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Generalized analytical displacement model for wind turbine towers under aerodynamic loading

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ABSTRACT

The goal of this work is two-fold: 1) to determine the angular deflection and displacement of the NREL 5 MW reference wind turbine tower under different atmospheric thermal stratifications, and under overlapping wind turbine wake effects using a comprehensive numerical analysis; 2) to develop and verify a generalized analytical model allowing to efficiently estimate wind turbine tower displacements under a variety of flow conditions. Large-eddy simulations are used to generate atmospheric flows similar to those of a characteristic diurnal cycle. One hour periods are selected and inputted into an aero-elastic simulation code which resolves the rotor-disk aerodynamic loading components, which are then used as inputs to a 3-D finite element model of the tower to compute the angular deflection and displacement. To improve efficiency in tower displacement predictions, a generalized analytical model is developed based on a simplified 2-D cantilever beam and 1-D momentum theory. Results are compared with those obtained from the numerical simulations. Results indicate that the tower deflection standard deviation increases with increasing atmospheric turbulence and wake superposition. Also, differentiated tower displacements are experienced under different atmospheric stratifications. Interestingly, lone standing wind turbines undergo larger tower deflections compared to those located within very large wind farms. The wind turbine rotor thrust and the aerodynamic thrust on the tower are found to have the greatest and least influence, respectively, on tower deflection. Displacement results from the finite element analysis are used to verify the accuracy of the new generalized analytical model showing a very good agreement. This new model has the advantage of estimating the tower deflection by just knowing the inflow velocity for any wind turbine, independent of the atmospheric stratification and wind farm arrangement.

1. Introduction

Wind turbine towers are prone to angular deflection, ϕ, and displacement, δ, because of the loads they sustain. These loads mainly result from the interaction of the rotor blades and tower structure with the atmospheric boundary layer (ABL) flow, as well as from the resultant forces due to the turbines regular operation, *i.e.* the rotation of the blades. As wind energy continues to globally develop (Watson et al., 2005), it is important to understand and reliably predict turbine structural response due to these external forcing actions. In this work, a complete analysis of the towers' loads and deflections is developed by considering the blades' rotational effect, different atmospheric stratifications, and the effect of wake superposition (characteristic of very large wind farms). A detailed structural analysis is necessary for ensuring the operational serviceability and safety of wind turbines. However, to numerically perform such detailed structural analysis, it is required to consider full realistic atmospheric conditions, from which the structural wind loads can be determined, together with a discretized multi-degree-of-fredom (MDOF) finite element analysis (FEA) (Bazilevs et al., 2011a, 2011b; Bang et al., 2012) to determine the tower angular deflections and displacement.

The Rankine-Froude momentum theory (Wilson and Lissaman, 1974) is one of the most widely used approaches to determine the structural loading. This approach assumes an unperturbed wind velocity field which is approximated by either a power-law (Bang et al., 2012; Peterson and Hennessey, 1978; Lavassas et al., 2003; Uys et al., 2007), or a log-law (Bisoi and Haldar, 2014). In essence, aerodynamic loads are traditionally derived considering a neutrally stratified and undisturbed wind velocity. While this approximation works well for offshore flows, it is far from

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realistic in most onshore conditions. Furthermore, this approach does not take into consideration the effect of multiple turbine wake interactions. To address this limitation, some studies have included a parameterization to account for turbulence intensity. For example, Jonkman (2007) included full-field, three component stochastic winds and varied the standard deviation of the velocity fluctuations to determine the relationship between the turbulence and the structural fatigue. To be able to consider more realistic flows, one must rely on high-resolution numerical simulations of the atmospheric flow. This can be effectively done with large-eddy numerical simulations (LES). In this direction, Sim et al. (2012), for example, stated the need of efficient spatial and temporal resolution of simulated inflow wind fields to properly represent wind turbine dynamics and derive appropriate loads. In their work, three numerical approaches to study loads on turbines were explored: using a conventional stochastic simulation, a large-eddy simulation, and a large-eddy simulation with fractal interpolation for a neutrally stratified boundary layer. Simulations were run at velocities of 12, 15 and 18 ms^{-1}, and the largest loads were found for the 12 ms^{-1} case. Their findings suggested that an inflow wind field with grid spacing approximately one-tenth that of the rotor diameter with a data frequency of 1 Hz would be adequate for load studies. Also, interesting work from Park et al. (2014) demonstrated that stochastic simulations of turbulent inflow fields used in wind turbine load computations cannot account for the varying atmospheric stratification and characteristics of realistic ABL flows. They stated that using LES generated wind fields for generating wind turbine loads is beneficial since LES is much more realistic. This is because it considers important wind parameters such as enhanced wind speed and directional wind shear. In their study, a total of 50 LES simulations were run to account for a large variability of flow characteristics such as mean geostrophic wind, surface roughness, surface cooling rate, initial boundary layer height, the change on the Coriolis parameter, and geostrophic departure.

