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A practical soil-structure interaction model for a wind turbine subjected to seismic loads and emergency shutdown

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Abstract

In seismically active areas the design of wind turbine must be verified for seismic load combinations. These consider a certain likelihood of earthquake occurrence during normal operation, which could eventually lead to an emergency stop. In order to simulate these scenarios, the computational model should take into account the aerodynamics of the rotor, the flexibility of tower and soil, transient operational phases and, first and foremost, the interrelation of all these aspects. At the same time, the complexity should be reduced in order to avoid enormous computational costs, especially when the soil-structure interaction is taken into account. This study presents a practical model for the analysis of the soil-structure interaction effects on the seismic behavior of wind turbine, during normal power production and emergency shutdown. The presented model is based on simplified lumped parameter model for the soil-foundation subsystem and is validated against a detailed model, based on a 3D coupled finite element method and scaled boundary finite element method approach. This article shows a demonstrative example for a reference 5MW wind turbine subjected to a seismic event which triggers an emergency shutdown. The application of the lumped parameter model allows a significant model size reduction and accurate approximation of the soil-structure behavior in time domain.

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1. Introduction

Referring to the ASCE/AWEA regulations \cite{1}, wind turbine (WT) design must be verified for seismic load combinations, where the suggested “best practice” combination considers the seismic load added to an operational load equal to the greater between 1) loads during normal power production at the rated wind speed and 2) characteristic loads calculated for an emergency stop at the rated wind speed. This assumes a certain likelihood of earthquake occurrence during normal operation, which could eventually lead to an emergency stop (ES). In order to simulate these scenarios, computational models should consider above all the interrelation of the aerodynamics of the rotor, the flexibility of tower and soil and the transient operational phases. To avoid computational costs, especially when the soil-structure interaction (SSI) is taken into account, it is of avail to reduce the complexity of the SSI model.

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There are several methods for dealing with the analysis of the unbounded soil, both in frequency and time domain. On the one hand, the soil is characterized by frequency-dependent dynamic behavior, which is efficiently modeled in the frequency domain, e.g. using the boundary element method (BEM) [2] or the integral transform method [3]. On the other hand, an emergency shutdown involves a non-linear event, where a sudden decrease of aerodynamic loads led to an impulse load, which excites the free vibration of the tower and therefore, time-domain analyses are of crucial importance. Presently, time-domain methods, such as finite element method (FEM) or multi-body methods are the most used approaches for WT design and a large number of aerodynamic computational tools are available. However, when the soil (a 3D infinite half space) is coupled to the FEM domain, the size of the model increases drastically [4] and the computational costs may become unacceptable. Therefore, some of the most common commercial aerodynamic tools simplified the modeling of SSI by activating six degrees of freedom (DoF) at the tower base (one for each vibrational mode) and representing the 6x6 stiffness and damping matrices through a set of springs, dashpots and masses. This simplified approach is appropriate for an homogeneous elastic half space, while unsatisfactory for a layered soil. In fact, single complex springs at mudline along each DoF cannot account for a non-homogeneous soil profile. Foundations with strongly frequency-dependent impedances require nested lumped-parameter models (LPM) [5]. An extensive state-of-the-art review can be found in [6]. In general, it is important to investigate accurately and efficiently an emergency shutdown during an earthquake, in order to assess whether it may be beneficial during the occurrence of an earthquake, by limiting the base moment (as discussed in [7] and [8]), or may cause larger free vibrations of the tower if activated at an inopportune time.

2. Method

In the present work the time domain analysis is carried out with the aid of FEM/LPM coupling. The turbine tower is idealized as a finite-element tapered Euler-Bernoulli beam, with bending and axial flexibility. Torsion is not considered. The rotor system as well as the nacelle are idealized as a concentrated mass with inertial properties, which represents also the application point for the operational aerodynamic loads. The time histories of the aerodynamic loads are obtained separately using the program FAST [9]. The main assumptions are:

- the aerodynamic loads are not noticeably influenced by the SSI and can be computed for a fixed base tower;
- the side-side (SS) and fore-aft (FA) direction are analyzed separately without considering coupling effects;
- the system remains linear and the superposition principle is applicable.

2.1. Lumped Parameter Model

A LPM is a block of springs, dashpots and masses, able to reproduce the dynamic behavior of a soil-foundation system. Its real frequency-independent coefficients are found by approximating the dynamic stiffness, or its reciprocal called flexibility (or compliance), by a ratio of two polynomials. The optimal polynomial coefficients can be found using the least-squares method, which minimizes the error between the target compliance functions and the approximated ones. The obtained polynomial fraction is decomposed into simpler fractions through a partial fraction expansion. These minimum-order fractions can be associated with basic spring-dashpot elements (Fig. 1a and Fig. 1b), which are then connected in series. The general requirements for the successful application of LPMs are:

\[ k_1 = \frac{c_t}{\omega_t^2} K_0 \]
\[ c_1 = \frac{R}{\omega c^2} K_0 \]

\[ k_{11} = \frac{h_{00}}{\omega_1^2} K_0 \]
\[ c_{11} = \frac{R}{\omega_1^2} K_0 \]

\[ k_{21} = \frac{h_{00} - h_{01} \frac{\rho_1}{\rho_0}}{\omega_1^2} K_0 \]
\[ c_{21} = \frac{R}{\omega_1^2} \left( \frac{h_{00} - h_{01} \frac{\rho_1}{\rho_0}}{\rho_0} \right) \]

\[ k_{12} = \frac{h_{01}}{\omega_2^2} K_0 \]
\[ c_{12} = \frac{R}{\omega_2^2} K_0 \]

\[ k_{22} = \frac{h_{01} - h_{02} \frac{\rho_2}{\rho_0}}{\omega_2^2} K_0 \]
\[ c_{22} = \frac{R}{\omega_2^2} \left( \frac{h_{01} - h_{02} \frac{\rho_2}{\rho_0}}{\rho_0} \right) \]

\[ \sigma_{\infty} = \frac{\rho c^2 A v C_0}{R} \]

\[ \sigma_{\infty}^V = \frac{\rho c^2 A v C_0}{R} \]

\[ \sigma_{\infty}^R = \frac{\rho c^2 A v C_0}{R} \]

Fig. 1: (a) First-order and (b) second-order element for the systematic LPM; (c) High-frequency damping coefficient \( \sigma_{\infty} \), where \( C_0^s \) is the static flexibility for the different vibrational directions.
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