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Experimental analysis of the wake of a horizontal-axis wind-turbine model

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ABSTRACT

The wake of a wind turbine is the driving phenomenon for energy recovery in a wind farm and for the interaction between wind turbines. The vortical structures of the wake of a horizontal-axis wind-turbine model are investigated in the Open Jet Facility wind-tunnel of Delft University of Technology. Velocity fields are acquired with stereoscopic particle image velocimetry, both unconditionally sampled and phase-locked with the blade motion, allowing for a statistical analysis of the mixing process of the wake, distinguishing between the contribution of the organised periodic motions and the random turbulent fluctuations. The evolution of the wake is measured up to five diameters downstream of the model. The stream-wise development of the wake velocity, pressure and total enthalpy of the flow is determined. Results show that the wake instability caused by the pair-wise interaction of the blade tip-vortices (so called "leapfrogging phenomenon") has a strong impact on the momentum deficit recovery of the wake, by enhancement of the mixing process downstream of the tip-vortex helix instability, where the contribution of the random fluctuations becomes predominant. The experimental data are made available online together with a complete description of the wind turbine model.

1. Introduction

The wake of a horizontal axis wind-turbine (HAWT) is a region of three-dimensional turbulent flow characterised by a deficit of kinetic energy and a complex vortical helical structure. Although several experimental and numerical analysis have demonstrated the link between the momentum deficit in the turbine wake and the rotor performance (see the works of [18,21,24]), an accurate prediction of the wake characteristics such as the recovery length and the expansion rate still is unfeasible, especially when considering wind-farm applications where multiple wakes are produced by arrays/clusters of turbine rotors. The large inaccuracies encountered in the numerical prediction of the kinetic energy recovery are typically associated with a poor modelling of the wake (see Ref. [2] and of the turbine loads, generally based on actuator disc or actuator line models. As shown by Ref. [17]; the actuator disc model in combination with the $k-\varepsilon$ turbulence model produce a strong region of high turbulence close to the blade, quickly decaying in proximity of the turbine model, as shown in Ref. [17]. The presence of this region is primarily artificial and in disagreement with in-field experimental observations [13], showing that a consistent turbulent mixing persists up to the turbine far wake. The effect of the incorrect representation of the wake re-energising mechanisms is confirmed by the large dispersion of current CFD results in the prediction of wind-farm power by different turbulence models, as in Ref. [22].

Refs. [3,9] showed how in large wind farms, the wake energy recovers via entrainment of kinetic energy from the flow surrounding the farm. The kinetic energy entrainment occurs at two different scales: the atmospheric turbulent flow level and the wake-induced flow level. The second one is of particular interest because it concerns the mixing process owing to the presence of the tip vortex helix, its instability and its breakdown, which are directly dependent on the turbine design and operation and on the interaction among multiple turbines and wakes. This is even more relevant for off-shore wind farms, where atmospheric turbulence is lower than on-shore.

Few studies focus on the self-induced mixing of the wake. Refs. [8,11,21] showed the influence of different parameters (such

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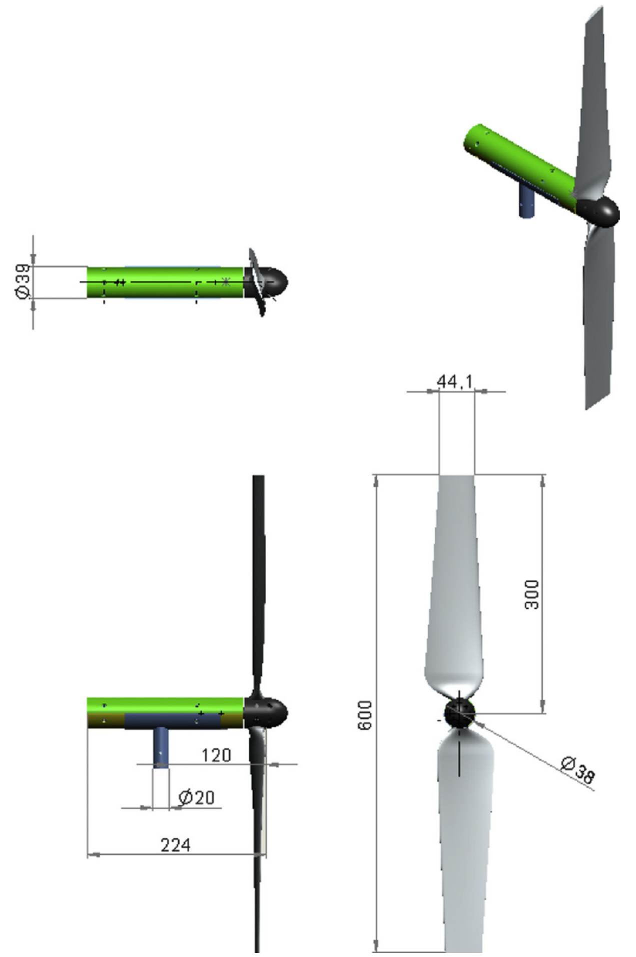

