COUPLED NONLINEAR DYNAMIC ANALYSIS OF ONSHORE WIND TURBINES WITH STEEL-CONCRETE HYBRID TOWER

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Extended Abstract

Under the “dual-carbon” target and the ongoing expansion of onshore wind energy development toward low wind speed regions, complex terrain, and extreme environmental conditions, the continuous upscaling of wind turbines and the adoption of ultra-high towers have become key trends in onshore wind power. Concrete–steel hybrid towers (HT) have been widely applied in ultra-high tower wind turbines due to their high global stiffness, superior structural stability, and strong adaptability to transportation and construction constraints[1]. However, compared with conventional steel tower wind turbines, HT wind turbines exhibit significantly increased complexity in structural configuration, load transfer mechanisms, and dynamic response characteristics. Their dynamic behavior is jointly influenced by material nonlinearity, geometric nonlinearity, boundary nonlinearity, prestressing effects, and strong aero–servo–elastic coupling. Existing design approaches based on linear assumptions or decoupled analyses are inadequate to accurately capture the true dynamic behavior of HT wind turbines, which has become a critical bottleneck for reliable safety assessment and performance optimization.

To address these challenges, this study proposes an integrated nonlinear dynamic design method for HT wind turbines. The proposed method is centered on a coupled multi-body dynamics (MBD) and nonlinear finite element (FE) co-simulation framework. By decomposing the system into interacting subsystems, the rotor–nacelle assembly and the HT are modeled in a coordinated manner, enabling fully coupled time-domain simulations of aerodynamic loading, servo-control responses, and nonlinear structural dynamics. To balance computational efficiency and modeling fidelity, a multi-fidelity dynamic modeling strategy combining medium-fidelity and high-fidelity models is developed. The medium-fidelity model integrates MBD, control systems, and nonlinear fiber beam finite elements, allowing efficient representation of material and geometric nonlinearities as well as aero–structure coupling effects[2]. The high-fidelity model further incorporates detailed three-dimensional nonlinear finite element modeling, enabling accurate characterization of critical structural details such as transition segments, flange connections, and local stress concentrations, thereby providing a reliable basis for structural optimization and failure mechanism analysis[3]. For method validation, the proposed co-simulation models are applied to a representative large-scale wind turbine and

compared with results obtained from mainstream wind turbine dynamic analysis tools. The results demonstrate good agreement in modal characteristics and key dynamic response indicators under both normal and extreme wind conditions, as illustrated in Figures 1 and 2. Moreover, under scenarios with pronounced nonlinear effects, the proposed method effectively avoids the underestimation of structural responses commonly observed in traditional linear models, as illustrated in Figures 3. Based on the validated framework, the influences of material nonlinearity, geometric nonlinearity, and their coupling effects on the dynamic response of HT wind turbines are systematically investigated, revealing the amplification mechanisms of tower-top displacement, acceleration, and internal force responses under extreme wind speeds. Furthermore, by integrating the nonlinear dynamic analysis results with existing engineering design standards, an integrated design and verification procedure for HT wind turbines is established. While retaining the structure of conventional decoupled design frameworks, the proposed procedure incorporates fully coupled dynamic response results to perform unified checks on key design criteria, including bending capacity, structural stability, crack control, fatigue performance, and tower-top horizontal displacement angles. Through parametric modeling and automated computation, the proposed approach significantly enhances design efficiency and reliability. The results indicate that the integrated nonlinear dynamic design method proposed in this study can systematically capture the realistic dynamic behavior of HT wind turbines under complex wind environments and operational conditions, providing a robust theoretical foundation and practical engineering tool for the safety assessment, structural optimization, and performance enhancement of ultra-high HT wind turbines.

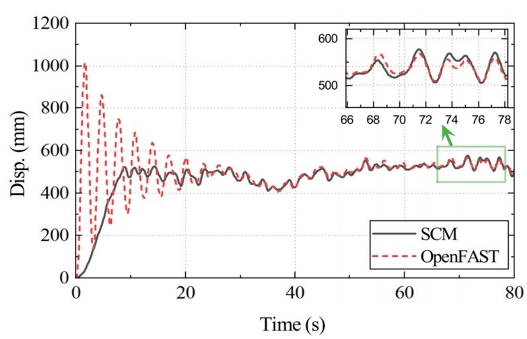


Figure 1-Comparison between the high-fidelity model and OpenFAST

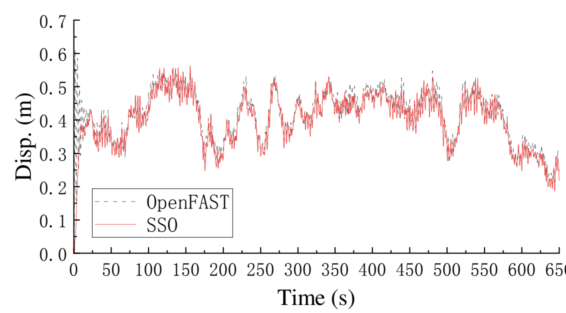
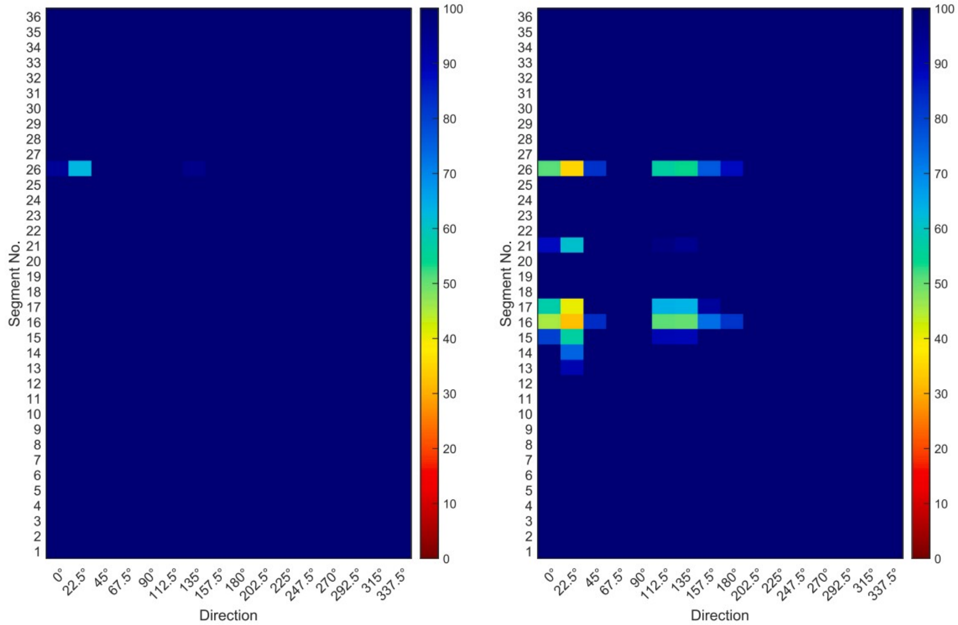


Figure 2-Comparison between the medium-fidelity model and OpenFAST



(a) Linear model

(b) Nonlinear model

Figure 3-Comparison of fatigue life between linear and nonlinear models.

Keywords: wind turbine; concrete–steel hybrid tower; nonlinear dynamics; co-simulation; high fidelity