Soil Dynamics and Earthquake Engineering 114 (2018) 174–185

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

# Stochastic response reduction on offshore wind turbines due to flaps including soil effects

Shilpa Thakur, K.A. Abhinav, Nilanjan Saha*

*Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai 600036, India*

ARTICLE INFO

*Keywords:*
Offshore wind turbine
Soil-structure interaction
Non-linear dynamical analysis
Blade slotted flaps
Probabilistic analysis

ABSTRACT

This work attempts to investigate the load mitigation effects on foundations of NREL 5-MW offshore wind turbine (OWT) supported on fixed structures using blade trailing edge flaps. The analysis is subjected to turbulent wind and irregular wave loads. The offshore wind turbine is simulated for five met-ocean conditions for Indian scenario, covering operational to the parked region of turbine. Sea states being stochastic, the responses are obtained using average of Monte Carlo simulations. The blade element momentum theory is used to obtain the aerodynamic loads by modelling in a multi-body framework while the hydrodynamic and geotechnical analysis are performed in a finite element framework. Soil-structure interaction is modelled using nonlinear Winkler spring model along the length of the pile. The trailing edge flaps are numerically implemented through a dynamic link library into the aerodynamic program. Loose sandy soils with uniform density is considered for analysis. The results bring out the importance of including blade trailing edge flaps in OWT studies with significant response reduction (2.1–16.0%) for designing pile foundations.

## 1. Introduction

Offshore wind energy is increasingly being considered as a reliable source of clean and renewable energy. Wind turbines sited offshore are attaining popularity world-wide due to accessibility of sites, stronger and consistent winds with lesser turbulence and smaller shear than on land. In offshore deployment, due to increment in rotor size, the offshore wind turbine (OWT) blades are more flexible and subjected to vibration by wind loads along with tower interaction, which leads to structural or mechanical damage, thus increasing the downtime of the wind turbine. From this point of view, the analysis of combination of load-effects plays an important role for OWT. Almost all of the existing OWTs in European waters are supported on fixed structures [1]. These wind turbines are mostly installed in shallow water depth (20–30 m) on either monopile or the concrete gravity bases, but these technologies are not economically feasible for deep water depth (more than 45 m). Thus in order to maintain strength and stiffness requirements, space frame (tripods) and lattice frame (jacket) sub-structures will be required. Foundations represent a sizeable component in the capital expenditure for an offshore wind farm [2]. Therefore, minimizing the offshore foundation (both the platform and pile support) cost becomes imperative.

In this paper, a small structural change in the blade section is proposed by which significant reductions may be achieved in the substructural loading. The present change is done by the introduction of slotted flaps (or aerodynamic active device that change with wind speeds) in the aerofoil section of blades. While the effects of the change may not be that predominant in offshore rigid construction, however in loose soils (of sandy nature), this can be an effective measure in mitigating loads wherein the deflection component becomes large due to parametric/flutter type excitations. In this paper, the NREL 5 MW benchmark offshore wind turbine [3] (having a NACA 64-618 airfoil section) is considered to be supported on three types of widely used fixed platforms – monopile, tripod and jacket sub-structures; which are all assumed to be located in loose sandy soils.

Existing literature related to load mitigation models of wind turbine through aerodynamic changes can be broadly classified into two categories: as some that focus on structural changes (turbine blade's trailing edge flaps); and others that include advanced control techniques (through pitching of blades and restricting rotatory motion of drivetrain) to mitigate the loads. In offshore structural analysis, the effect of soil structure interaction (SSI) can become a guiding factor for design [4,5]. Being an interdisciplinary topic, the geotechnical analysis of OWTs usually resort to describing the soil effects on turbine by heuristically assuming aerodynamic/hydrodynamic loads (wind loads as sinusoidal loads, ignoring wave loads or assuming platforms as Euler-

---

* Corresponding author.
*E-mail addresses:* thakur.iitm29@gmail.com (S. Thakur), abhinavka@gmail.com (K.A. Abhinav), nilanjan@iitm.ac.in (N. Saha).

https://doi.org/10.1016/j.soildyn.2018.07.004
Received 29 April 2018; Received in revised form 23 June 2018; Accepted 8 July 2018

Bernoulli beams). In this work, therefore a comprehensive attempt is made to examine the blades trailing edge-flaps (TEF) effect on OWT response by coupling the influence of soil along with aerodynamic loads and hydrodynamic loads. Also the load mitigation technique accomplished here is through introduction of aerodynamic active devices i.e., trailing edge blade flaps in the rotor blade.

Aerodynamically active devices, showing more effectiveness with spanwise controls have gained significant research interest over the last decade as it ensures stability and reduces the fatigue experienced in the wind turbines. Several numerical investigations have been done, i.e., the modelling and optimization by including blade trailing edge flaps with the aim to reduce the cost of energy [6–8]. These investigations have shown the significance of the aerodynamic devices in power capture optimization. Smit et al. [9] has shown that through the flap deflection, the maximum power output can be increased in low fatigue wind region by proper flap sizing configuration and control. Effect of deformable TEF (DTEF) in reduction of fatigue load of OWT have shown promising results in comparison with collective pitch method [10]. Also the DTEF resulted in the improved performance of the turbine. Zhang et al. [11] also showed that through the DTEF not only there is a reduction of fluctuations in power and thrust, but also in the blade fatigue loads.

