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# Aerodynamics of wind turbine wakes in flat and complex terrains

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ABSTRACT

The wake evolution measured downstream of multi-megawatt wind turbines located in flat and complex terrains are described here. These high-resolution measurements at full-scale Reynolds number conditions are made with an instrumented drone that is equipped with a suite of sensors and detail the characteristics of the mean flow and turbulent kinetic energy in the evolving wake. Reynolds decomposition yields the nature of turbulent fluctuations in surface layer, and this decomposition is used to detail the turbulence statistics, degree of anisotropy and friction velocity. These measurements are shown to be suited for the further development of three-dimensional wake models that are currently under intensive development.

## 1. Introduction

The expansion of wind energy across Europe is mainly driven by the European Union's 2020 target of generating 20% of its energy from renewable sources [1]. As the wind energy market matures, flat sites with good winds are becoming increasingly scarce, thus sites in complex terrain with moderate winds are increasingly of interest. Such sites, which were previously considered suboptimal for investment, have gained prominence in recent years [2]. However, wind resource assessment in complex terrain is challenging, due to limited field measurement data and due to the difficulty in the accurate modelling of flow in complex terrain [3,4]; thus there are higher uncertainties in wind resource estimates in complex terrain compared to flat terrain [2]. These higher uncertainties often result in a mismatch between the predicted annual energy yield and the actual annual energy yield – which consequently result in larger risk in the development of wind farm projects. Furthermore the loads on wind turbines located in complex terrain are higher due to higher wind shear and increased levels of turbulence, thus resulting in a reduced lifetime of wind turbine components [5]. Micrositing of wind turbines in complex terrain is further complicated by the fact that the flow downstream of a wind turbine is highly unsteady and three-dimensional. This highlights the need to understand the flow behaviour in two important areas – one is the behaviour of atmospheric boundary layer close to ground in complex terrain and the second is the wind turbine wake behavior in different terrains including its interactions with other downstream turbines. In recent years, wake evolution in flat and complex terrains has been a topic of focus that requires improved modelling for optimised wind farm layouts [6,7]. Thus there have been efforts directed to the development of both semi-empirical wake models [8–11] and more complete field models ([12] and [13]) to predict the evolution of wakes in wind farms located in different terrain conditions.

As wind farms in both complex terrain and flat terrain operate inside the turbulent atmospheric boundary layer, an understanding of the nature and structure of turbulence in the different terrains is needed. As there are several discrepancies between predictions and measurements, there continues to be a need for full-scale measurements in order to validate and calibrate the prediction methods [14]. While wind tunnel and water tunnel tests provide an environment to conduct detailed parametric studies under carefully controlled conditions, their Reynolds number is at least one order of magnitude smaller than in full-scale conditions, this may be a concern regarding the widespread applicability of sub-scale experiments. Indeed the scale of the Reynolds number is relevant in physical process such as turbulent mixing, the entrainment of kinetic energy, the evolution and breakdown of tip vortices, etc, all of which are features of wakes in wind farms. The present work extends the authors prior work [15,16] with detailed measurements of the wake up to six diameters in flat and complex terrains. Thus the primary objective of this work is to detail and distinguish the

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### Nomenclature

| | |
|---|---|
| D | rotor diameter |
| f, F | frequency |
| P, $P_0$ | static pressure |
| $u_2$, V | wind speed in Earth's frame of reference |
| $V_f$ | FRAP air speed |
| $V_0$ | SCADA 10-min average wind speed |
| X | longitudinal axis (along rotor axis) |
| Y | lateral axis |
| Z | vertical axis |
| $Z_{HH}$ | hub height |
| $p_v$ | vortex pitch |
| u, v, w | unfiltered velocity components, u along streamwise and w is in vertical direction |
| $u'$, $v'$, $w'$ | resolved stochastic fluctuations |
| $\overline{u}$, $\overline{v}$, $\overline{w}$ | mean velocity components |
| $u_*$ | friction velocity |
| $t_0$ | time |
| $\sigma_{u'}$, $\sigma_{v'}$, $\sigma_{w'}$ | standard deviation of velocity fluctuations |
| $\rho$ | density |
| $\tau$ | integral time scale |
| $\mathscr{L}$ | integral length scale |
| $\lambda$ | tip speed ratio |

*Abbreviations*

| | |
|---|---|
| AGL | above ground level |
| DA | Degree of anisotropy |
| FRAP | Fast response aerodynamic probe |
| GPS | global positioning system |
| GUM | guide to uncertainty in measurements |
| HH | hub height |
| IMU | inertial measurement unit |
| MW | megawatt |
| Pdf | probability density function |
| SCADA | supervisory control and data acquisition |
| STFT | short-time Fourier transform |
| TKE | turbulent kinetic energy |

vortex structure and mixing properties of wakes in flat and complex terrains.

