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Time-domain uncoupled analyses for seismic assessment of land-based wind turbines

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ABSTRACT

Seismic analysis plays an important role in the design of land-based and offshore wind turbines in areas at seismic hazard. For seismic assessment, International Standards and Guidelines allow combining two separate analyses, one under wind and another under earthquake only, as alternative to computationally expensive, fully-coupled time-domain simulations. In these uncoupled analyses, the separate earthquake response is generally computed using the standard acceleration response spectrum, upon including an additional damping referred to as *aerodynamic* damping. By a response-spectrum approach, however, important sources of nonlinearity, such as those related to foundation flexibility, cannot be properly accounted for.

Focusing on land-based wind turbines, this paper investigates a time-domain implementation of uncoupled analyses, which may involve a nonlinear foundation model. The case study is a 5 MW baseline wind turbine, resting on a pile foundation modeled by nonlinear springs. For different earthquake records and wind velocities, comparisons with fully-coupled simulations show that the combination of uncoupled analyses implemented in the time domain yields accurate results, provided that an appropriate level of aerodynamic damping is included in the model. Notably, it is seen that such aerodynamic damping level agrees with the one generally recommended for response-spectrum based uncoupled analyses.

1. Introduction

In view of the increasing number of wind farms being installed in many countries of Europe, Asia and America, including seismically-active areas [1,2], the seismic assessment of land-based horizontal-axis wind turbines (HAWTs) has been the subject of several studies in the last decade. Investigations have been carried out adopting different system models, load combinations and methods of analysis [3,4]. Simplified models or full models including support structure, rotor, as well as mechanical/electrical/control components of the turbine, have been used as system models. Combinations of earthquake loads with operational wind loads or emergency-stop loads, and earthquake loads acting in parked rotor conditions with or without wind loads, have been considered as typical loading conditions. Methods of analysis have been implemented in the time domain or using the classical response spectrum approach.

Simplified finite element (FE) models have been implemented in Refs. [5–7], under earthquake loads acting in parked rotor conditions without wind loads. Bazeos et al. [5] studied a 38 m high, 450 kW HAWT resting on a concrete square footing in a semi-rock soil, using shell or beam elements for the tower, a top lumped mass and a rigid block to model rotor-nacelle assembly (RNA) and square footing, respectively, springs/dashpots and added soil mass to account for soil-structure interaction [8]. Lavassas et al. [6] studied a 44 m high, 1 MW HAWT on a concrete circular footing in a rock soil, using shell elements for the tower, 3D-solid elements for the circular footing, and a top lumped mass to model the RNA. Stamatopolous [7] investigated a 53.95 m high HAWT resting on a circular footing, using beam elements for tower and blades, 3D-solid elements for the footing, nonlinear unilateral springs below the footing to model foundation flexibility. For the relatively low ground accelerations of the project sites under consideration, time-domain analyses in Ref. [5] and response-spectrum based analyses in Refs. [5,6] found that earthquake loads acting in parked rotor conditions, without wind loads, induce low stress levels as compared to other design loads. On the other hand, time-domain analyses and response-spectrum based analyses in Ref. [7] demonstrated that shear and bending-moment demand at the tower base can be underestimated significantly by the Greek Design Code, when near fault ground motions are considered. Notice that, in Ref. [7], the response-spectrum approach was implemented on a linearized model of the structure, where the nonlinear unilateral

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springs below the footing are replaced with an equivalent linearly-elastic rotational spring, whose stiffness is calibrated by an approximate iterative procedure. FE models under earthquake loads and operational wind loads have been investigated in Refs. [9–11]. Sapountzakis et al. [9] have proposed a FE approach formulated by the boundary element method. They studied the National Renewable Energy Laboratory (NREL) 5 MW HAWT [12,13] on either surface or monopile foundation, using beam elements for the tower, a top mass for the RNA, nonlinear springs/dashpots to model foundation flexibility, and including axial load effects. Responses for surface and monopile foundations were compared under earthquake loads and a top force modelling wind loads, with the latter built by applying the combined blade element and momentum (BEM) theory on the rotor, taken as fixed on a rigid tower. A FE model accounting for flexibility of the blades in the flapping direction, bending and twisting flexibility of the tower, gyroscopic effects of the rotor, has been proposed by Diaz and Suarez [10]. They investigated the seismic response of a 76 m high, 1.65 MW HAWT, modelling the tower by beam elements and the blades by rigid rods with rotational springs at the roots. Considering four strong ground motions with operational wind loads, they showed that stresses at some tower sections may exceed those from extreme winds. A FE model of the NREL 5 MW HAWT, involving shell elements with nonlinear material behavior for the tower, beam elements for the blades and a coupling joint between rotor and rigid nacelle has been developed by Asareh [11] for fragility analyses under operational loads generated by Aerodyn [14].