Fig. 1. Wind turbine model. Dimensions are in millimetres.

as tip-speed ratio, inflow turbulence, tip-vortex core size) on the stability properties of the wake. Ref. [13]; in contradiction with previous statements of [10]; hypothesized that the near wake tip-vortices inhibit the wake mixing and the outer air entrainment; however, this hypothesis is presented without a clear quantification of the effect of the vortices and their break-down on the mixing process. Ref. [9] demonstrates the importance of the vertical transport of kinetic energy to replenish the wake, analysing the mixing process due to the large scale atmospheric turbulence and its effect on the smaller scale flow structures within a wind farm.Refs. [20,24] experimentally studied the dynamics of the turbulent mixing in the wake of perforated discs as simulation of an actuator disk.

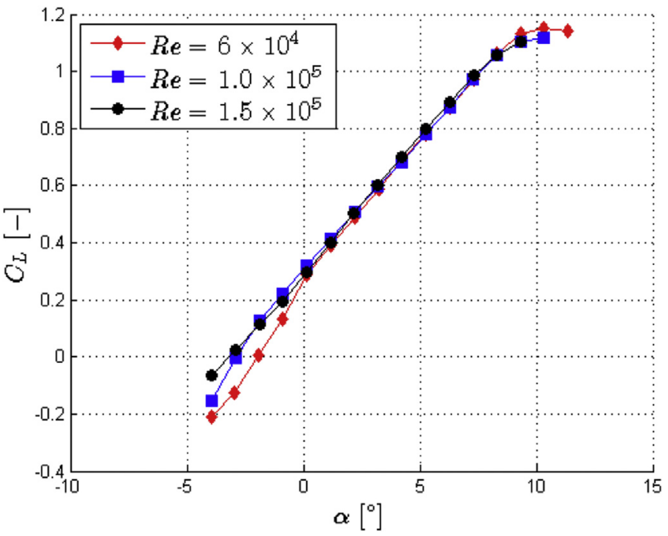

Fig. 2. C_l-α curves of airfoil E387 from $Re = 0.6$ to $Re = 1.5\ 10^5$.

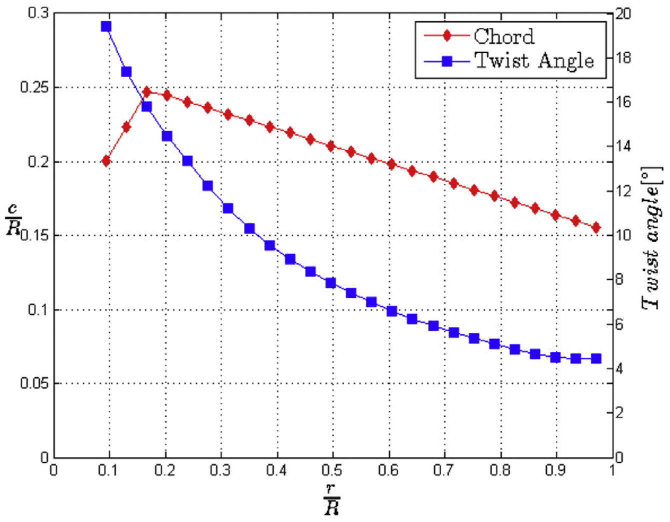

Fig. 3. Chord-radius ratio and twist-angle distribution of the wind-turbine model blades.

In the present manuscript, a detailed measurement and analysis of the vortical structures in the wake of a HAWT is performed with stereoscopic particle image velocimetry (SPIV), in order to visualise the dependency between the wake re-energising process and the tip-vortex helix development, in the near and far wake of the turbine. The wake velocity field is measured up to 5 diameters downstream. The different measurements are acquired with both phase-locked and unconditioned sampling techniques, respectively by triggering the acquisition system in phase with the rotor and randomly. The complete statistical representation of the phase-averaged and mean flow allows for the distinction between the contributions of the random fluctuation and the organised periodic fluctuations in the mixing process of the wake with the outer flow. A series of measurement with a six-

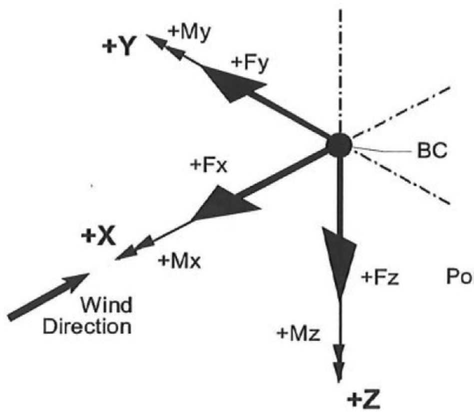

Fig. 4. Reference system for the balance measurements.