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Complex terrain effects on wake characteristics of a parked wind turbine

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ABSTRACT

In order to extend lifetime and enhance energy production of wind turbines in complex terrain it is important to learn about their wake characteristics. Hence, wind-tunnel experiments are carried out to analyze the wind-turbine wake downwind of a mountain. The wind-tunnel simulation of the neutrally stratified atmospheric boundary layer (ABL) developing above a flat terrain is first generated using the well established Counihan approach. Once a well developed ABL simulation is achieved for a flat terrain, three various mountain models are separately exposed to that ABL simulation, as well as the flat terrain as a reference case. Wake characteristics of a single wind-turbine model in the wake of those four various terrain models are then studied. The ratios between the height of different mountains to the wind-turbine hub height are 0, 0.417, 0.833, 0.833 (0.417) for the flat terrain, small mountain, large mountain, mountain with a bay, respectively. For the mountain with a bay, there are two different ratios between the mountain height and the wind-turbine hub height; 0.833 at the lateral edges of the mountain, 0.417 in the lateral center of the mountain. All three mountain models are 600 mm long in the main wind direction and 1000 mm wide laterally to the main wind direction. Small mountain model is 100 mm uniformly high, large mountain model is 200 mm uniformly high. The mountain with a bay model is 200 mm high with a normal slope to 100 mm height in the lateral center of the mountain model, whereas this cavity is 200 mm wide in the lateral direction. The calculated ABL simulation length scale factor is 1:300, and it is applied on mountain models and the wind-turbine model as well. The wind-turbine model is designed to correspond to commonly used prototype wind turbines. The experiments are carried out for the wind-turbine model in parking position to analyze trends expected in a strong wind situation, when there is no rotation of the rotor blades. Wake characteristics analyzed with respect to the mean wind velocity, turbulence intensity and velocity power spectra indicate several important findings. In particular, the observed flow retardation is more exhibited near the ground surface and the mountains. The mountain-induced flow disturbance enhances with increasing the size and complexity of the mountains. Turbulence intensity in the wake of the mountain and wind turbine is considerably larger than in the atmospheric boundary layer. Velocity power spectra are strongly influenced by the terrain complexity, whereas the effects of the mountain and surface roughness are mostly constrained up to the double mountain height. There is a strong energy content at frequencies corresponding to a free shear layer separating from the mountain ridge. Dominant turbulence structures are displaced vertically, as the wake is transported with the flow in the main wind direction.

1. Introduction

A considerable amount of information is available on wake characteristics of wind turbines at the flat terrain and open sea. However, little is known on aerodynamic characteristics of wind-turbine wake in complex terrain. Hence, further work is required on this topic that is crucial to extend the lifetime and enhance energy production of wind turbines.

Along with other important topics relevant to wind energy, Sørensen [1] reviews advanced numerical simulation tools for wind-turbine wakes, including models for simulating wind-turbine wakes and flows in wind farms. Crespo et al. [2] survey different modeling methods to predict wind-turbine wake characteristics along with loading effects on wind turbines exposed to multiple wakes. In the near wake, which extends from the turbine to one rotor diameter downwind, the flow is characterized by the aerodynamics of the rotor blades, as the helical tip vortices due to rotating blades determine the wake characteristics, e.g. Zhang et al. [3], Hu et al. [4], Chamorro and Porté-Agel [5]. Those vortices

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are considered to be a source of noise and blade vibration, Massouh and Dobrev [6]. In the far wake (downwind of the near wake), the wind-turbine tower and rotor influence the wake characteristics less than it is the case in the near wake, as in the far wake the flow interaction with the surrounding terrain and structures starts to dominate the wake physics. Small-scale laboratory experiments prove to be a valuable research toll in studying wind-turbine wakes. In particular, Ebert and Wood [7–9] investigate the formation and development of the 3D wind-turbine near wake focusing on the tip and hub vortices in various operating conditions. Grant and Parkin [10] study the velocity field of the vortices trailing from the blades and show the creation of the trailing vortex circulation. Whale et al. [11] indicate that the fundamental behavior of the helical vortices may be relatively insensitive to blade chord Reynolds number as long as similarity of tip speed ratio is observed. Medici and Alfredsson [12] investigate wake rotation in the direction opposite to the wind turbine, whereas a yawed turbine deflects the wake flow to the side thus indicating a potential of controlling the wake by yawing the wind turbine. An interesting flow feature is the appearance of a low frequency peak in the velocity spectra both in the wake and in the flow outside the wake that is observed both with and without freestream turbulence, while the Strouhal number proves to be independent of the freestream velocity and turbulence level. The vortex shedding frequency changes with the yaw angle in agreement with the concept that the wind turbine sheds flow structures similarly as bluff bodies.

While previous studies are predominantly carried out assuming uniform wind conditions, which are not fully representative of the atmospheric boundary layer (ABL) that wind turbines are subjected to, wind-tunnel tests are carried out with respect to the ABL effects on the wind-turbine wake characteristics. The particular focus with respect to wake characteristics is on terrain roughness [13], thermal stability and ABL characteristics [5,14,15], flow patterns inside and above a wind farm [16], wind farm layout [17], while Cal et al. [18] highlight the importance of turbulent energy fluxes influencing wind-turbine wake characteristics.

