Finite Element Modelling and In Situ Modal Testing of an Offshore Wind Turbine

Erfan Asnaashari¹ · Andy Morris² · Ian Andrew² · Wolfgang Hahn² · Jyoti K. Sinha¹

Received: 10 November 2016 / Revised: 13 December 2016 / Accepted: 21 December 2016 / Published online: 1 August 2018
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Abstract

Purpose Generating electricity from wind turbines is currently a viable option to meet the electric power requirements in many countries. The structure of offshore wind turbines is constantly subjected to external dynamic loads due to wind, waves and rotor loads due to the rotation of blades. The frequency content of these dynamic loads is in the range of natural frequencies of the wind turbine. Therefore, determining the in situ dynamic characteristics of a wind turbine is very beneficial, as it can lead to further improvements in its design, performance and safety.

Methods In this paper, the dynamics of the structure of an offshore wind turbine is investigated numerically and experimentally. The finite element (FE) model of structural components is developed based on design specifications. The model takes the effect of rotor–nacelle assembly into account by considering its mass and moment of inertias relative to the top centre of the tower. In situ modal tests using impulse excitations were carried out on the actual wind turbine when the rotor blades were not rotating to identify the modal parameters.

Results This paper presents predicted natural frequencies from the FE model based on design conditions and those identified from the modal and ambient excitation tests.

Conclusion It was observed that the first two bending modes are close to the natural frequencies identified experimentally by the in situ modal tests. It was also observed that the in situ modal tests were not able to excite other higher natural frequencies of the structure.

Keywords Offshore wind turbines · In situ modal testing · Structural dynamics · Finite element modelling

Introduction

Developing and harvesting alternative sources of energy has become vital over the past few years due to concerns about global warming caused mostly by using fossil fuels for energy production. Some countries have set targets to produce a specific fraction of total required electricity from renewable sources for the next decade to gradually decrease their dependency on fossil fuels. Wind energy is one of the alternatives, which can be converted into electricity by installing wind turbines at locations with consistent winds. Offshore wind farms are rapidly being developed especially in Europe, mainly because larger wind turbines can be placed offshore leading to higher energy production capacity.

The structure of offshore wind turbines is constantly subjected to external dynamic loads due to wind and waves, as well as rotor loads due to the rotation of blades. The frequency content of these dynamic loads is in the range of

✉ Erfan Asnaashari
erfan.asnaashari@manchester.ac.uk

Andy Morris
andy.morris@edfenergy.com

Ian Andrew
ian.andrew@edfenergy.com

Wolfgang Hahn
wolfgang.hahn@edfenergy.com

Jyoti K. Sinha
jyoti.sinha@manchester.ac.uk

¹ School of Mechanical, Aerospace and Civil Engineering,
University of Manchester, Manchester M13 9PL, UK

² EDF Energy, West Burton, UK

natural frequencies of the wind turbine. Therefore, determining the dynamic characteristics of a wind turbine is very beneficial not only to improve the design and performance, but also to understand their sensitivity to different load cases for structural health monitoring purposes.

Zaaijer [1] investigated the accuracy of several simplified dynamic models for the foundation of offshore wind turbines. The first and second natural frequencies of the support structure for five different wind turbines were obtained from the finite element model and experimental data. The difference between computed and measured natural frequencies was in the order of 0.5–35% and 3–57% for the first and second natural frequencies, respectively. The dynamic responses of an offshore wind turbine with jacket foundation were studied by Ong et al. [2] through numerical simulations. Bisoi and Haldar [3] also conducted numerical studies to understand the dynamic behaviour of offshore wind turbines supported on monopiles in clay soil. The tower and monopile were modelled as Euler–Bernoulli beam elements, while the foundation was simulated using nonlinear Winkler model. Adhikari and Bhattacharya [4] also utilised Euler–Bernoulli beam theory to propose a model for characterisation of the dynamic behaviour of offshore wind turbines. Andersen et al. [5] obtained the probability density function of the first natural frequency of an offshore wind turbine with monopile foundation based on a simple model integrating a nonlinear p – y curve for calculation of pile displacement. Their model did not consider soil damping due to material dissipation or wave radiation.

Damgaard et al. [6] carried out experimental investigations to obtain the first bending frequency of an offshore wind turbine in the North Sea. Ten rotor stop tests were conducted to evaluate the dynamic properties of the wind turbine. They also developed a numerical model considering soil damping based on Winkler approach to perform modal analysis and presented the first bending frequency obtained from the numerical model and experiment. A comparison between dynamic responses of monopile, tripod and jacket foundation structures for an offshore wind turbine was made by Shi et al. [7]. In addition to natural frequencies, different responses such as displacement, bending moment and shear force were compared for all the foundations. The modal analysis results showed that marine growth has negligible effect on the natural frequencies. Ibsen [8] equipped a prototype of a bucket offshore wind turbine with accelerometers at different locations to obtain the natural frequencies of the wind turbine for three conditions: idle conditions, turbine without blades and turbine without blades and nacelle. The effect of different conditions on the first two natural frequencies was illustrated.

