Numerical and Experimental Methods for Wake Analysis in Complex Terrains

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1. Introduction

The assessment of power output quality of wind farms operating in complex terrains is extremely challenging. The widespread diffusion of SCADA control systems and the current availability of considerable computational power have provided brilliant developments to performance evaluation and forecast, condition monitoring and fault diagnosis. Complex terrains provide a very challenging testing ground, which stresses to the limit techniques which are well established for the offshore case. The main agents are the intertwining of complex wind flow, wake effects and control system response to these non-trivial phenomena. On these grounds, the present work aims at a numerical and experimental investigation of a wind farm sited in Italy on a very complex terrain. This farm has attracted a considerable amount of attention in the scientific literature, because it is also a test case of the IEA-Task 31 Wakebench project. The terrain is indeed quite steep, with very high slopes (up to 60%) close to the turbines; also the layout is complex and large. In particular, a subcluster of machines has been analyzed, which is also object of investigation of the present work: for example, it has been observed that the most downstream turbine is by far the best performing. This has been considered a sharp symptom of complex flow. For these reasons, a numerical and experimental analysis of this subcluster is proposed here on, through Computational Fluid Dynamics (CFD) on one side and SCADA data analysis on the other side. Particular attention is devoted to the effects of complex flow on machine capability of optimally following meandering wind direction.

2. Approach

In Figure 1, the layout of the wind farm is sketched. Seventeen aerogenerators are installed, with 2.3 MW of rated power; the rotor diameter is 93 meters and the hub height is 80 meters. The wind rose is depicted in Figure 2. A zoom on the selected subcluster (SGM10-SGM13) is provided by Figure 3. Further, Table 1 provides an estimate of the complexity of the terrain at turbine site, through the RIX values.

The numerical simulations are performed with the WindSim numerical tool. The objective is simulating the behaviour of the SGM10-SGM13 cluster of turbines when there are certain conditions at met-mast. Two test cases are chosen: 10 and 6 m/s at met mast. The inlet boundary is assumed to be a logarithmic profile blowing from 270°. The intensity at the top of the boundary layer (assumed equal to 800 meters a.g.l.) is iteratively adjusted, in order to obtain 10 (6) m/s at hub height at met-mast position. These regimes are also investigated by the point of view of free wind flow, producing a prediction for the undisturbed wind speed,

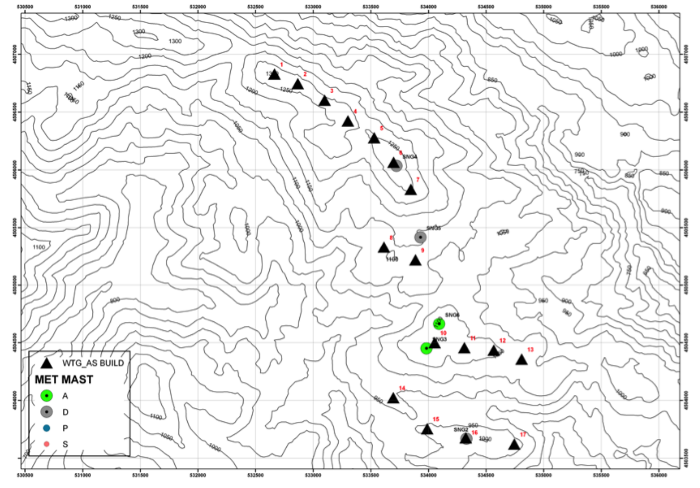

Figure 1. Wind farm layout.

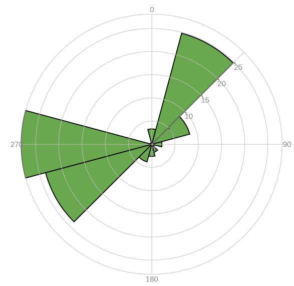

Figure 2. Wind rose: percentage of occurrence.

Table 1. Ruggedness Index at turbine site.

Turbine	RIX value (%)
SGM10	24.9
SGM11	23.1
SGM12	21.7
SGM13	20.4

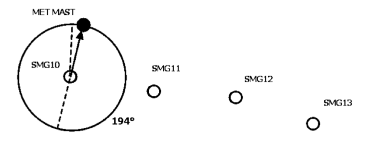

Figure 3. Layout of SGM10-SGM13 subcluster and met-mast

turbulence intensity and wind direction at each turbine site. The presence of the rotors is simulated through the Actuator Disc (AD) model both on the real terrain and on flat terrain. The turbulence model is RNG k-ϵ.

