dioxide is emitted from non-renewable energy resources such as fossil fuels. Renewable energy resources like wind energy and solar energy play a significant role in addressing carbon footprint. Among these resources, wind energy is one of the most widely used resources and it is proven to be one of the most efficient and reliable [1].

Offshore wind turbines (OWTs) are more effective than onshore wind turbines because the speed of the wind and its direction are consistent, so fewer turbines are required to produce the same amount of electricity as offshore turbines generate. The foundations of offshore wind turbines contribute up to 20-25% of total cost of the structure [2]. This leads to the need to optimise both the design and installation of the structure. The majority of offshore foundations across the world are monopile based foundations [3]. In general, monopile foundations may have a diameter of 8-10 m [4] and embedment lengths depend on the water depth, soil properties and turbine size.

Due to the advancement of technology in offshore industry, OWTs are becoming taller with relatively deeper foundations in order to produce more energy. OWTs are unique structures due to their operational conditions where they are working under harsh environmental conditions [5]. In general, they are subjected to various environmental loads such as wind, wave and current. Further, the interaction of foundation structure with soil along with external loads make it complicated to design and analyse the OWT structure. The natural frequencies of the structure are close to the rotor frequency during operational condition and wave frequencies which may result in fatigue damage of the structure [6]. Therefore, it is important to understand the dynamic response of the OWT subjected to external loads considering soil-structure interaction (SSI) under different loading conditions in which OWTs operate.

In this study, an integrated approach for modelling OWTs considering SSI is introduced. An NREL 5MW monopile supported OWT is used as a reference model. The

environmental loads including wind, wave and current are modelled using OpenFAST software. The foundation and SSI are modelled in a software called SESAM. The SSI is then integrated to the OpenFAST model using the mudline stiffness matrix which is extracted from SESAM model. The integrated model is used to analyse dynamic behaviour of the OWT under external loading conditions.

2 EXTERNAL LOADS

This section introduces various external loads acting on the OWTs. Primarily, there are two types of loading that OWTs experience i.e., aerodynamic loads and hydrodynamic loads. These are the governing loads that should be considered during the design of offshore wind structure. Figure 1 shows the components of the OWT and various loads experienced by the wind turbine during the service time of the structure.

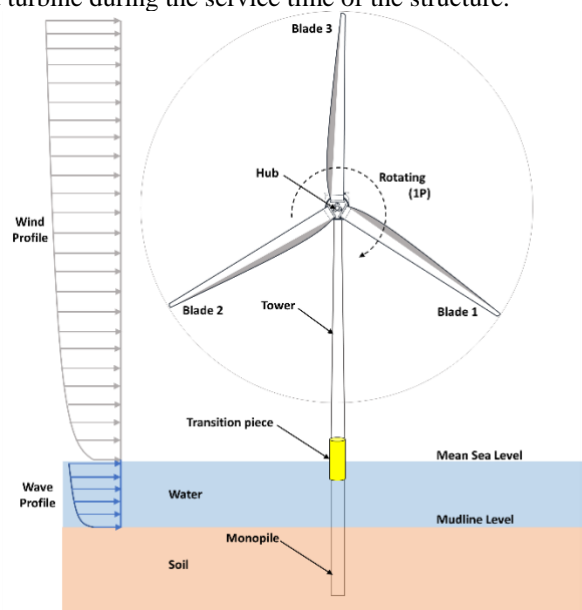


Figure 1. Components and loads on OWT.

2.1 Aerodynamic Loads

The wind loads acting on the structure are the dominant load during the operation of OWTs. The turbine tower and blades are subjected to the wind loads acting on the wind turbines. OpenFAST uses the blade element momentum (BEM) theory [7] to calculate the aerodynamic loadings along the blades. BEM theory is the combination of blade element theory (or propeller theory) and momentum theory. Blade element theory calculates the forces by dividing the blade into a number of segments along the length and then the force is calculated on each segment. Momentum theory calculates the reduction in velocity when wind passes through the rotor. BEM uses these two concepts to find the axial forces and torques acting on the rotor blades.

In addition to this, power law is used to calculate the wind load along the turbine tower as wind speed along the vertical height changes [8]:

$$V(z) = V_{hub} \left(\frac{z}{z_{hub}} \right)^\beta \quad (1)$$

where $V(z)$ and V_{hub} are the mean wind speeds at the height z above the MSL and hub height, z_{hub} , respectively, and the power law coefficient, β of 0.143 has been considered in this study [9].