In this paper, the finite element (FE) model of structural components of an offshore wind turbine is developed based on design specifications to predict the natural frequencies

Fig. 1 Schematic view of the offshore wind turbine

Table 1 Specifications of the offshore wind turbine

Turbine name	SWT-2.3-93
Rotor diameter (m)	93
Rated power (MW)	2.3
Hub height (m)	83.15
Water depth (m)	12.52
Pile driven length (m)	39.8
Structure diameter (conical) (m)	2.5–4.6
Wall thickness (mm)	16–90

and mode shapes. The model takes the effect of rotor–nacelle assembly into account by considering its mass and moment of inertias relative to the top centre of the tower. Nonlinear support springs obtained from a p – y curve are used to model the interaction between the monopile and the surrounding soil. Also presented in this paper are the results of in situ modal and ambient excitation tests carried out on the actual wind turbine.

Case Study

A Siemens SWT 2.3 MW offshore wind turbine with monopile foundation is chosen for this case study. The wind turbine is located 1.5 km off the coast of North-East England. As shown in Fig. 1, the monopile was connected to a conical transition piece which is larger in diameter. The 90 mm

annulus between the monopile and transition piece (TP) was filled with an ultrahigh performance grout. The length of the overlap zone for the grouted joint connection is 9 m. The tower was installed on top of the TP through a bolted flange connection to support the rotor–nacelle assembly. The hub height of the turbine is 83.15 m with respect to the lowest astronomical tide (LAT) and the water depth is 12.52 m. The monopile was driven 40 m inside the soil. Table 1 summarises the specifications of this case study.

Finite Element Analysis

This section describes how the components of the turbine shown in Fig. 1 are modelled and assembled together to build a complete FE model. The geometry of the components is created and meshed using open source software called Salome and the analysis is done in Code_Aster which is a mechanical solver.

Rotor–Nacelle Assembly

The rotor–nacelle assembly (RNA) is modelled as a point mass on top of the tower of the wind turbine. The total mass of RNA including the blades and all the components inside the nacelle is applied according to the specifications provided by the turbine manufacturer. Mass moments of inertia of the RNA relative to the top centre of the tower are also applied to the point mass. These values are presented in Table 2.

Tower and Transition Piece

Euler–Bernoulli beam element is used to model the entire tower and a part of the transition piece which is above the grouted joint connection (Fig. 1). Each beam element consists of two nodes and each node has three translational and three rotational degrees of freedom and representing a section with constant wall thickness along the tower and transition piece. In total, 211 beam elements are used for modelling this section.

Point and distributed masses of appurtenances such as ladders, platforms and boat landing bumpers on the tower and transition piece are also incorporated into the model. Note that the stiffness contribution of these elements to the wind turbine tower is neglected in the FE model.

Table 2 Mass properties of the RNA

Total mass (kg)	134, 300			
Mass moment of inertias (kg m ²)	I_{xx}	I_{yy}	I_{zz}	
	7.43×10^6	1.21×10^7	7.34×10^6	

Grouted Joint Connection

The 20 noded quadratic hexahedral element is used to model the grouted connection between the monopile and transition piece which is 9 m in length. The monopile and transition pieces are made of steel with Young's modulus of 210 GPa, density of 7850 kg/m³ and Poisson's ratio of 0.3. The grout is modelled as a linear elastic material with Young's modulus of 55 GPa, density of 2440 kg/m³ and Poisson's ratio of 0.19. As shown in Fig. 2 (left), the inner surface of the transition piece (master) is tied to the outer surface of the grout (slave). Similarly, the inner surface of the grout (master) is tied to the outer surface of the monopile (slave). These connections are made using *LIAISON_MAIL* command in Code_Aster. The grouted connection is therefore assumed to transfer forces from the transition piece into the monopile as if they are one structure. A total of 4560 hexahedral elements (2 segments along the thickness, 40 along the perimeter and 57 along the length) were used altogether for meshing each component of the grouted joint connection.

Monopile and Surrounding Soil

Similar to the tower and the upper part of the transition piece, Euler–Bernoulli beam elements are used to construct the FE model of the monopile structure below the grouted joint connection. The hydrodynamic mass of water displaced by the submerged monopile and transition piece is calculated and included in the FE model by defining an equivalent density for each submerged element.