The structure of the paper is as follows. In the next section, the wind farms and instrumented drone are described. The results are then presented and discussed in detail. The paper finally concludes with a summary of the key observations.

## 2. Description of measurement sites

The drone based wind measurements are carried out at the Mont Crosin wind farm in Switzerland, which is located in complex terrain at an average elevation of 1250 m AGL. Fig. 1 shows the layout of wind turbines at the Mont Crosin wind farm on an aerial imagery from Google map, a digital elevation map and a land cover map. The locations of the wind turbines are shown by circle symbols; the turbine at which measurements are made is shown as a filled white circle, whereas the other turbines are shown as filled black circles. This wind farm is located in complex terrain, with patches of dense, tall coniferous forest surrounding the wind farm. During the measurements, the predominant wind direction observed at the Mont Crosin wind farm was from North-East and the wind direction changed overall by no more than 10°, with wind speeds in the range of 5–9 m/s. Thus the turbine at which measurements were made was not in the wake of any other turbine. The turbine at which measurements are made is a 2 MW Vestas V90 wind turbine. The rotor diameter is 90 m and hub height is 95 m AGL, with cut-in and cut-out wind speeds of 4 m/s and 25 m/s respectively. The location of this wind turbine is indicated with a white dot at center in Fig. 1. The wind turbine has an automatic yaw control system, which aligns the rotor into the incoming wind direction. The wind farm operator provided access to the turbine's 10-min average SCADA data, which were used for comparison to supplement the drone based wind measurements.

The second wind farm is the Altenbruch II wind farm in northern Germany. The wind farm is located in flat terrain at a distance of 5 km from the North Sea coast, Fig. 2. The locations of the nine wind turbines in the wind farm are shown by the circle symbols in Fig. 2; the turbine at which measurements are made, shown as a filled white circle, is a Vestas V90 with a rated power 3.0 MW and a hub height of 105 m AGL. The other turbines are shown as filled black circles. During the measurements at the Altenbruch II wind farm, the predominant wind direction was from South-West and the wind direction changed overall by no more than 8°, with average wind speeds of 8 m/s.

In addition to the measurements at the two above wind farms, freestream measurements at two other wind farms are also reported here. The first of these is Freudenberg–Beiersdorf wind farm in Brandenburg, Germany that is in a flat terrain and surrounded by patches of dense tall coniferous trees. The second of these wind farms is at Collonges, Switzerland. The Collonges wind farm is in a valley, that extends approximately northwest-southwest, and has hills on its sides rising up to 2500 m AGL. Thus this second site is in complex terrain. Table 1 summarises the characteristics of these two wind farms.

## 3. Drone measurement system

The unsteady, three-dimensional flow field around the wind turbine is measured using drones instrumented with a seven-sensor fast response aerodynamic probe. The drones are detailed elsewhere [15,16] but some salient characteristics are summarised in Table 2. The seven-sensor fast response aerodynamic probe that is used for wind measurements is described in detail by Mansour et al. [17]. The sensing elements of the probe are miniaturised silicon piezo-resistive chips, which are encapsulated into a 20 mm hemispherical probe head, and are installed on a cylindrical shaft to give an overall probe length of 70 mm. The probe's measurement chain consists of the sensing elements, power supply units, signal conditioners, a 14-channel 24 bit analog-to-digital converter (sampling at upto 500 Hz) and an on-board flash card for data storage. The aerodynamic calibration of the probe was carried out in a fully automated free-jet facility at ETH Zurich [18], and yields less than 0.1% relative error in angles and dynamic pressure. The drone's on-board autopilot system, which is based on Paparazzi [19], is used for fully autonomous flight. Other components in the hardware suite include an absolute pressure sensor (with resolution of ±1.2 Pa), an ambient temperature sensor (with a resolution of 0.01 °C), humidity sensor (with accuracy of 1.8%), IMU (with angular accuracy of 2%), a GPS (with position accuracy of 3 m) and a magnetometer (with an accuracy of 1°). The hardware suite transmits data in real-time through an on-board modem, and the data is logged on a ground-based computer. At a cruise speed of