However, the studies on effects of complex terrain on wind-turbine wake characteristics, like for example Yang et al. [19] and Howard et al. [20], are quite rare, while topographical features are likely to considerably influence the unsteady wake aerodynamics. Hence, an extensive set of wind-tunnel experiments is carried out to study wake development downwind of an alone-standing wind turbine with particular focus on effects of complex topography. The ABL impinging the mountain is simulated with respect to commonly applied empirical laws, international standards and codes, while the wind-turbine wake physics is studied by analyzing the mean wind velocity, turbulence intensity and power spectral density of velocity fluctuations.

2. Experimental setup

Experiments are carried out in the CRIACIV boundary layer wind tunnel described in Augusti et al. [21]. The neutrally stratified atmospheric boundary layer (ABL) simulation upwind of the mountain models is created by applying the Counihan [22] technique with basic principles of this procedure outlined in [23–27], Fig. 1. This experimental hardware generally allows for generating wind-tunnel boundary layers with the thickness approximately equal to the height of the Counihan vortex generators, e.g. [27].

The simulation hardware consists of three Counihan 1.53 m high quarter-elliptic constant-wedge-angle spires, a castellated barrier wall and a fetch of roughness elements. The basic barrier wall height (without castellation) is 180 mm, while the castellation height is 60 mm. The surface roughness consists of 0.05 m high, 0.05 wide, 0.05 m long wooden cubes placed in a staggered pattern with distance between the cubes 0.145 m in lateral and 0.110 m in longitudinal direction. Three different mountain models are used, as well as the smooth surface representing the flat terrain (FT), Fig. 2.

All three mountain models are $L = 600$ mm long in the main wind direction and $W = 1000$ mm wide laterally to the main wind direction. Small mountain (SM) model is 100 mm uniformly high, large mountain (LM) model is 200 mm uniformly high. The mountain with a bay (BAY) model is 200 mm high with a normal slope (90°) to 100 mm height in the lateral center of the mountain model, whereas this BAY cavity is 200 mm wide (in the lateral direction). The outward lateral slope is 45° for all mountain models. The windward and leeward slopes are 18° for SM, while for LM and BAY those slopes are 34°. Leading edge of all terrain models is placed 5300 mm downwind of the trailing edge of the vortex generators. Downwind of the trailing edge of the mountain models, the test-section surface is smooth representing the flat terrain. The wind-turbine model is placed 50 mm downwind of the trailing edge of the mountain models in the lateral center of the mountain models and the wind-tunnel test section.

The cylindrical wind-turbine tower with a diameter of 12 mm is 240 mm high. The diameter of the 28 mm long cylindrical nacelle is 16 mm. Three 160 mm long turbine blades designed similar to DOWEC-NREL 5MW and EU 56.1400-2 blades are fixed in a parking position (no rotation). Non-rotating case comparable to strong-wind situations (wind velocity larger than 25 m/s) is important, particularly for structural engineers, as this configuration needs to be carefully investigated with respect to dynamic loading and response of energy structures. The rotor blade length to wind-turbine hub height ratio is adopted to correspond to a common wind-turbine design, as for example Siemens 6.0 MW Sapiens. In all tests, the blockage is below 5%, which is commonly considered as a maximum tolerable limit, e.g. Simiu and Scanlan [28], Holmes [29]. The ratios between the height of different mountains to the wind-turbine hub height are 0, 0.417, 0.833, 0.833 (0.417) for the flat terrain, small mountain, large mountain, mountain with a bay, respectively. For the mountain with a bay, there are two different ratios between the mountain height and the wind-turbine hub height; 0.833 at the lateral edges of the mountain, 0.417 in the lateral center of the mountain.

Measurement technique includes conventional Aeroprobe Cobra sensor and Prandtl–Pitot tube for velocity measurements, as well as pressure and temperature sensors. Cobra sensor is of a conventional type that consists of 5 holes with a maximum sampling frequency of 50 Hz. It is calibrated within the calibration cone of 60°. This type of sensor is generally not that suitable for measurements in the reversed flow that can likely occur in the wake of mountain models. Hence, preliminary tests are carried out to determine a percentage of valid data recorded inside the calibration cone for each of the studied terrain models. The flow for FT and SM proves not to be reversed, as 99% of respective data samples are recorded inside the calibration cone. For BAY, there are some indications of the reversed flow immediately downwind of this mountain model near the ground, whereas at least 90% of respective data samples are recorded inside the calibration cone. Further downwind, the number of BAY data samples inside the calibration cone is 98% and more. The flow reversal is observed for the LM model, particularly exhibited immediately downwind of the mountain model close to the ground, where the percentage of data samples inside the calibration cone is between 70% and 80%, while in the remaining LM experiments it is larger than 97%. The measurement uncertainty for both the Prandtl–Pitot tube and the Cobra sensor is 1% in the smooth flow.

The ABL flow and turbulence are analyzed with respect to the mean velocity, turbulence intensity, Reynolds shear stress, integral