On the other hand, MDOF analysis is required to accurately model the tower and rotating blades assembly to properly obtain their aerodynamic and structural loading. For example, such analysis is used by Park et al. (2015) to investigate the effect of different ABL flow characteristics on the associated loads. In their study, wind turbine loads are computed using the aero-elastic simulation code FAST (Fatigue, Aerodynamics, Structures and Turbulence) developed at NREL (Guntur et al., 2016). In a similar work, Murtagh et al. (2005) used the MDOF analysis to investigate the vibration response of a wind turbine tower and rotating blades assembly to estimate tower tip displacements. Comparisons were performed between two different study cases, one that accounts for the blade/tower interaction, and another one that does not. Results demonstrated the importance of having in consideration the blade/tower assembly. Otherwise, results underestimate the wind turbine response at the top of the tower, especially if the fundamental frequencies of the tower and turbine blades are close to each other.

Because detailed structural analysis of the wind turbine assembly are computationally expensive and time consuming, it is important to develop simplified models that can alternatively be used for preliminary design stages. In this regard, a simplified approach to determine the tower angular deflection often used for design optimization purposes is to consider a cantilever beam under point and distributed loading (Uys et al., 2007). Additionally, given that deflections of the turbine tower fluctuate with aerodynamic loads, studies have also examined the turbine's vibration behavior (Bisoi and Haldar, 2014; Jonkman, 2007; Murtagh et al., 2005; Larsen and Hanson, 2007; Fadaeinedjad et al., 2008; Guo et al., 2011), fatigue response (Lavassas et al., 2003; Jonkman, 2007; Grujicic et al., 2010; Hansen et al., 2014; Holtslag et al., 2016), buckling characteristics (Bang et al., 2012; Guo et al., 2011; Bazeos et al., 2002), and gyroscopic loading on the generator and transmission assemblies (Shokrieh and Rafiee, 2006; Heege et al., 2007; Pao and Johnson, 2009).

Currently, it is clear that realistic wind turbine inflow conditions are needed to numerically determine the wind turbine structural loading, which will directly influence the angular deflection and displacement of the tower tubular-structure. For this purpose, this study uses LES of realistic atmospheric flows (Kumar et al., 2006) to generate realistic wind fields. In this work, we further exploit the flexibility of LES to evaluate the wind turbine behavior under two different scenarios: a lone standing wind turbine and a wind turbine immersed within a very large wind farm (VLWF). Similar to the work from Jonkman et al. (Jonkman, 2007), FAST will be used to study the loads and turbine performance characteristics. Finally a finite element analysis (FEA) is used to determine the deflection or displacement of the tower-tip. In a second stage, this numerical analysis is used to develop and validate a new analytical model for determining tower displacements. The advantage of this new analytical model is that it only requires the wind turbine inflow velocity, the structural characteristics of the tower, and swept area of the rotor disk. The methodology presented here has the potential to become a basis for the design codes, where the tower-tip displacement has to be taken into account in the design stages. Also, it has the potential to be used for tower optimization studies as previously done (Negm and Maalawi, 2000; Nicholson, 2011; Muskulus and Schafhirt, 2014).

In summary, the objective of this research is to study how the aerodynamic loading affects the structural response of a turbine tower during operational conditions under different thermal stabilities. To do so, a coupling between LES, FAST, and ABAQUS (finite element computer code) is performed. Details can be found in Section 2 where the numerical simulations are described and the distinct case studies are listed. Section 3 presents and discusses the results arising from the FEA. In Section 4, a generalized deflection model is developed and validated. Finally, Section 5 provides the conclusions of this work.

2. Numerical simulations

2.1. Large-eddy simulations of a diurnal cycle and case studies

To obtain a realistic atmospheric flow field, an LES approach is used where the energy containing turbulent eddies are resolved and the smaller ones are parametrized. Because of the large Reynolds number characteristic of ABL flows, viscosity effects are neglected. The effect of the unresolved scales is accounted for with the Lagrangian scale dependent model of Bou-Zeid et al. (2005a) in the filtered momentum equations and with the Lagrangian scale dependent model for scalars of Calaf et al. (2011) in the advection-diffusion equation for the temperature. The thermal effects are coupled to the Navier-Stokes equations by means of a buoyancy term, considering the Boussinesq approximation. A vertically staggered grid is used to discretize the equations which are integrated using second order finite-differences in the vertical direction, and a Fourier decomposition in the horizontal direction, similar to Moeng (1984) and Albertson et al. (Albertson and Parlange, 1999). Because of the use of spectral methods in the horizontal directions, the flow is horizontally periodic and hence in practice equivalent to a horizontal infinite domain. The equations are time integrated using a second order Adam-Bashforth scheme. The numerical algorithm is fully parallelized using the Message-Passing Interface (MPI). At the top of the domain, a zero-flux boundary condition is imposed for momentum and temperature. At the bottom, the no-slip condition is applied for the vertical velocity and, because of the staggered grid, equivalent shear stress is imposed at the first grid point for the horizontal momentum components. The shear stress at the surface is parameterized using the traditional log-law and includes the effects of stratification (Monin and Obukhov, 1954; Parlange, 1993; Bou-Zeid et al., 2005b). To model a diurnal flow variation, a time varying surface temperature is imposed. This approach has been previously used in other similar LES studies (Kumar et al., 2006; Kumar et al., 2010; Svensson et al., 2011; Abkar et al., 2016; Sharma et al., 2016a; Cortina et al., 2017a; Cortina and Calaf, 2017; Cortina et al., 2016; Cortina et al., 2017b; Cortina et al.,).

To generate an atmospheric flow under different thermal