2.2 Hydrodynamic Loads

These are the loads caused due to the action of waves on the structure submerged below the water. Hydrodyn is a module in the OpenFAST which is used to calculate the hydrodynamic loads. Regular waves have been considered for the calculation of hydrodynamic loads on the structure in this study. The hydrodynamic loads on the structure are calculated based on strip theory using Morison's equation [10]. In this study, Morison coefficients (C_d and C_m) are calculated by considering the marine growth thickness of 100mm and diameter of pile as 6m with wave height of 6m and wave period of 10sec. C_d and C_m are obtained as 0.64 and 2, respectively ([8] and [11]). Morison's equation is a function of water particle velocity and acceleration along the depth and the force per unit length along the cylinder is given by,

$$dF_h = 0.5 \rho_w C_d D dz |v_r| v_r + C_m \rho_w A(z) dz a_r \quad (2)$$

where ρ_w represents the density of water, Ddz is the area of the strip with diameter (D) of 6m and $A dz$ is the displaced volume, v_r is the relative water velocity with respect to velocity of the body and a_r represents the relative fluid acceleration.

A surface current velocity of 1.5m/s has been considered where OpenFAST calculates the current velocity along the depth using the power law [12].

3 INTEGRATED APPROACH

This section introduces the integrated model in order to understand the behaviour of OWTs considering soil-structure

interaction. In this study, an NREL 5MW turbine is considered as the reference model.

OpenFAST software is used for structural analysis including the external loads. The software currently does not support the foundation modelling which creates a limitation for scour modelling. However, the dynamic contribution of soil properties below the mudline can be simplified using a stiffness matrix which represents soil-structure interaction. To overcome this drawback, the scour process and soil-structure interaction are modelled accurately in a software called SESAM. Figure 2 shows the integration of the two software - SESAM and OpenFAST. The following modelling approach is used to integrate the SESAM and OpenFAST,

Step 1: Initially, the maximum interface load among the time series from the OpenFAST with a rigid connection at the bottom are calculated for each load scenario.

Step 2: The above obtained loads are used as inputs in SESAM where the soil model and wave loads are incorporated to enable soil structure interaction to be considered.

SESAM considers the pile below the mudline by subdividing it into a number of elements that are rigidly interconnected at nodal points and each node has six degrees of freedom. Further, the soil profile in the SESAM is modelled by multiple sublayers in order to capture the pile soil interaction at each node. The soil spring stiffness at the mudline level is obtained.

Step 3: The mudline spring stiffness 6x6 matrix is obtained for each load condition as the output of SESAM. These spring stiffness values are then integrated in OpenFAST for a medium dense soil profile.

The integrated model is then used to analyse the behaviour of the structure for which acceleration data at nine different levels are extracted along the tower of the OWT (Figure 3). Power Spectral Density (PSD) is then applied to these acceleration data to extract the global natural frequencies for a soil profile.

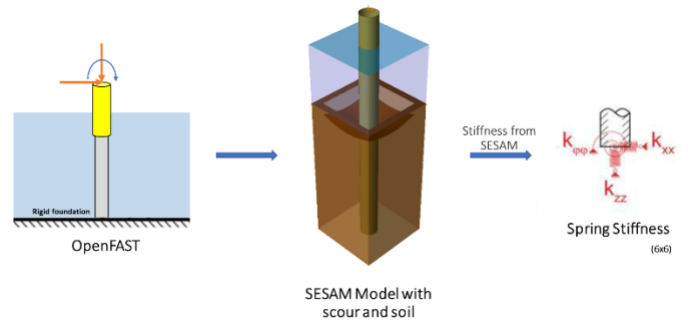


Figure 2. Modelling Approach

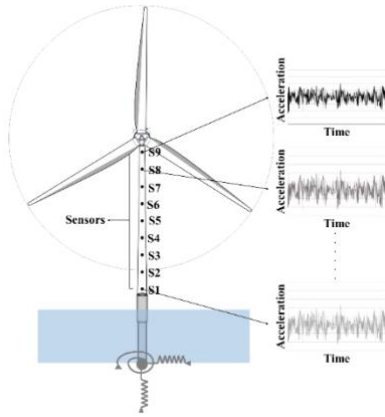


Figure 3: Sensor locations in the simulations

4 RESULTS

In this study, medium dense sand with unit weight, angle of internal friction and initial modulus of subgrade reaction of 19 kN/m^3 , 35 deg and 22000 kN/m^3 , respectively, are considered [13]. Figure 4 shows the power spectral density of an OWT supported on medium dense sand. PSD peaks correspond to the harmonics of the system (3P, 6P and wave harmonics) and the natural frequencies. The presence of these frequencies makes it difficult to identify the system natural frequencies. The first two natural frequencies of the system are detected at 0.244 and 1.419 Hz .