The two simulation regimes are chosen for the following reasons:

- 10 m/s is a critical value because, within one typical standard deviation, velocities associated to rated power are approached.
- 6 m/s is chosen because the thrust coefficient is high and wakes are very relevant.

SCADA data are post-processed in order to reproduce the regimes simulated through the numerical models. Basically, three filters are employed:

- Time steps are selected during which the subcluster of interest is producing output in unison.

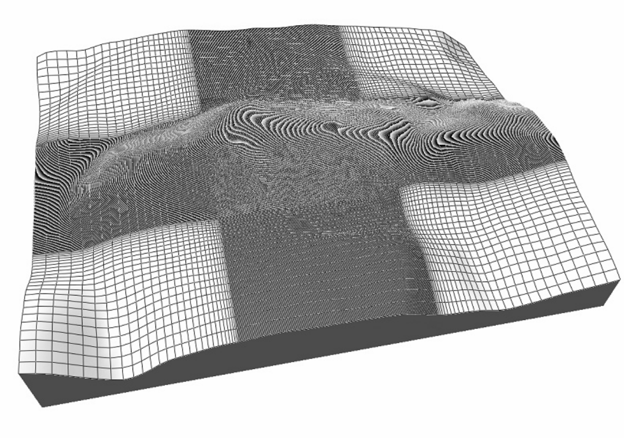

Figure 4. The computational domain: free flow model on actual terrain

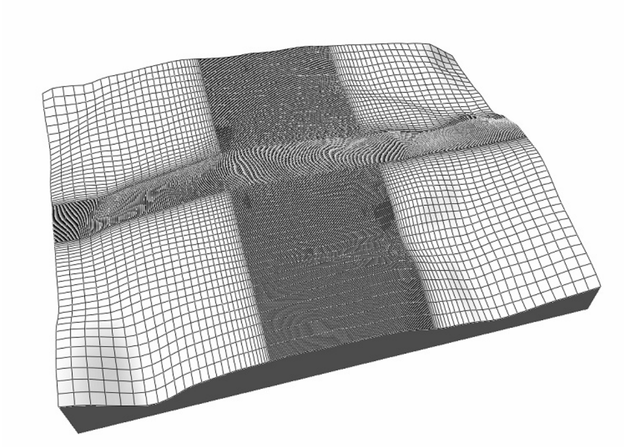

Figure 5. The computational domain: AD model on actual terrain

- With a 10% tolerance around the two selected values (10 m/s and 6 m/s), data are filtered on met-mast wind speed.
- The AD model assumes disk orientation under orthogonal directions. Since SGM10 is upstream when the wind blows from 270°, it is expected to orientate correctly. Data are thus filtered on the request of 270° SGM10 nacelle orientation, with a 10° tolerance.

A further specific investigation is devoted to how turbines align to wind direction. Measurements are filtered on the regime of the subcluster producing output in unison, and the speed-up ratio between couples of nearby turbines is computed and averaged against bins of yaw position measurements of each turbine. It is intuitively expected the speed-up is maximum (or minimum) along the geometric line connecting nearby turbines. In Section 3 it is shown that non-trivial effects arise when complexity of the terrain conspires with wakes.

3. Main body of the abstract

Figures 6 and 7 summarize some results for the 10 m/s test case and Figures 8 and 9 display some results for the 6 m/s case.