In order to study the earthquake response under operational wind loads, full models including support structure and RNA components with different levels of detail, have generally been preferred over simplified models. Full system models have been used in conjunction with fully-coupled, nonlinear time-domain simulations capable of accounting for the inherent coupling between aerodynamic and seismic responses [15]. Indeed, tower top oscillations due to ground motion affect rotor aerodynamics, in particular the relative wind speed at the blades, depending on which the aerodynamic loads, i.e. lift and drag forces on the blades, are calculated.

Fully-coupled, nonlinear time-domain simulations on full system models have been implemented in Refs. [16–20]. Using FAST [21], a NREL simulation tool where motion equations of the system are derived by a combined multi-body dynamics and modal approach (for the seismic module, see in particular Refs. [22,23]), Prowell et al. [16–18] showed that earthquakes may produce, in the NREL 5 MW HAWT, a bending-moment demand at the tower base well above the one from extreme wind events, in operational, emergency shutdown and parked simulations. Also, Prowell et al. [18] demonstrated that not only first but also second modes contribute significantly, in both fore-aft (FA) and side-to-side (SS) directions (i.e., parallel and perpendicular directions to the rotation axis of the rotor, respectively), in agreement with previous findings on the importance of the second modes in seismic response of large turbines [10,24]. Zhao et al. [19,20] developed a hybrid multi-body system (MBS) where nacelle and tower are discretized into an ensemble of rigid bodies coupled elastically by constraint joints and springs, the wind rotor is treated as a rigid disk, and a 3D set of uncoupled frequency-independent spring-damper devices, including translations and rotations, is used to model the foundation. Governing equations are derived using Lagrange's equations and no external calculation of component mode shapes is required. By the MBS approach, Zhao et al. [19] studied the seismic response of a 65 m high, 1.5 MW HAWT, showing that shear force and bending moment at the tower base are affected considerably by earthquake loads, in both FA and SS directions. This result was found for operational conditions, with a weak real earthquake record. Studies in Refs. [16–20] demonstrated that earthquake loads may be design driving in regions of high seismic hazard.

Although fully-coupled, nonlinear time-domain simulations are certainly most indicated to build a numerical solution for seismic assessment, the main disadvantage is that computational costs may be significant, almost prohibitive when several analyses have to be implemented for different environmental states and system parameters, as in the early stages of design. For these reasons, a considerable attention has been devoted to assess whether the response to simultaneous wind and earthquake loads can be obtained by combining two uncoupled analyses, one under wind and another under earthquake only, instead of running a fully-coupled analysis. In this manner, the response to a given wind state, once computed, could be combined with the response to different potential earthquake events, with a significant reduction of computational costs with respect to fully-coupled time-domain simulations.

The implementation of uncoupled analyses is currently the subject of active research. Early investigations have been made by Witcher [25]. Using GH BLADED [26], a simulation tool where equations of motion are derived by a combined multi-body dynamics and modal approach, he studied a 2 MW HAWT mounted on a 60 m high steel tower, showing that, if the separate earthquake moment demand at the tower base is computed from a 5% damped FA-response spectrum and then linearly combined with the separate wind moment demand computed by a time-domain simulation, a good matching is attained with the moment demand at the tower base computed from a fully-coupled, nonlinear time-domain simulation. Considering that steel structures can reasonably be given a 1% structural damping, using a 5% damped FA-response spectrum means that an additional 4% damping is included in the FA modes, when computing the separate earthquake response. The 4% additional damping has been named as *aerodynamic* damping, to point out that its source is essentially the aerodynamics of the spinning rotor. In a rather intuitive way, aerodynamic damping arises from the observation that forward/backward motion of a structure vibrating in a wind field induces a change in the aerodynamic forces that, in general, reduce the dynamic response of the structure [27]. Following the work of Witcher [25], Asareh and Volz [28] considered a total 5% structural damping to analyze the FE model of the NREL 5 MW HAWT in Ref. [11] under earthquake ground motion and operational loads generated by Aerodyn [14]. Experimental tests run on a 65 kW HAWT by Prowell et al. [16], in operational state with earthquake shaking in FA and SS directions, confirmed that aerodynamic damping effects affect the FA response, and showed that are negligible in the SS direction. Recently, an analytical estimate of aerodynamic damping has been proposed by Valamanesh and Myers [27], based on BEM theory, under the assumption of laminar flow (no turbulence) and rigid rotor. The proposed estimate was found to depend on the wind velocity. Working on a FE model of the HAWT with beam elements along the tower and lumped masses at the element nodes and top, subjected to seven ground motions and a top thrust force built in steady-state laminar flow by FAST [21], the authors found a good agreement between top median drifts computed by combining separate wind and earthquake responses, when the earthquake response is built with either the proposed analytical estimate of aerodynamic damping depending on the wind velocity or, alternatively, with a 4% aerodynamic damping in the FA direction and 0% in the SS direction [27].

International Standards such as IEC 61400-1 [29] and Guidelines as ASCE-AWEA RP2011 [30] allow combining uncoupled analyses, instead of performing fully-coupled, nonlinear time-domain simulations. In Annex C, IEC 61400-1 [29] proposes a method to compute the response under earthquake and operational wind loads. It is based on the assumption that the whole structure is