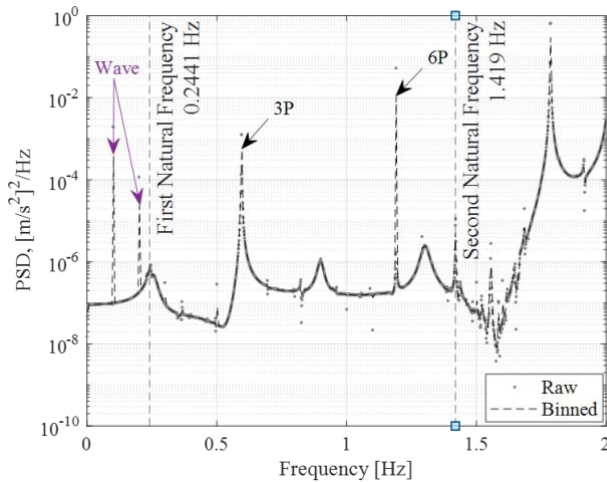


Figure 4. Power spectral density of structure

5 CONCLUSION

The paper introduces an integrated approach to the analysis of OWTs in order to understand the response of the structure to external loads such as aerodynamic and hydrodynamic loads, taking account of soil-structure interaction at foundation level. An NREL 5MW turbine is considered as the reference model where OpenFAST is used for structural analysis and SESAM is used to model the foundation part of the OWT. This model enhances the understanding of the structural response of OWTs founded on medium dense sand under environmental loads.

ACKNOWLEDGMENTS

The authors wish to express their gratitude for the financial support received from the Irish Research Council (IRC) EBPPG/2020/259.

REFERENCES

- [1] K. A. Abhinav and N. Saha, "Dynamic analysis of monopile supported offshore wind turbines," *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, vol. 170, no. 5, pp. 428-444, 2017, doi: 10.1680/jgeen.16.00022.
- [2] W. Carswell *et al.*, "Foundation damping and the dynamics of offshore wind turbine monopiles," *Renewable Energy*, vol. 80, pp. 724-736, 2015, doi: 10.1016/j.renene.2015.02.058.
- [3] WindEurope, "Offshore Wind in Europe," in "Key trends and statistics 2020," 2021.
- [4] C. Reale, J. Tott-Buswell, and L. J. Prendergast, "Impact of Geotechnical Uncertainty on the Preliminary Design of Monopiles Supporting Offshore Wind Turbines," *ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg*, vol. 7, no. 4, 2021, doi: 10.1115/1.4051418.
- [5] I. B. Løken and A. M. Kaynia, "Effect of foundation type and modelling on dynamic response and fatigue of offshore wind turbines," *Wind Energy*, vol. 22, no. 12, pp. 1667-1683, 2019, doi: 10.1002/we.2394.
- [6] L. J. Prendergast, K. Gavin, and P. Doherty, "An investigation into the effect of scour on the natural frequency of an offshore wind turbine," *Ocean Engineering*, vol. 101, pp. 1-11, 2015, doi: 10.1016/j.oceaneng.2015.04.017.
- [7] P. J. Moriarty and A. C. Hansen, "AeroDyn Theory Manual," in "NREL/TP-500-36881," National Renewable Energy Laboratory, 2005.
- [8] DNV-RP-C205 *Environmental Conditions and Environmental Loads*, DNVGL, 2014.
- [9] S. Bhattacharya, *Design of Foundations for Offshore Wind Turbines*. John Wiley & Sons Ltd, 2019.
- [10] J. R. Morison, J. W. Johnson, and S. A. Schaaf, "The force exerted by surface waves on piles," *Journal of Petroleum Technology*, no. 2, pp. 149-154, 1950. [Online]. Available: <https://doi.org/10.2118/950149-G>.
- [11] IEC 61400-3-1:2019&A11:2020 *Wind energy generation systems - Part 3- 1: Design requirements for fixed offshore wind turbines*, IEC, 2020.
- [12] J. Jonkman and B. Jonkman, "OpenFAST Manual," National Renewable Energy Laboratory, 2020.
- [13] L. J. Prendergast and K. Gavin, "A comparison of initial stiffness formulations for small-strain soil-pile dynamic Winkler modelling," *Soil Dynamics and Earthquake Engineering*, vol. 81, pp. 27-41, 2016, doi: 10.1016/j.soildyn.2015.11.006.