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Numerical Investigation and Wind Tunnel Validation on Near-Wake Vortical Structures of Wind Turbine Blades

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Abstract. Computational fluid dynamics (CFD) has been used by numerous researchers for the simulation of flows around wind turbines. Since the 2000s, the experiments of NREL phase VI blades for blind comparison have been a de-facto standard for numerical software on the prediction of full scale horizontal axis wind turbines (HAWT) performance. However, the characteristics of vortex structures in the wake, whether for modeling the wake or for understanding the aerodynamic mechanisms inside, are still not thoroughly investigated. In the present study, the flow around N-REL phase VI blades was numerically simulated, and the results of the wake field were compared with the experimental ones of a one-to-eight scaled model in a low-speed wind tunnel. A good agreement between simulation and experimental results was achieved for the evaluation of overall performances. The simulation captured the complete formation procedure of tip vortex structure from the blade. Quantitative analysis showed the streamwise translation movement of vortex cores. Both the initial formation and the damping of vorticity in near wake field were predicted. These numerical results showed good agreements with the measurements. Moreover, wind tunnel wall effects were also investigated on these vortex structures, and it revealed further radial expansion of the helical vortical structures in comparison with the free-stream case.

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Key words: Wind turbine, numerical simulation, wind tunnel experiment, vortex wake.

1 Introduction

In recent decades large-scale horizontal axis wind turbines (HAWT) and wind farms spre-

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ad rapidly all over the world. Accurate prediction of their performance is crucial from the view point of a designer. For blind validation of both analytical and/or computational methods, the experiments of the phase VI blades have been conducted in National Renewable Energy Laboratory (NREL) of United States, where the experimental results became the de-facto standard of numerical simulation for horizontal axis wind turbines [1,2]. Among the methods involved in that comparison, in addition to the classical blade element theory-based methods [3], both vortex wake model methods and CFD methods were used for the simulation of flow field around the turbine blades. Typical results by prescribed vortex wake model methods can be found from Coton et al. [4], in which the blade sectional aerodynamic loading from the computation was compared with NREL experimental data. The influence from the dynamic stall model was also discussed. The CFD simulation for the 3D incompressible flow of NREL phase VI blades was performed by Sørensen et al. [5]. Not only overall results, such as the shaft torque and flap and edge moments, but also the sectional pressure distribution and aerodynamic coefficients were obtained and put into comparison. Good agreements were observed for the moments and torques in the low and marginal speed range. However, the turbulence model used in that solver still cannot provide a universally good simulation in all wind speed range, especially for both the intermediate speed cases where flow separation occurred on the middle of blades and the high speed ones where leading edge flow separation and turbulence are dominant. Further numerical investigation on the normal force distribution from Duque et al. [6], which was based on a overset grid system and the Baldwin-Barth turbulence model, also showed that discrepancy at post-stall state. Advanced numerical methods such as detached eddy simulation (DES) was used by Johansen et al. [7] as well, but no significant improvement over the full RANS solution was obtained yet for the computation of NREL phase VI blade.

In the meantime, the fundamentals of wind turbine wake became the interests of research in recent decades. Extensive investigation of WT wakes was reviewed by Crespo et al. [8] and Vermeer et al. [9]. Among various aspects, two aspects will be studied in this work. Firstly, the flow around the wind turbine is considerably influenced by the induction from the wake downstream. Blades of a wind turbine rotor are under the downwash of the helical tip vortices. The latter significantly affects the motion of turbulent wake structure and then the considerable interaction between them. Many researches were conducted for the behaviours of near wake, both for the accurate prediction of wind turbine performance and for the development of vortex wake models (prescribed or free). Secondly, the rapid growth of wind farms recently requires good estimates for the interaction between the wakes and downstream turbines. Then the characteristics of far wake also become important topics among the researches [10].

The formation and spatial structures of wind turbine wakes have been obtained by various experimental methods. Typical studies are found from Grant and Parkin [11]. They used a digital particle image velocimetry (PIV) and obtained clear pictures of the trailing vortices and the induced velocity field from the blades of a horizontal axis wind-turbine in yaw. The time varying convective features of trailing vortices were studied as