The p – y method [9] is employed to model the lateral interaction between the monopile and its surrounding soil. As shown in Fig. 1, the soil in this study consists of three main layers along the driven length of the monopile (27 m below the mudline); marine sand, clay and mudstone. The beam elements of the monopile are supported by nonlinear springs applied at nodal points between the elements (Fig. 3). These support springs are characterised by one p – y curve at each nodal point. The angle of internal friction of marine sand can be used to obtain the stiffness of springs along this layer. The stiffness per unit length of the clay is equal to the initial slope of the p – y curve as

$$k_{\text{clay}} = \frac{p_u \left(\frac{y}{y_c} \right)^{-2/3}}{6y_c}, \quad (1)$$

where y is the lateral displacement of the pile and p_u is the static ultimate lateral resistance which can be calculated as:

$$p_u = \min \left[(3s_u + \gamma X) D + J s_u X, 9s_u X \right], \quad (2)$$

$$y_c = 2.5\epsilon_c D, \quad (3)$$

Fig. 2 Schematic (left) and FE model (right) of the grouted joint connection

where s_u is the undrained shear strength of the soil, γ is the effective unit weight of soil, J is an empirical constant, X is the depth below mudline, D is the monopile diameter and ε_c is the strain which occurs at half of the maximum stress in laboratory undrained compression tests.

As recommended in DNV [9], the first discretisation point of the curve beyond the origin is localised at the relative displacement of $\frac{y}{y_c} = 0.1$. The compressive strength for the mudstone layer is more than 6.9 MPa, which means the rocks are strong. Here, the p - y curve suggested by Reese [10] for strong rocks is used to calculate the stiffness of springs within the mudstone layer. The interaction between the monopile and the surrounding soil consists of 70 elements in the FE model.

Complete Assembly of the FE Model

Figure 3 shows the FE model of the complete wind turbine by assembling together all parts from Sects. “Rotor–Nacelle Assembly” to “Monopile and Surrounding Soil”. All the degrees of freedom of the node of the monopile at the bottom are restricted. As shown in Fig. 3(right), the nacelle was positioned at an angle of 20° with respect to the x direction during the in situ experiments; hence, this position of the nacelle is considered in the FE model. The 1-D beam models of the upper and lower parts of the turbine structure are connected to the 3-D model of the middle part through rigid links as shown in Fig. 3. The joint connection using *LIAISON_ELEM* command is used for these rigid links.

Fig. 3 Schematic view of the FE model (left) and nacelle position (right)

Modal Analysis

The complete FE model is further used to perform eigenvalue and vector analysis to compute the natural frequencies and mode shapes of the offshore wind turbine. Table 3 presents the computed first and second natural frequencies.

Table 3 Computed natural frequencies from the FE analysis

FE model	<i>x</i> direction	<i>y</i> direction
1st bending mode (Hz)	0.353	0.350
2nd bending mode (Hz)	1.466	1.378

Fig. 4 The first (left) and second (right) bending mode shapes of the wind turbine obtained from the FE analysis

Figure 4 also shows the bending mode shapes of the structure of the wind turbine in one direction.

In Situ Modal Testing

In situ modal tests using impulse excitations were carried out on the actual wind turbine when the rotor blades were not rotating. The excitation was applied to the structure from inside the transition piece using an instrumented

hammer. Low-frequency accelerometers were installed on the inner wall of the transition piece approximately 10.15 m above LAT in the *x* and *y* directions as shown in Fig. 5. Measured forces and accelerations were recorded simultaneously at a sampling rate of 500 Hz by a data acquisition card connected to a laptop. The frequency response function (FRF) of measured data for both directions is shown in Fig. 6. Table 4 lists the measured natural frequencies obtained from the modal tests.

Ambient Excitation Test

The acceleration vibration responses of the wind turbine were also recorded under ambient excitation when the rotor was stationary. Such ambient excitation should also excite the turbine natural frequencies. Figure 7 shows the amplitude acceleration spectrum in the *x* direction due to ambient wind excitation. The peaks observed in the spectrum are also

Fig. 5 Location of accelerometers with respect to LAT**Fig. 6** Typical FRF plots obtained from measured acceleration and applied impulsive forces in the *x* direction (left) and *y* direction (right)

Table 4 Experimentally identified natural frequencies

Modal tests	x direction	y direction
1st bending mode (Hz)	0.378	0.352
2nd bending mode (Hz)	1.714	1.663

Fig. 7 A typical amplitude acceleration spectrum in the x direction due to ambient excitation of the wind turbine

close to the natural frequencies identified for the structure in the x and y directions. An additional peak at 0.2772 Hz may be related to the blade frequency which needs to be verified by carrying out modal tests on the blades.

Conclusion

The FE model of the wind turbine structure based on the design conditions is used to compute its natural frequencies and mode shapes. It was observed that the first two bending modes are close to the natural frequencies identified experimentally by the in situ modal tests. However, the initial FE model may need to be updated to match the computed natural frequencies to the experimental ones. This may provide better understanding of the turbine dynamics. It was also

observed that the in situ modal tests were not able to excite higher natural frequencies of the wind turbine structure and this should be further investigated.

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