Marine Structures 57 (2018) 18–37

Contents lists available at ScienceDirect

Marine Structures

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

Experimentally supported consideration of operating point dependent soil properties in coupled dynamics of offshore wind turbines

Clemens Hübler*, Jan Häfele, Cristian Guillermo Gebhardt, Raimund Rolfes

Institute of Structural Analysis, Leibniz Universität, Hannover, Germany

ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 15 August 2017
Accepted 20 September 2017

Keywords:
Soil-structure interaction
Dynamic soil experiments
Offshore wind turbine
FAST
p-y curves
Component-mode synthesis

ABSTRACT

The consideration of soil properties is necessary to predict the time domain dynamic behavior of offshore wind turbines. Accurate soil-structure interaction models are in essence very expensive in terms of computing time and therefore, not directly applicable to transient calculations of wind energy converters. In this work, the incorporation of dynamic soil properties is addressed. The basic model, previously developed by the authors, is based on a linearized approach using stiffness and mass matrices representing the soil-structure interaction. This approach already leads to significant reductions of the eigenfrequencies compared to clamped boundary conditions which are still commonly used. Here, the basic approach is enhanced by two aspects. Firstly, different numerical soil models, based on nonlinear springs, to calculate the matrices are compared to experimental results for embedded piles at conditions similar to the North Sea. Comparisons of numerically and experimentally determined eigenfrequencies of the piles show that nonlinear spring models are only suitable for dynamic analyses to a limited extent. Secondly, a piecewise defined response surface, which enables a linearization of the nonlinear soil behavior at different approximated operating points, is introduced. This approximation proves to be sufficiently accurate in the current setting. By analyzing two full offshore wind turbine examples in time domain, a monopile substructure and a jacket substructure anchored by piles, further shifts of the eigenfrequencies, being caused by the load-dependent mechanical properties of the soil, are determined by considering the operating point.

1. Introduction

Time domain simulations are entailed in design and certification of offshore wind turbines. Standards and guidelines require ultimate and fatigue limit state verifications. In this connection, fully coupled aero-hydro-servo-elastic simulation codes for the whole offshore wind turbine including the substructure are state of the art. One major challenge is the consideration of effects of the soil on the dynamic behavior of the whole turbine in the aforementioned coupled models. The behavior of the soil is highly nonlinear and its stiffness strongly depends, inter alia, on the acting loads. This applies to all kinds of anchorages like piles or suction buckets. Still, in this work only pile foundations are considered. The spectrum of soil-

* Corresponding author.
E-mail address: c.huebler@isd.uni-hannover.de (C. Hübler).

https://doi.org/10.1016/j.marstruc.2017.09.002
0951-8339/

structure interaction models for pile foundations reaches from very complex and nonlinear finite element models [6,14] to simplified but still nonlinear static p-y curves [4,39]. Furthermore, there exist other nonlinear models based on CPTs cone penetration tests [2]; or spring-damper combinations with varying complexity [36]. However, these sophisticated, nonlinear soil-structure interaction models are commonly not coupled with the whole wind turbine, but loads - for example calculated with previously run turbine simulations - are just applied at mudline. The high number of degrees of freedom required by all sophisticated soil-structure interaction models and the complexity of offshore wind turbines are the reasons for this decoupled procedure. To illustrate this problem: For jacket structures in the oil and gas industry, wind loads and controller actions can be neglected or are not existent and fewer load cases have to be calculated. Therefore, in the oil and gas industry nonlinear soil models in combination with time domain simulations are used for example by Ref. [7] or [28]. For transient, coupled wind turbine simulations with noticeable demands for numerical efficiency in their current form due to high computational cost for a single simulation and the large number of simulations that is required to satisfy the certification standards, these models are only partly suitable. That is why, nowadays in transient simulations, offshore wind turbines are often modeled as clamped to the seabed, for instance, see Ref. [9]. These authors outline the implementation of a structural dynamics module for offshore wind turbines with space-frame substructures into the current FAST framework (an aeroelastic simulation code by the National Renewable Energy Laboratory, NREL) where the soil is considered to be rigid [26]. use nonlinear spring models in wind turbine simulations even for optimization purposes. However, the authors only analyze eigenfrequencies, and no time domain simulations are conducted. The work of [3] is one of the few recent cases that incorporates a nonlinear soil model in time domain simulations of offshore wind turbines and studies seismic responses. However, this leads to very high computing times, as a full FE model of the substructure is needed, and the substructure cannot be condensed. Hence, only a few load cases can be simulated in an adequate time.

