Renewable Energy 80 (2015) 724–736

Contents lists available at ScienceDirect

Renewable Energy

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

Foundation damping and the dynamics of offshore wind turbine monopiles

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ARTICLE INFO

Article history:
Received 15 July 2014
Accepted 23 February 2015
Available online

Keywords:
Offshore wind turbine
Monopile
Soil-structure interaction
Damping

ABSTRACT

The contribution of foundation damping to offshore wind turbines (OWTs) is not well known, though researchers have back-calculated foundation damping from "rotor-stop" tests after estimating aerodynamic, hydrodynamic, and structural damping with numerical models. Because design guidelines do not currently recommend methods for determining foundation damping, it is typically neglected. This paper investigates the significance of foundation damping on monopile-supported OWTs subjected to extreme storm loading using a linear elastic two-dimensional finite element model. The effect of foundation damping primarily on the first natural frequency of the OWT was considered as OWT behavior is dominated by the first mode under storm loading. A simplified foundation model based on the soil-pile mudline stiffness matrix was used to represent the monopile, hydrodynamic effects were modeled via added hydrodynamic mass, and 1.00% Rayleigh structural damping was assumed. Hysteretic energy loss in the foundation was converted into a viscous, rotational dashpot at the mudline to represent foundation damping. Using the logarithmic decrement method on a finite element free vibration time history, 0.17%-0.28% of critical damping was attributed to foundation damping. Stochastic time history analysis of extreme storm conditions indicated that mudline OWT foundation damping decreases the maximum and standard deviation of mudline moment by 7–9%.

1. Introduction

Economics are a major impediment for utility-scale offshore wind installations. Offshore wind farms require large capital investments and can have approximately two to three times the operation and management costs as compared to onshore wind [1]; however, due to higher, more consistent wind speeds, offshore wind farms can offer more renewable energy than their onshore counterparts and it is expected that monopile foundations will continue to have a large market share despite some increase in deployment of larger turbines at greater water depths [2]. For monopiles in deeper water, the dynamic effect of wave loads becomes a design driver for OWT support structures, leading to an increased sensitivity to soil stiffness and damping [2]. Higher damping in the support structure can lead to lower design load estimates, which in turn can correspond to reduced amounts of material required to resist loading. Because support structures contribute approximately 20–25% of the capital cost for OWTs [1,3], it is imperative to identify and assess sources of damping in the effort to improve the economics of offshore wind energy.

Sources of damping for OWTs include aerodynamic, hydrodynamic, structural, and soil damping. In addition, for some turbines, tuned mass dampers are also installed in the nacelle. Aerodynamic damping occurs when the OWT blades respond to increases and decreases in aerodynamic force due to the relative wind speed from tower top motion [4,5]. During power production, aerodynamic damping is a dominant source of damping in the fore-aft direction; however, aerodynamic damping is far less significant in the fore-aft direction for parked and feathered rotors or in the side-to-side direction for design situations including wind-wave misalignment [5–7]. During design situations such as these, other sources of damping play a much larger role in the dynamics of the structure.

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http://dx.doi.org/10.1016/j.renene.2015.02.058
0960-1481/

Nomenclature

A	amplitude
$c_{\theta\theta}$	rotational damping constant
C_m	inertia coefficient
C_D	drag coefficient
D	damping factor
E_h	hysteretic energy loss
f	frequency
G	shear modulus
H_x	horizontal mudline shear
k	mudline spring stiffness
k'	decoupled spring stiffness
k_{mud}	mudline stiffness matrix
L_{eq}	rigid decoupling length
M_ϕ	mudline moment
n	number of amplitudes
s_u	undrained shear strength
u	mudline displacement
u_{top}	tower top displacement
x	horizontal translation degree of freedom
α	Rayleigh mass coefficient
β	Rayleigh stiffness coefficient
δ	log decrement
η	loss factor
ϕ	rotational degree of freedom
θ	mudline rotation
μ	mean
ν	Poisson's ratio
σ	standard deviation
ξ	critical damping ratio
ω_n	frequency (rad/s)
Δ	perturbation
IEC	International Electrotechnical Commission
MSL	mean sea level
NGI	Norwegian Geotechnical Institute
NREL	National Renewable Energy Laboratory
OWT	offshore wind turbine
LPM	lumped parameter model

