Renewable Energy 123 (2018) 450–459

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Fatigue life sensitivity of monopile-supported offshore wind turbines to damping

Ramtin Rezaei [a], Paul Fromme [b,*], Philippe Duffour [a]

[a] Department of Civil, Environmental & Geomatic Engineering, UCL, London, WC1E 6BT, UK
[b] Department of Mechanical Engineering, UCL, London, WC1E 6BT, UK

A R T I C L E I N F O

Article history:
Received 8 May 2017
Received in revised form
8 January 2018
Accepted 17 February 2018
Available online 19 February 2018

Keywords:
Offshore wind turbine
Fatigue life calculation
Vibration analysis
Renewable energy

A B S T R A C T

Offshore wind energy is an important renewable electricity source in the UK and Europe. Monopiles are currently the most commonly used substructures to support offshore wind turbines. The fatigue life of offshore wind turbines is directly linked to the oscillatory bending stresses caused by wind and wave loading. The dynamic response of the structure is highly dependent on the combined aerodynamic, hydrodynamic, structural, and soil damping present. The fatigue life sensitivity of a reference 5 MW wind turbine under operational and non-operational conditions has been investigated using time-domain finite element simulations. The model uses beam elements for the monopile and tower and includes nonlinear p-y curves for soil-structure interaction. The effects of the wind turbine operation, environmental loads, and variable damping levels on the fatigue life were investigated systematically. The fatigue life increases significantly as a result of reductions in the bending stress caused by increased damping. From a practical point of view, significant cost-savings could be achieved in the design of a wind turbine by fitting supplemental damping devices. An efficient approximate method is proposed to assess the influence of damping, by scaling the vibration amplitudes around the first natural frequency of the system.

1. Introduction

Offshore wind electricity generation has become one of the fastest growing renewable energy technologies. Europe has focused extensively on the development of offshore wind energy, to the extent that almost 90% of the largest offshore wind farms in the world are located there [1,2]. Monopiles are currently the most common type of support structure for offshore wind turbines. The fatigue life of offshore wind turbines (OWT) is directly linked to the stress induced by the structural vibrations due to environmental (wind and wave) loading. As a dynamic system, the magnitude of the response of an OWT depends on the amplitude of the applied forces, the proximity of the natural frequencies to the dominant forcing frequencies and the damping. As wind turbines are lightly damped structures, a good estimate of the damping is crucial to predicting their dynamic response accurately. The overall damping in offshore wind turbines is mostly comprised of aerodynamic, hydrodynamic, structural and soil damping, and damping due to supplemental damping devices such as tuned-mass dampers. There is significant uncertainty about each of these contributions. Soil damping depends on the soil type and is particularly difficult to measure directly. Different values for soil damping ratios in offshore wind turbines mounted on monopiles have been suggested in literature [3–6], varying from 0.17% [4] up to 1.3% of critical damping [6]. Aerodynamic damping is the highest contributor to the overall damping, but it mostly acts in the fore-aft direction when the turbine is in operation. In parked conditions, good agreement is found for the side-side and fore-aft damping levels reported in literature [7–9]. In this case, the overall damping is reported to be about 1% of critical damping in the fore-aft direction and 1.5% for the side-side mode. In the operational range, the aerodynamic damping is known to be variable and the levels proposed in the literature vary from 2% to 8%, depending on the wind speed, size and operation of the wind turbine [10–12].

Offshore wind turbines are generally designed for a minimum of 20 years of service life [13] and the predicted fatigue life of the system has to match this [14,15]. Four methods of fatigue assessment for structures are commonly used; simplified method, spectral method, time-domain method and deterministic method [16].

* Corresponding author.
E-mail address: p.fromme@ucl.ac.uk (P. Fromme).

https://doi.org/10.1016/j.renene.2018.02.086
0960-1481/

As the aerodynamic loading has a wide bandwidth, damage calculation methods in the frequency domain lead to very conservative estimates [17]. Time-domain approaches are considered the most reliable for the prediction of fatigue life as nonlinear and stochastic load effects caused by the environmental loads and soil-structure interaction can be taken into account [18]. In addition, various hybrid frequency/time-domain fatigue analysis methods have been proposed [17–21], typically using transfer functions to obtain the response in the frequency-domain [17,18,22–25]. However, in general predictions of fatigue life are considered less accurate than using time-domain methods.

The influence of damping on the fatigue damage of offshore wind turbines has been mostly considered in parked/non-operational conditions in the literature. The fatigue assessment of OWT is usually carried out by simulating and analysing the stress at critical locations such as the tower base [25,26] or the mudline [27]. The effect of damping in a parked condition was studied and it was demonstrated that the maximum bending moment could increase by 20% as a result of a 50% change in damping [6]. It was further shown that the mudline bending moment during an extreme wind and wave event is decreased by 5% if damping is increased by 1% [4]. The effect of soil damping has been studied and up to 47% reduction in fatigue damage due to a 4% increase in soil damping has been reported [26]. It was also suggested that a complete lifetime simulation including damping effects could clarify the influence on the fatigue life of OWTs, which has not been reported in literature.

