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Short communication

Wind characteristics in wind farms situated on a hilly terrain

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ABSTRACT

Wind characteristics in wind farms situated on a hilly terrain are considerably different than on a flat terrain. This issue is particularly important in strong-wind situations, when the wind velocity exceeds 25 m/s. In those situations, wind turbines are designed to remain in the parking position (no rotation of rotor blades) to prevent damage or even collapse of wind turbines. The present wind-tunnel study thus focuses on flow and turbulence characteristics in wind farms situated on a hilly terrain subjected to strong winds. A particular emphasis is on wind conditions for wind turbines placed at various positions in wind farms, as well as on a distance between a hill and a wind farm. The hill model is observed to strongly influence flow and turbulence characteristics at the wind-turbine model position in the wind-farm model. The most prominent aerodynamic features are flow retardation and turbulence enhancement, whereas the velocity power spectra show different trends along the height of the wind-turbine tower model. These experimental results present an important input for engineers attempting to design more robust and reliable wind turbines for hilly terrains.

1. Introduction

Wind turbines situated on a hilly terrain experience wind loads considerably different than it is the case for wind turbines on a flat terrain, e.g. Botta et al. (1998), Mouzakis et al. (1999). This may cause damage, collapse and shorter lifetime of wind turbines in terrain that consists of mountains, hills, valleys, escarpments and other irregularities. Particularly critical is a strong-wind situation, when the wind velocity is larger than 25 m/s, and wind turbines are in parking position, i.e. there is no rotation of rotor blades.

The atmospheric boundary layer (ABL) flow changes as it develops through the wind farm. Nevertheless, the properties of the approaching flow field impinging the windward edge of the wind farm are expected to remain, for the most part, unaffected by the wind farm layout, and in agreement with previous relevant studies on atmospheric flow in complex terrain, e.g. Jackson and Hunt (1975), Mason and Sykes (1979), Pearse et al. (1981), Taylor et al. (1987), Castro and Apsley (1997), Cao and Tamura (2007).

Various aerodynamic aspects of wind energy conversion were previously studied, e.g. Grant and Parkin (2000), Whale et al. (2000), Vermeer et al. (2003), Medici and Alfredsson (2006), Sørensen (2011). While the focus was mostly on uniform wind conditions, some studies emphasized the ABL flow and turbulence effects, e.g. Chamorro and Porté-Agel (2011), Markfort et al. (2012), Zhang et al. (2012). In strong-wind situations, the atmosphere can be considered neutrally thermally stratified due to an intense mixing of the wind flow. Flow and turbulence characteristics in the wake of wind turbines become even more complex for irregular terrain topography, e.g. Kozmar et al. (2016).

It is hence of great interest to study exact wind conditions in strong-wind situations at a particular site, when wind turbines are designed as a part of wind farms in hilly terrain. This data is expected to enable wind and structural engineers creating more robust and reliable wind turbines. For that purpose, wind-tunnel experiments were carried out to determine flow and turbulence characteristics at various positions of wind turbines in wind farms at various distances of wind farms downwind of a hill.

2. Experimental setup

Model experiments were carried out in the CRIACIV boundary layer wind tunnel, Augusti et al. (1995). In this wind tunnel, flow velocity in the test section can be regulated between 0 m/s and 30 m/s using a 160 kW engine. The test section is 1.6 m high, 2.2 m wide and 22 m long.

Flow and turbulence characteristics were determined using Aeroprobe Cobra sensor and Prandtl-Pitot tube for velocity measurements, as well as pressure and temperature sensors. This Cobra sensor is a conventional one with 5 holes and the maximum recording frequency of

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Nomenclature

d	Displacement height
f	Frequency
I_u, I_v, I_w	Longitudinal, lateral, vertical turbulence intensity, respectively; normalization is performed locally using the mean flow velocity in the main flow direction at the measurement point height
L	Distance between the hill-model trailing edge and the leading wind-turbine model
$L_{u,x}$	Integral turbulence length scale
$R = D/2$	Length of the rotor-blade models
Re	Reynolds number
$\overline{u}(z)$, $\overline{v}(z)$, $\overline{w}(z)$	Mean velocity components in the x-, y-, z-direction, respectively
u', v', w'	Fluctuating velocity components in the x-, y-, z-direction, respectively
$\overline{u}_{ref}$	Mean reference flow velocity in the main (x) flow direction
$\overline{u}_{\infty}$	Mean undisturbed freestream velocity in the main (x) flow direction
x	Distance in the main flow direction
y	Spanwise distance from the test-section centerline
z	Vertical distance from the wind-tunnel floor
z_{hub}	Height of the wind-turbine tower model (hub height)
z_{ref}	Reference height
z_0	Aerodynamic surface roughness length
α	Power-law exponent of the mean velocity profile in the main (x) flow direction
S_u	Power spectral density of longitudinal velocity fluctuations

50 Hz. It was calibrated within the calibration cone of 60°. Experimental results recorded outside the calibration cone were removed from the analysis.

