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An improved two-step soil-structure interaction modeling method for dynamical analyses of offshore wind turbines

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ABSTRACT

The detailed modeling of soil-structure interaction is often neglected in simulation codes for offshore wind energy converters. This has several causes: On the one hand, soil models are in general sophisticated and have many degrees of freedom. On the other hand, for very stiff foundations the effect of soil-structure interaction could often be discounted. Therefore, very simple approaches are utilized or the whole structure is assumed to be clamped at the seabed. To improve the consideration of soil-structure interaction, a six-directional, coupled, linear approach is proposed, which contains an implementation of soil-structure interaction matrices in the system matrices of the whole substructure. The aero-hydro-servo-elastic simulation code FAST has been modified for this purpose. Subsequently, a 5 MW offshore wind energy converter with pile foundation is regarded in two examples.

1. Introduction

According to standards and guidelines (e.g. [1]), the design and certification process of offshore wind energy converters is based on holistic time domain simulations. Therefore, the improvement of simulation techniques is a significant factor in research. With special regard to the foundation, several simulation codes with the ability to represent the dynamic behavior of support structures have been developed and verified in the last decade. Well-known verification efforts are the so called "Offshore Code Comparison Collaboration" (OC3) [2] and "Offshore Code Comparison Collaboration Continuation" (OC4) [3] projects. As there are diverging demands on results, different representations of soil-structure interaction are used nowadays: the spectrum of soil-structure interaction models reaches from complex and non-linear finite element models to simplified *p*–*y*-curves. However, all representations have in common that they add usually many degrees of freedom (DOFs) to the system assembly of an offshore wind energy converter model and time domain simulations are often performed with the structure assumed to be clamped at the seabed, which is in fact a massive simplification.

Zaaijer [4] presents a simplified dynamical model for the foundation of offshore wind turbines and considers the first two flexural frequencies of the structure as indicators of the dynamic response of the whole assembly. The author by means of a detailed analysis shows that the stiffness matrix at the mudline represents the best solution for monopiles. Pinto and Prato [5] developed a symmetric formulation of the indirect boundary element method for buried frames and show how the formulation could be extended to account rotation of the piles due to combined loads acting on the buried structure. Bienen and Cassidy [6] introduced a software, which allows the analysis of fluid-structure-soil interactions in three dimensions. The authors analyze an offshore structure under combined loads and make the change of the response due to the loading direction and stresses evident. Bhattacharya and Adhikari [7] analyzed the dynamical behavior of wind turbines with monopile foundations, with focus on the soil-structure interaction. The authors validated a theoretical model against finite element calculations as well as against experimental results for some interesting cases and show that the frequencies of the complete system are strongly related to the stiffness of the foundation. AlHamayde and Hussain [8] performed the design optimization of multiple onshore wind towers under consideration of the soil-structure interaction. A detailed three-dimensional finite element model of the tower-foundation-pile system was created and soil springs were included in the model based on soil properties obtained from geotechnical investigations. Finally, the natural frequency from the model was verified against analytical and experimental values of the tower manufacturer. Harte et al. [9] investigated the along-wind forced vibration response of an onshore wind turbine. The study includes the dynamic interaction effects between the foundation and the underlying soil. The soil-structure interaction is shown to affect the response of the wind turbine. This was examined in terms of the turbine structural displacement, the base shear force, and the bending moment in the tower and the foundation. Bisoi und Haldar [10] conducted a comprehensive analysis of an offshore wind turbine structure with monopile foundation. The system was

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modeled using a beam on nonlinear Winkler foundation model, and the soil resistance was modeled using p–y- and T–z-curves. The study proves that soil-monopile-tower interaction increases the response of tower and monopile, and the soil nonlinearities increase the system response at higher wind speeds. Damgaard et al. [11] evaluated the formulation and quality of an efficient numerical modeling for the surface foundation of offshore wind turbines, in which the geometrical dissipation related to the wave propagation was accounted. Finally, Damgaard et al. [12] developed a modeling approach to allow the integration of the soil-structure interaction into an aeroelastic software intended for offshore wind turbines by means of the employment of semi-analytical solutions in the frequency domain to include the impedance of the soil-pile system for a given discrete number of frequencies.

This article presents the development of an improved two-step soil-structure interaction modeling method for dynamical analyses of offshore wind turbines, which is fully implemented in FAST. After the definition of a desired operating point the method requires the calculation of the matrices for the soil-structure interaction at first. Secondly, the assembly of the system matrices and the reduction for the substructure representation are performed. The work is partitioned in four further sections: in Section 2 the fundamentals like Component-Mode-Synthesis in FAST, necessary modifications to account soil-structure interaction, derivation of the interaction matrices, and description of the method scheme are described. In Section 3, some results obtained with the current approach are presented and analyzed. Section 4 discusses the benefits and limits of the method. And lastly, in Section 5 some concluding remarks are drawn.