This paper investigates systematically the effects of damping on the fatigue life of offshore wind turbines. The study is based on time-domain finite element (FE) simulations carried out on a reference offshore wind turbine supported by a monopile, including soil-structure interaction. The fatigue life was calculated by adding the damage contributions from representative environmental states in the operational wind speed range. The methodology is described in section 2. Section 3 discusses the relevant features of the wind and wave loads. In section 4, the effects of variable damping and operational state (shutdowns) are studied systematically. The contribution of increased damping on increased fatigue life is investigated. A novel approximate method is proposed, significantly reducing the computational costs associated with time-domain simulations for multiple damping levels (requiring only one full time-domain analysis for one level of damping with little additional computational effort for other damping levels), while allowing accurate predictions of the effect of increased damping on prolonged fatigue life.

2. Methodology

2.1. Modelling approach

As fatigue affects mostly structural details (e.g. welds), it must be assessed using a comprehensive and realistic structural model. Following other researchers [26,28–31], this study is based on a reference 5 MW case study wind turbine model mounted on a monopile, for which the US National Renewable Energy Laboratory (NREL) has provided a significant amount of data [32]. According to initial design reports [33], it was due to be constructed at a location approximately 10 km off the Dutch coast in the North Sea. The complete fatigue analysis was carried out in different stages using a combination of software packages. The process is shown schematically in Fig. 1. The wave and wind loads were calculated based on available meteorological data for the proposed site. Wave load time-series were obtained in MATLAB by inverse-Fourier Transform of the JONSWAP spectrum [34]. Wind load time histories were calculated using FAST, a software package provided by NREL, which includes a validated model of the turbine chosen here. FAST simulates an incoming turbulent wind field (TurbSim module) and then computes the aerodynamic interaction of the flow with the blades using Blade Element Momentum theory. FAST also provides an estimate of the aerodynamic damping, which is otherwise difficult to obtain. As FAST has limited capabilities for modelling soil-structure interaction and only allows for a basic structural model of the tower/monopile, the wind loads obtained from FAST and wave loads from Matlab were used as input to an FE model (ABAQUS) of the OWT which comprised the tower, monopile and soil system. Response stress time histories were computed and recorded in ABAQUS at critical locations for various load time series.

2.2. Geometry and properties of the OWT and monopile

The reference wind turbine is a 3-bladed wind turbine, shown schematically in Fig. 2 with key dimensions. The rotor diameter is 126 m, and the hub height at 92 m above mean sea level. The monopile embedded depth is 45 m for a water depth of 21 m. The NREL 5 MW wind turbine uses a Repower 5M machine. The rotor blades are based on a LM-Glasfiber Holland design with a length of 62.7 m [35]. A slight modification to the blades adopted here was suggested in Ref. [32], which truncated the length of the blades by 1.1 m to be similar to those suggested for the Repower 5M machine. The operational range of wind speeds for this turbine is between 3 m/s to 25 m/s, with the rated rotor speed at 12.1 rpm.

The pile has a 6 m diameter with a constant thickness, while the tower has a tapered section with the diameter decreasing linearly from 6 m at the bottom to 3.87 m at the top (Fig. 2). In this study, the thickness of the pile and tower sections were modified from the original documents [32] to ensure that the natural frequency of the wind turbine lies between the 1 P (rotor) and 3 P (blade passing) frequencies with a margin of 10%. A pile thickness of 80 mm and linearly varying tower thickness of 28–38 mm were used to ensure that the first natural frequency of the system lies at 0.25 Hz.

The steel used for the monopile is assumed to have an elastic modulus of 210 GPa, a Poisson ratio of 0.3 and a density of 7850 kg/m^3. A higher density steel ($\rho = 8500$ kg/m^3) was used for the tower section to take into account the added mass of secondary steel [32].

2.3. Numerical simulation

The OWT time response due to the combined non-periodic aerodynamic and wave loading was simulated using the FE software ABAQUS. The equation of motion of the structure was implicitly solved for small amplitude vibrations. The FE Model comprises the tower and monopile, modelled using linear Timoshenko beam elements (ABAQUS: B21 element). The rotor was modelled as a lumped mass located at the top of the tower. The soil-structure interaction was modelled with nonlinear horizontal springs (p-y curves) connecting the monopile to a fixed reference (see section 2.4). A preliminary study showed that 0.5 m length elements produced sufficiently converged results, with less than 0.5% change in the results when the element size was reduced from 1 m in length. Good agreement with relevant reports on the 5 MW NREL wind turbine was obtained [32]. The dynamic analysis for fatigue calculations was done using implicit simulations with time increments of 0.1s. Following recommended practice, a one-hour simulation length was used throughout this paper. A preliminary study of fatigue damage sensitivity to simulation time confirmed that this was acceptable. Four hundred seconds were added at the start of the load time series and the corresponding simulation data was later discarded to avoid any potential initial transient effects. Numerical damping is normally applied by default in ABAQUS to