According to an engineering note issued by Germanischer Lloyd [8], soil damping is the contributor to OWT damping that is most uncertain. The International Electrotechnical Commission states that "Compared with the other components of the total damping discussed, the characterization and modeling of soil damping is the most complex parameter and has a high damping contribution. Soil damping is a diffuse subject and the contribution to energy dissipation here from is not intuitive in all forms [9]." Det Norske Veritas [10] requires that realistic assumptions with regard to stiffness and damping be made in the consideration of OWT soil-structure interaction but does not recommend a method to estimate soil damping.

Soil damping comes in two main forms: radiation damping (geometric dissipation of waves from spreading) or hysteretic material (also known as intrinsic) damping. Geometric dissipation is negligible for frequencies less than 1 Hz [6,8,11], and the majority of wind and wave loads have frequencies below 1 Hz (e.g. Refs. [12,13]). While the first and second fore-aft and side-to-side natural frequencies of the National Renewable Energy Laboratory 5 MW Reference Turbine (NREL 5 MW) [15] used in this paper are from 0.3 Hz to 3 Hz, the NREL 5 MW under extreme storm loading is dominated by first mode behavior. Because this first mode is at approximately 0.3 Hz, this paper neglects geometric dissipation and focuses solely on hysteretic material damping from soil. This type of soil damping should be more specifically labeled OWT monopile foundation damping (or generally referred to in this paper as "OWT foundation damping") due to the specific formulation and mechanism of hysteretic material soil damping within the OWT soil-structure foundation system.

Some researchers [3,6,11,14] have examined the signals from instrumented OWTs during emergency shutdown (sometimes referred to as a "rotor-stop test"), ambient excitation, and overspeed stops [7] to estimate OWT natural frequency and damping. Subsequently, OWT foundation damping values from 0.25 to 1.5% have been estimated from the residual damping after aerodynamic, hydrodynamic, structural, and nacelle tuned mass damping have been accounted for in numerical modeling. Previous analytical methods have estimated OWT foundation damping using Rayleigh damping as a function of soil strain [6] or from a hysteresis loop created by loading and unloading *p-y* curves [11].

A two-dimensional finite element model of the NREL 5 MW is used in this paper, taking into account added hydrodynamic mass for the substructure, Rayleigh structural damping, and foundation damping. Hydrodynamic and aerodynamic damping are not included in the scope of this paper, as the focus is specifically on the contributions of foundation damping. Because total damping for the OWT is typically estimated as a linear combination of independently modeled damping sources (e.g. Refs. [6,7,14]), neglecting aerodynamic and hydrodynamic damping is assumed to not influence estimations of foundation damping. Any added mass due to the mobilization of the soil during pile motion is also neglected.

The primary objective of this study is to determine the influence of OWT foundation damping on dynamic response. Section 2 describes the methodology, Section 3 describes how the foundation stiffness and damping were established, and Section 4 describes the combined model of the OWT structure and foundation. In Section 5, the percent of critical damping for the NREL 5 MW OWT model which can be attributed to foundation damping is quantified via logarithmic decrement method of a free vibration time history and compared to the experimental and numerical results available in literature. Subsequently, in Section 6 stochastic time history analysis corresponding to an extreme sea state and extreme wind conditions is used to determine the significance of OWT foundation damping.

2. Methodology

The methodology introduced in this paper uses four types of model: a structural model of the OWT superstructure (the part of the OWT that extends above the mudline), a lumped parameter model (LPM) that approximates the soil-pile system with a rigid bar supported by springs at its tip below the mudline and a mudline damper, an aero-hydro-elastic model constructed in the software package FAST, and a continuum finite element model of the soil-pile system. Each of these models provides a different degree of fidelity with respect to different aspects of OWT loading and response and coupling these models in the manner described here allows the determination of wind and wave loads, soil-pile interaction, and structural dynamics in a way that is not possible within any one of the models or attendant software packages.