2. Fundamentals

As most simulation codes are proprietary, FAST – developed by the National Renewable Energy Laboratory and being open source – has become a well-accommodated code in research. Hence, it is an appropriate basis for the implementation of a new soil-structure interaction approach. Depending on the requests of the user, the structural model of a land-based wind energy converter in FAST comprises up to 23 DOFs, including 9 for the rotor blades (in case of a three-blade-rotor), 4 for rotor-teeter motion, drive-train, generator and yaw rotation and 10 for tower bending and platform movement. While this limited number of DOFs allows adequate simulation times and qualifies FAST even for optimization applications, the implementation of offshore substructures in the model is challenging, because the dynamical behavior of bottom-fixed multi-member steel structures is commonly computed by FE-method using beam elements with hundreds of nodes and often thousands degrees of freedom. Therefore, a reduction method called Component-Mode-Synthesis has been implemented in FAST, which is based on the work of Craig and Bampton [13]. This reduction method allows an appropriate structural representation with about 5–15 degrees of freedom [14], but in the native implementation it is assumed that there are at least six DOFs as boundary conditions (so called reaction DOFs) to prevent the stiffness matrix from getting singular [15]. Therefore, integrating a soil-structure interaction in the fully assembled system requires an adjustment of the theory.

2.1. Component-Mode-Synthesis of multi-member substructures in FAST

The proposed procedure for the reduction of multi-member substructures in FAST [15] is described as under. For further information it is referred to [16].

It is presumed that the equations of motion have been derived within a linear frame finite-element beam model and are on hand in the general form:

$$\mathbf{M}\ddot{\vec{u}} + \mathbf{C}\dot{\vec{u}} + \mathbf{K}\vec{u} = \vec{F}. \tag{1}$$

In the above equation, $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ the damping matrix, $\mathbf{K}$ the stiffness matrix, $\vec{u}$ the displacement vector along all degrees of freedom and $\vec{F}$ comprises of the corresponding external forces. Dots represent derivatives with respect to time. In addition, the vector $\vec{u}$ is partitioned into the so called vectors of boundary displacements $\vec{u}_R$ and interior displacements $\vec{u}_L$ in the following way:

$$\vec{u} = \begin{pmatrix} \vec{u}_R \\ \vec{u}_L \end{pmatrix}. \tag{2}$$

It is important to note that the rank of the stiffness matrix in Eq. (1) is lower than its dimension, as no constraints are applied.

Substituting Eq. (2) in (1) yields:

$$\begin{pmatrix} \mathbf{M}_{RR} & \mathbf{M}_{RL} \\ \mathbf{M}_{LR} & \mathbf{M}_{LL} \end{pmatrix} \begin{pmatrix} \ddot{\vec{u}}_R \\ \ddot{\vec{u}}_L \end{pmatrix} + \begin{pmatrix} \mathbf{C}_{RR} & \mathbf{C}_{RL} \\ \mathbf{C}_{LR} & \mathbf{C}_{LL} \end{pmatrix} \begin{pmatrix} \dot{\vec{u}}_R \\ \dot{\vec{u}}_L \end{pmatrix} + \begin{pmatrix} \mathbf{K}_{RR} & \mathbf{K}_{RL} \\ \mathbf{K}_{LR} & \mathbf{K}_{LL} \end{pmatrix} \begin{pmatrix} \vec{u}_R \\ \vec{u}_L \end{pmatrix} = \begin{pmatrix} \vec{F}_R \\ \vec{F}_L \end{pmatrix}. \tag{3}$$

R and L as subscripts indicate the affiliation to the corresponding DOFs. While $\vec{u}_L$ is the vector of all remaining interior degrees of freedom, the vector $\vec{u}_R$ can be partitioned into the displacements at the interface $\vec{u}_{\text{int}}$ and the displacements at the bottom of the structure $\vec{u}_{base}$:

$$\vec{u}_R = \begin{pmatrix} \vec{u}_{\text{int}} \\ \vec{u}_{base} \end{pmatrix}. \tag{4}$$

To reduce the size of $\vec{u}_L$, a Ritz transformation is applied and the vector of m generalized interior coordinates $\vec{q}_m$ is obtained:

$$\vec{u}_L = \mathbf{\Phi}\vec{q}_m. \tag{5}$$

As the boundaries are unaffected, the new vector of displacements $\vec{u}$ is

$$\vec{u} = \begin{pmatrix} \vec{u}_R \\ \vec{q}_m \end{pmatrix}. \tag{6}$$

Now, the essential supposition of the Component-Mode-Synthesis is that the matrix $\mathbf{\Phi}$ consists of constraint modes $\mathbf{\Phi}_R$ and fixed-interface normal modes $\mathbf{\Phi}_L$:

$$\mathbf{\Phi} = \begin{pmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{\Phi}_R & \mathbf{\Phi}_L \end{pmatrix}. \tag{7}$$

where $\mathbf{I}$ is the identity matrix and $\mathbf{0}$ the zero matrix.

Regarding the homogenous, static case (excitation and all derivatives zero) of the rigid body ($\vec{q}_m = \vec{0}$) and setting all boundary DOFs to unit displacement, the matrix of constrained modes $\mathbf{\Phi}_R$ can be calculated according to

$$\begin{pmatrix} \mathbf{K}_{RR} & \mathbf{K}_{RL} \\ \mathbf{K}_{LR} & \mathbf{K}_{LL} \end{pmatrix} \begin{pmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{\Phi}_R & \mathbf{\Phi}_L \end{pmatrix} \begin{pmatrix} \vec{I} \\ \vec{0} \end{pmatrix} = \begin{pmatrix} \vec{0} \\ \vec{0} \end{pmatrix}. \tag{8}$$

It follows

$$\mathbf{\Phi}_R = -\mathbf{K}_{LL}^{-1}\mathbf{K}_{LR}. \tag{9}$$