FLOW Final Report

Project title : **DUWIND's far offshore wind farm design PhD's**
WP2: Near and Far Wake Effects

1. Project Summary

The wake flow of a horizontal axis wind turbine is characterised by lower wind speed and higher turbulence than the free-stream conditions. When clustered in large wind farms, wind turbines regularly operate inside the wake of one or more upstream machines. This is a major cause of energy production loss and a source of higher fatigue loads on the rotor's blades. In order to minimise the wake effects, a smart optimisation of the wind-turbine layout is essential and reliable method for modelling the wake behaviour is fundamental. The scientific community has broadly recognised the high level of uncertainty, which still affects the state-of-the-art numerical wake models and, in turn, leads to miscalculation of the wake effect. In order to develop more advanced models it is valuable to follow a back-to-basic approach and to investigate the physics of the transition from near-wake flow to far-wake flow. The near wake is characterised by the presence of organised structures as the tip- and root-vortex helices, which are trailed at the two extremities of each blade. In the far wake, the influence of the blade flow is no longer visible: this is the region where most of the turbulence mixing happens and the wake undergoes a re-energising process. Given the different physics governing the two regions, including in a single model a set of assumptions able to encompass both flow characteristics and to account for the influence of the near-wake features on the far-wake development is still problematic.

This research explores two aspects of the wake problem, adopting an experimental, numerical and theoretical approach. In the first place, the physics of the transition from near to far wake is explored. In particular, the main aim is to study how the near-wake turbulent flow structures affect the re-energising process of the far wake, by understanding the relationship between the near-wake vortex system and the resulting coherent turbulence structures in the wake. In second instance, the actuator disc approach, which is at the basis of most rotor as well as wake models, is studied for shedding more light onto its limitations and potentials. In the framework of the FLOW project, the main objective of this research are:

Objective 1: the delivery of an experimental database of wind turbine near- and far- wake development in controlled conditions (wind tunnel).

Objective 2: (modified) validation of several simulation codes for the development of the near-wake and its transition to a far-wake, for use in the design environment.

Stereo particle image velocimetry (SPIV) is adopted for mapping the three-component velocity field in a meridian plane encompassing a large portion of the near, transition and far wake of a two-blade wind turbine model. Measurements are carried out in the presence of an artificially-triggered tip-vortex pairing instability, the so-called leapfrogging instability, which determines the tip-vortex breakdown and the onset of a more efficient wake mixing. The analysis of the data revealed a major influence of the vortex instability on both the time-average velocity field and on the turbulence field. In particular, it was shown that the wake begins its re-energising process after the tip vortices have broken down. A second step in this analysis is the application of a filter (triple decomposition) on the flow field for separating different flow structures of different nature in order to study their role in the wake mixing. The analysis shows that only the small-scale non-periodic flow fluctuations are yielding considerable entrainment of kinetic energy, while the near-wake vortex structures seem to act as a shield preventing the wake mixing.

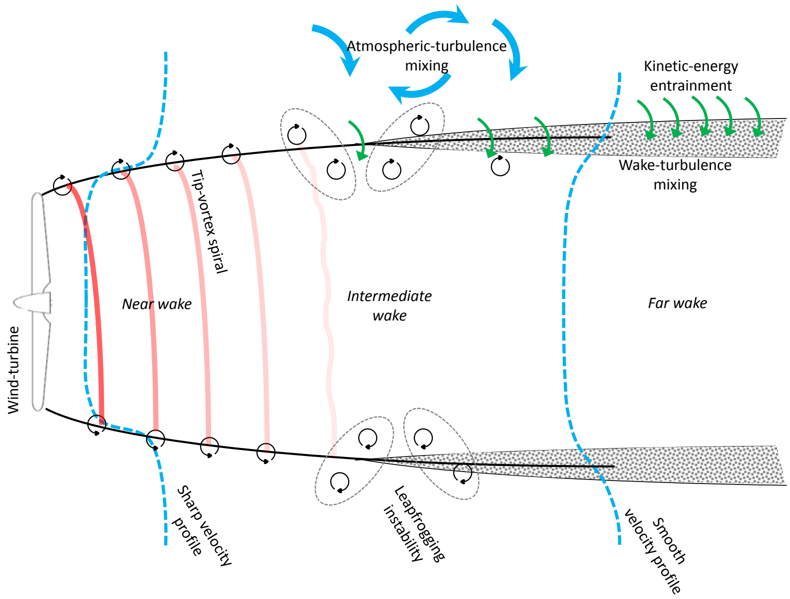

Figure 1. Schematic of a wind-turbine wake with tip-vortex leapfrogging instability, near and far wake, tip vortex spiral and kinetic energy entrainment.

