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Nonlinear dynamical behaviour of jacket supported offshore wind turbines in loose sand

K.A. Abhinav, Nilanjan Saha*

Dept. of Ocean Engineering, Indian Institute of Technology - Madras, Chennai, India

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A B S T R A C T

Soil-structure interaction (SSI) is a vital aspect in the performance of bottom fixed offshore wind turbine (OWT) structures. This paper investigates the response of a jacket supporting a 5-MW OWT in intermediate water depths of 70 m, under the influence of hydrodynamic and aerodynamic loading. SSI is incorporated by means of a Winkler-spring formulation and sands of varying densities are considered.

A spectrum of wind speeds are considered, increasing from the cut-in value of 3 m/s to an extreme case of 45 m/s. Response charts have been proposed in terms of rotations at various levels of the jacket, to serve as design-aids for similar structures. The effect of SSI becomes predominant for OWT in loose sands (with friction angle less than 30°). Parametric resonant responses have been observed for the jacket in loose sands, in the region bounded by the rated and cut-out wind speeds.

1. Introduction

The type of substructure and foundation for supporting an offshore wind turbine (OWT) is generally determined by the water depth at the site of installation. Monopiles are popular in shallow waters (<25 m), owing to ease of production, transportation and installation. However, the number of space-frame structures (jacket, tripod and tripile) has been on the rise, with offshore wind farms slowly conquering deeper waters. According to [15] 80% of the OWTs in European waters are supported on monopiles, while jackets, tripods and tripiles together account for 11%. A comprehensive review of OWT structures and foundations is available in Ref. [5].

Jackets are 3-dimensional space frame structures, traditionally used to support offshore platforms for the oil industry. In recent times the offshore wind community have resorted to the application of jackets for intermediate water depths, borrowing from the concepts prevailing in the oil and gas industry. The study of soil-structure-interaction (SSI) is important for the establishment of an offshore wind farm, as foundations account for over 50% of the capital cost [17].

Several studies are available in literature, pertaining to the SSI of jackets without a turbine on the top. For instance [29]; studied the response of jacket structure subjected to transient loading under extreme waves. Dynamic *p-y* curves were made use of and a reduction in structural response was observed. Ref. [18] evaluated the response of an offshore jacket subjected to extreme waves, under a probabilistic framework, by employing an incremental wave analysis procedure. Here, the pile-soil model was represented using soil curves. Ref. [6] proposed the use of pile-stubs as a possible replacement for a full SSI study. SSI effects are often ignored when studying the dynamic response of jacket OWTs, as in Refs. [16,34,39], by fixing the structure at the mudline. However, this could result in overestimation of the structural stiffness and thus lead to resonance from wind and wave effects [1].

There has been limited attempts in literature to study the jacket supported OWT under dynamic wind and wave loads, while

* Corresponding author.
E-mail address: nilanjan@iitm.ac.in (N. Saha).

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taking the SSI effects into consideration. Ref. [35] investigated the effect of SSI on a jacket supporting the NREL-5 MW OWT in 50 m water depth under dynamic loading. *p-y* curves were used for modelling the pile-soil interaction and a single dynamic load case was considered, for a dense layered sand profile.

In this paper, the authors discuss the structural response of jacket supported OWTs in sandy soils in general and loose sands in particular. The benchmark NREL 5 MW OWT is assumed to be supported by a 4-legged jacket in a water depth of 70 m. Sands of densities varying from loose to dense are considered and the structure is subjected to a whole range of met-ocean conditions corresponding to wind speeds from the cut-in to extreme region (when the turbine is shut down to prevent overloading and structural damage). The study involves the combining of two numerical programs FAST [25] and USFOS [12], for an effective analysis encompassing the wind, wave and soil regimes. Soil properties are derived from *p-y*, *t-z* and *Q-z* curves.

A Monte Carlo based probabilistic framework has been adopted to address the uncertainty arising from the modelling of turbulent wind and irregular wave loading. Initially, fidelity checks are performed for the jacket model in the two numerical codes. Also, the dynamic analysis module of USFOS has been validated by comparison with a similar program. Response charts have been prepared for the jacket structure, for various soil properties. Resonance conditions in loose sand which has been observed was investigated by means of power spectral density plots.

Section §2 describes the OWT and the supporting jacket used in the study. The numerical tools for dynamic analysis, FAST and USFOS are also described in detail. Section §3 deals with the theory behind the generation of aerodynamic and hydrodynamic loads and combining their influences on the OWT structure. Section §4 defines the probabilistic environmental conditions assumed for the present work, along with the various analysis parameters. The findings of the present work are described in Section §5 and the paper concludes with Section §6.

2. Description of numerical tools

The present study makes use of the finite element method to analyze the response of a jacket supported fixed OWT under dynamic loading. The turbine and jacket models are described in detail, in the following subsections, along with the numerical tools used in the work.

2.1. NREL 5-MW offshore wind turbine

The NREL 5 MW turbine, conceptualized by Ref. [26] has been regularly used as a representative model of a utility scale OWT, by researchers around the world. The 3-bladed turbine is variable speed, pitch controlled, with an upwind rotor orientation. The major design parameters of the NREL 5 MW OWT have been defined in Table 1.

The turbine is supported by means of a tapering tower, whose diameter increases from 4 m at the top to 5.6 m at the base. The tower is joined to the jacket substructure, through a transition piece of length 4 m and mass 666 t. To account for the absence of the connecting welds, bolts and flanges in the numerical model, the density of steel has been increased to 15.14×10^3 kg/m^3. The tower model is adapted from Ref. [40] and is defined in Table 2.

2.2. FAST

FAST [25], which stands for Fatigue, Aerodynamics, Structures, and Turbulence, is an open source program, developed by the National Renewable Energy Laboratory, Golden, CO, USA, capable of coupled aero-hydro-servo-elastic analysis. A modular concept is made use of, and the various components pertaining to aerodynamic, hydrodynamic, structural analysis and control system are loose-coupled by means of a driver program. The present work makes use of version 8.10.00 of the code. However, FAST is incapable of geotechnical analysis - herein, the support structures are considered to be fixed at the mudline.

2.3. USFOS

USFOS [12] is a finite-element method based program, tailored for the static and dynamic analyses of framed offshore structures, such as jackets and tripods. It is capable of performing coupled hydrodynamic-SSI analysis. USFOS is based on a simplified nonlinear

Table 1
Properties of NREL 5 MW OWT [26].

Parameter	Value
Rotor, Hub diameter	126 m, 3 m
Rated rotor speed	12.1 rpm
Cut-in wind speed	3 m/s
Rated wind speed	11.4 m/s
Cut-out wind speed	25 m/s
Rotor-nacelle-assembly mass	350,000 kg
Tower top level	+ 88.15 m
Tower base level	+ 20.15 m