A promising approach to enhance time domain simulations of offshore wind turbines by considering soil properties effectively with reasonable computing times is a two-step approach by Ref. [19]. This approach is based on linear 6×6 stiffness and mass matrices representing the soil-structure interaction and allows an effective consideration of soil characteristics in transient, coupled simulations of offshore wind turbines, even if the substructure is - as in common practice - condensed with reduction methods like a Craig-Bampton reduction, for instance. However, as the matrices are linear, the nonlinear behavior of the soil is not taken into account. A linearization is carried out at the zero-deflection point of the piles. This means that no loads are applied to the pile head and therefore, the pile is not deflected. As the soil stiffness reduces with higher pile deflections due to increasing loads, disregarding the operating point (i.e. the load conditions) is a simplification, though it is much less serious than assuming clamped boundary conditions.

The contribution of the present work comprises two aspects. The approach developed by Ref. [19]; named "basic approach" throughout this work, uses nonlinear springs (i.e. p-y curves) of the American Petroleum Institute [4] to determine the soil matrices. However, in literature, other p-y curves are available as well. On the one hand [39], and approaches developed by Refs. [33,34] are supposed to give better approximations of the soil stiffness for ultimate loads. One the other hand [25], give a changed formulation for p-y curves being more suitable for small and initial loads [27]. introduce a new formulation for initial stiffnesses and reduce the internal friction angle in order to get better results for small and ultimate loads [35]. compare different p-y curves with a calibrated FE model. On the basis of their findings that none of the p-y curves leads to sufficient results, completely new p-y curves are developed that are supposed to be more suitable for all load conditions. In this work, firstly, large-scale experiments to determine the dynamic soil properties of embedded piles are presented. These results are then compared to numerical results obtained with different p-y models. An assessment, based on the experimental results, of the nonlinear spring models in the current dynamic context is possible, although it has to be kept in mind that p-y curves are initially derived from static conditions. Still, due to the lack of alternatives, they are used for dynamic applications as well. Secondly, an enhancement of the basic approach concerning the linearization is presented. As the method requires linearized interaction matrices, the present refined approach linearizes at the actual operating point and no longer at the zero-deflection point. This improvement allows the incorporation of variable soil stiffnesses for different environmental conditions. Even for the different piles of a jacket substructure, the soil stiffness can vary. In order to determine the acting loads at a specific operating point effectively, response surfaces (RSs) linking the environmental conditions to the loads at mudline are utilized.

The present paper is structured as follows: Firstly, a short overview of the basic two-step soil consideration approach is given. For detailed explanations, it is referred to [19]. Subsequently, different nonlinear spring models for calculating the stiffness matrices are introduced. Experimental results of the dynamic behavior of soil-pile combinations are presented and discussed. These results are then compared to numerical results using the different nonlinear spring models in order to evaluate the suitability of these models. A new approach to determine loads at the operating point, using response surfaces, is described afterwards, and some results of the load approximation by the response surface method are presented. In this connection, results of coupled time domain simulations of an offshore wind turbine with jacket substructure and monopile substructure are given, whereas the operating point is neglected in the first place. The calculations are conducted with the aero-hydro-servo-elastic simulation code FAST. Then, further examples illustrate the effect of using different p-y models on the interaction matrices and on the overall turbine behavior. Furthermore, differences between the use of the zero-deflection point and the response surface method for the consideration of the operating point are pointed out. Lastly, conclusions are drawn, pointing out limitations and giving an outlook on future work.