The preliminary tests were performed for the time records of 30 s, 60 s, 90 s, and 120 s. The results differed insignificantly for the time records longer than 60 s. Nevertheless, the experiments for the ABL simulation were performed for the time record length 120 s, while further (wind-farm) experiments were carried out for the time record length 60 s. The sampling rate was 500 Hz in all tests.

The flow and turbulence were analyzed with respect to the mean velocity, turbulence intensity, Reynolds shear stress, turbulence length scales, power spectral densities of velocity fluctuations, as this set of parameters enables a detailed analysis of the ABL characteristics, e.g. Kozmar (2011, 2012).

The mean undisturbed freestream velocity at 930 mm height and 1000 mm upstream of the leading edge of the hill model was $\overline{u}_{\infty} = 15.5$ m/s. The mean velocity at the hill-model height, when there was no hill model in the test section, was 10.0 m/s. The Reynolds number calculated using the hill-model height and the mean velocity at the hill-model height, when there was no hill model in the test section, was $Re \approx 1.3 \cdot 10^5$.

In order to create characteristic vertical profiles, the results in ten measuring points equidistantly distributed from the ground surface up to the top-tip height were used. Vertical distance between two neighboring measuring points was $z_{hub}/6$. The power spectral density of longitudinal velocity fluctuations was analyzed in three measuring points that represent relevant positions of the wind-turbine tower, i.e. half-hub height, hub height, and top-tip height.

The ABL simulation created using the Counihan (1969) method (Counihan vortex generators, castellated barrier wall, surface roughness elements) impinged the hill model and the wind-farm model downstream of the hill model, Fig. 1.

The hill model with rather smooth surface is 600 mm long in the main flow direction (along the wind-tunnel test section), 1000 mm wide at the hill-model top (lateral to the main flow direction), and 200 mm uniformly high. The slope of the lateral hill-model edges is 45°, while it is 34° for the leading and trailing hill-model surfaces, Fig. 2. The geometry of the hill model was selected to keep the test-section blockage at approximately 5% in agreement with Simiu and Scanlan (1996).

The experiments were carried out for the flat terrain type as well, which configuration served as a reference case. In that configuration, the ground surface of the wind-tunnel test section, which was subsequently used to place the hill model, was smooth (not covered with surface roughness elements).

The wind-turbine models approximately correspond to the Siemens 6.0 MW Sapiens prototype wind turbine with respect to some basic design characteristics, i.e. tower height to blade length to nacelle length and diameter ratios. The cylindrical wind-turbine tower model is $z_{hub} = 120$ mm high with 6 mm in diameter. The 14 mm long cylindrical nacelle is 8 mm in diameter. Three $D/2 = R = 80$ mm long wind-turbine blade models were designed similar to DOWEC-NREL 5 MW and EU 56.1400–2 rotor blades ($D/z_{hub} = 4/3$). As the prototype Siemens 6.0 MW Sapiens wind turbines may be of different size for the same characteristic geometrical rations, the configuration tested in the present study may be in practice valid for various sizes of prototype wind turbines.

The wind-farm model consisted of eleven wind-turbine models arranged in a uniform, staggered pattern. Nevertheless, during the experiments there were only ten wind-turbine models present in the test section at the same time, as one wind-turbine model was removed from each experiment to perform measurements at a position of that particular wind-turbine model when this wind-turbine model was not in place. This was done to determine the flow and turbulence that would impinge this wind-turbine model, when it would be on its place in the wind-farm model.

In all the experiments, the wind-turbine models were not rotating (parking position), as to model strong-wind conditions at wind velocities larger than 25 m/s. The goal was to determine strong-wind conditions that the particular wind turbine is subjected to. The wind-farm model was placed at various distances downstream of the hill model, as well as downstream of the flat-terrain model.

An overview of analyzed experimental configurations and the layout of the wind-farm model are reported in Table 1 and Fig. 3, respectively.

The maximum L/D was limited by the length of the wind-tunnel test section. Previous wind-tunnel experiments (Simpson et al., 2002) performed at the similar Re on a hill model with a slightly gentler slope indicated that the separated flow reattached at some 3.7 hill-model heights downstream of a hill-model crest. This suggests that all the wind-turbine positions analyzed in the present study were likely downstream of a recirculation zone, whereas it needs to be noted that the hill slope and surface roughness may influence flow characteristics, e.g. Cao et al. (2012).

The created ABL simulation for the flat terrain type (without the hill model) proved to be well developed and uniform, Fig. 4.

The ABL simulation length scale factor calculated as suggested by Cook (1978) is 1:300. Due to the Jensen similarity requirement that the ABL simulation length scale needs to be the same for the structural and terrain models, this 1:300 scale may be applied on the wind-turbine and terrain models to determine the corresponding prototype values. At the model-scale, $z_0 = 6$ mm, $d = 50$ mm, $\alpha = 0.26$. More details of the created ABL simulation and a thorough justification of similarity with the full-scale conditions were provided in Kozmar et al. (2016).

3. Experimental results

The obtained experimental results generally indicate a strong influence of the hill model on flow and turbulence characteristics in the wind-