The study continues with the analysis of the wake of the wind turbine model compared with the one of an actuator disc. The latter is reproduced experimentally by means of a porous disc manufactured with metal mesh, having the same diameter and drag coefficient of the turbine model. Differences between the two wakes (velocity deficit, turbulence levels, mean-flow kinetic-energy transport, etc.) are quantified with SPIV measurements. The study shows that the actuator disc is in fact able to reproduce the time-average velocity field also in the very near wake with good accuracy, contrary to what is found in previous literature. The application of a flow filter (POD) is adopted as an alternative method for separating flow motions of different nature. The analysis confirms that major contribution to the energy entrainment in the wind turbine wake is provided by the small-scale non-periodic flow fluctuations, while the periodic fluctuations have a zero or even negative contribution. In the actuator disc wake the kinetic energy transport is only positive and of a larger magnitude compared to the one in the wind turbine wake.

Five state-of-the-art computational fluid dynamics (CFD) codes are validated against the experimental data in a benchmark workshop organised among several academic and industrial organisations. Four large eddy simulation (LES) codes and one vortex models are used for reproducing the near wake of the porous disk. The comparison shows that, despite the lack of viscosity and turbulence models, the vortex model is capable of reproducing the wake expansion and the centreline velocity with very high accuracy. Also all tested LES models are able to predict the velocity deficit in the very near wake well, contrary to what was expected from previous literature. However the resolved velocity fluctuations in the LES are below the experimentally measured values.

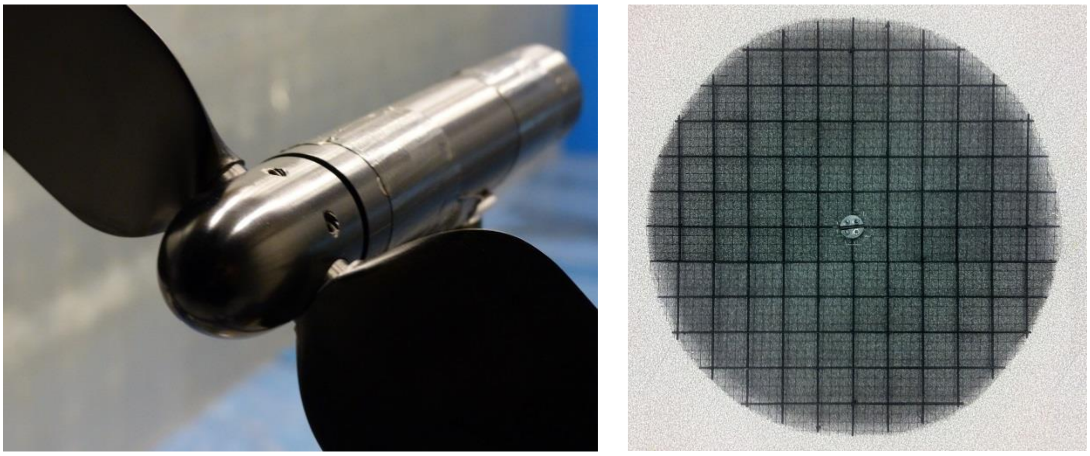

Figure 2. Left: wind turbine model. Right: actuator disc model.

The anticipated effect on energy yield can be measured in a reduction of the wake losses. For a large wind farm the overall wind farm wake losses are in the order of 15% or more. With better wake modelling it is expected that the wake losses can be reduced with 1 to 2 % increasing the energy yield approximately with the same percentage, say 1,5%. This is expected to lead to a 1.48% energy cost reduction (see Section 8). The reduction on the structural fatigue loads will be small (e.g. 3%) and will lead to a reduction of the blade mass. However, this reduction will be marginal. An indirect effect of the reduced uncertainties will also be better financing conditions. The reduced uncertainty, in fact, will have a positive effect on the risk related to the project and will encourage the financers to allow for a lower interest rate.