Attempts have made for reduction of loads through rotor blade control schemes [12]. These schemes also reduce the loads on platforms followed by reduction in the total design cost of OWT [13]. For examples, individual pitch control alleviates the cyclic loadings on rotor by adjusting the entire blade individually, resulting in response delay whereas activating smart rotor control devices alters the aerodynamics of the blades with comparatively less power requirement [14,15]. For this study, since the focus is on understanding response effects due to aerodynamic active device, the widely preferred control approach based on proportional integral derivative (PID) method is chosen. None of these works have focussed on understanding the effects on fixed OWT response with the additional appendage effects. Most of these works have ignored the effects of soil assuming the soil to be stiff [16,17] or the stiffness curves (lateral and longitudinal ones) are modelled by static springs (independent of loads) [18] or by extending the tower into the soil to a fixity level [19,20]. In the past, it was shown that the dynamic response with the inclusion that SSI greatly influenced the fatigue characteristics of the OWTs [21].

In many countries, the preferable wind farm locations are in areas of soft soil and therefore, the soil structure interaction (SSI) of pile supported OWT has gained significant importance. Bazeos et al. [22] pointed out that for soft soil the interaction between OWT platforms and soil may be the critical consideration in designing the structure. Byrne and Houlsby [23] had shown that the chances of failure also increases due to the stochastic nature of load, the direction of wave and the uncertainty associated with the same. For such OWTs, the foundation and tower structure design is greatly altered due to SSI. Therefore, there is an important requirement to mitigate the uncertain loads, thereby increasing factor of safety as they are installed in harsh locations.

Experimental investigations on the influence of soil stiffness on wind turbine response were conducted by Bhattacharya & Adhikari [24]. The results were validated by means of the finite element method (FEM), considering the wind turbine as an Euler-Bernoulli beam and assuming boundary conditions by replacing soil through translational and rotational springs. The rotor-nacelle-assembly was modelled as a lumped mass. Adhikari and Bhattacharya [25] obtained an expression for fundamental frequency for a wind turbine considering soil-properties which can be used as an initial guess in design process. Bhattacharya et al. [26] examined the change in the natural frequency due to cyclic loading through g tests on a scaled Vestas V90 3 MW model. They observed that formation of strains in soil and the relative position of natural frequency with respect to exciting frequency changes under cyclic loading. The studies were extended to different foundations – monopile, tripod of asymmetric nature and tetrapods on suction caissons [27,28]. The results showed the importance of rocking modes of vibrations in the response of OWT supported through multipod foundations.

In the present study, Winkler based FEM is used to account for soil-structure interaction which has been reviewed in previous studies [29–31] and acquired by standards [32,33]. Effectiveness of this $p-y$ method has been investigated for monopile design with the suggestion for the load-displacement curves to be modified in order to mark observed soil-pile stiffness overestimation [34,35]. Also the $p-y$ approach is assessed experimentally for dynamic application [36]. Certain limitations of the $p-y$ method has been discussed and suggestions has been proposed [35,37]. The effect of SSI using two different flexible foundation models ($p-y$ and $p-y$ with pile group effect) on the response of an OWT with jacket foundation has also been investigated [38].

The aerodynamic code FAST [39] and the hydrodynamic program USFOS [40] are used in this work. The geotechnical effects are captured by a combination of USFOS and FAST to obtain the full system model. The TEFs are modelled using computational fluid dynamics (CFD) and appropriate changes are done in the FAST model to account for their effects. Simulations were then performed for various load cases of the wind turbine supported by fixed-bottom platforms. The load analysis helped to characterize the potential design loads and the instabilities resulting from the coupling between the OWT with flaps in the presence of combined wind and wave excitation by including SSI. Design modifications using these trailing edge flaps on turbine blades are detailed, which will reduce loads and improving turbine response thus lowering the foundation cost.

The objective of this study is to examine the response of OWT with the TEFs, taking into consideration the SSI. Section 2 describes in detail, the numerical modelling of the OWT using the blade flaps, support structures and the soil model. In Section 3, the methodology adopted for the analysis is explained. Section 4 presents the results of the work and highlights the importance in lowering the foundation cost. The paper ends with Section 5 mentioning the important takeaways from this work.

## 2. Numerical modelling

With continual increase in rotor/blade size, the aerodynamic and structural load are also increasing. Therefore, if one can reduce the loads at the blade root through the design innovation (slotted flaps), then there would be significant savings in the tower, drive train and ultimately the foundations. For mitigating the overall response, small appendages (as trailing edge flaps) are provided in the blade profile of the OWT [41].

Flaps are devices which are affixed to the aerofoil section to increase the lift forces in the blades. The flow control active devices, i.e., trailing edge flaps (TEF), are small appurtenances that are fixed to the aerofoil section in the aero-dynamically sensitive area of the blades. The assemblage consists of a fanning arrangement in addition to the existing blade profile. The introduction of the flaps cause a change in the variation of pressure over the aerofoil due to the gap that occurs between the aerofoil section and the TEF. Due to passage of air over the top of the aerofoil, the pressure gets lowered and camber increases this effect. With this change, lift coefficient increases and therefore the boundary layer effects gets modified along with camber effects. Due to the flaps, the flow of stay remains attached at higher angle of attacks also thus delaying separation. The air velocity that is leaving the TEF increases and therefore the total lift along the entire chord increases. TEFs are usually deployed at tips to obtain highest significance. Note that the drag coefficient also changes due to the distorted span-wise lift coefficient. Fig. 1 shows the flap hinge location in accordance with NACA airfoil sections [42]. The modelling of the slotted flaps in the wind turbine along are explained in the subsequent sections. For this study,