From Figures 6 and 8 it arises that the free flow model fails in capturing the trend of speed intensity moving from SGM10 to SGM13. The model predicts a non-stop decreasing trend, experimental analysis shows instead a severe speed loss from SGM10 to SGM11, but also a turnaround at SGM12 and peak at SGM13. SGM13 displays indeed a velocity even slightly higher than the upstream turbine SGM10. The AD model on real terrain brilliantly captures the fall from SGM10 to SGM11 and at least predicts a plateau from SGM11 to SGM12. The AD model on flat terrain instead predicts a further decrease: in other words, if there were only wakes, performances of SGM12 should be worst than SGM11, but exactly the opposite happens. The role of the terrain is fundamental also to understand alignment patterns: from Figure 7 and 9, it arises that the free flow model predicts a decreasing inclination moving from turbine SGM10 to SGM13. Actual nacelle orientations indeed display a decreasing trend, but with a much higher range of variability: 15° against 5°. These are brilliantly captured, especially at turbine SGM11, by the AD model on the real terrain. Further, experimental analysis of nacelle orientations highlights that SGM11 is by far the more stationary turbine, while a much greater positions variability occurs at SGM12 and especially SGM13. This might be interpreted as follows: the sharper the wake effect (SGM10 to SGM11 in this case), the more stationary the nacelle is while the wind meanders. The lesson is that in a complex site actual nacelle alignment patterns can be numerically estimated only if one takes into account also the terrain. The results demonstrate that the AD model is capable of reproducing a realistic flow deviation from the main stream, resembling actual alignment patterns, even if it is based on the hypothesis of perfectly orthogonal rotors.

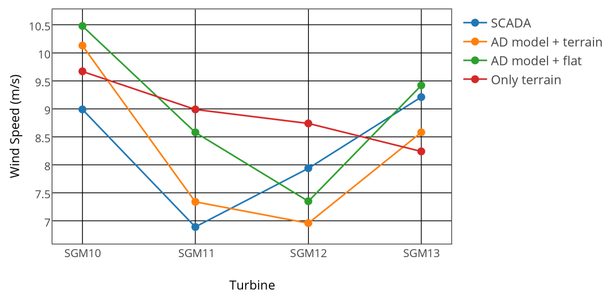

Figure 6. Models vs. experimental: wind speed. 10 m/s

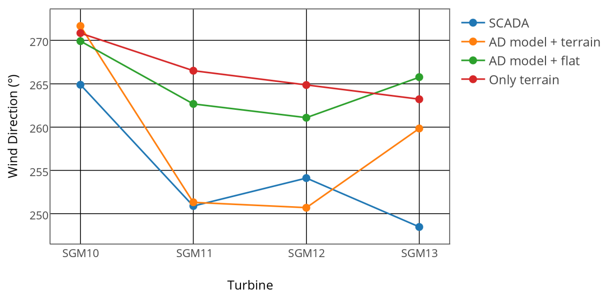

Figure 7. Models vs. experimental: wind direction. 10 m/s

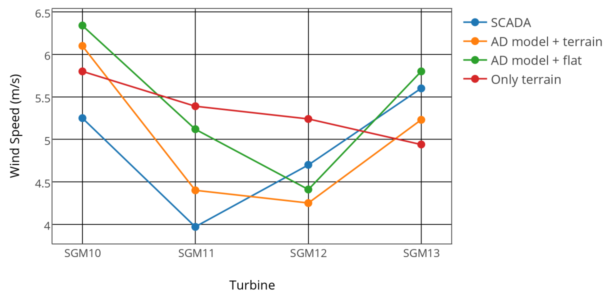

Figure 8. Models vs. experimental: wind speed. 6 m/s

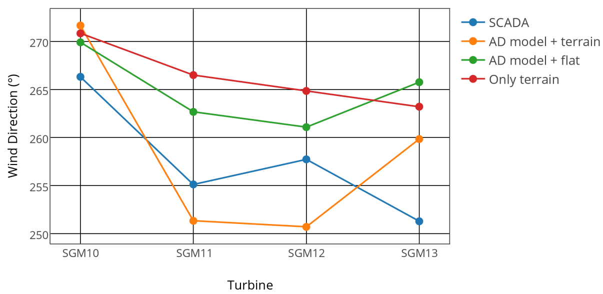

Figure 9. Models vs. experimental: wind direction. 6 m/s

Figures 10 and 11 show the speed-up ratio between SGM10-SGM11 and SGM12-SGM13 couples of turbines. It arises that in the first case the experimental maximum speed-up occurs quite near the geometric line connecting the machines, while instead a more considerable mismatch arises in the SGM12-SGM13 case. These machines are actually affected, as discussed above, by a more complex combination of wind flow and wakes, and this seems to resemble in the degraded ability of optimally following the wind direction.

4. Conclusions

In the present work, a cluster of turbines of an onshore wind farm sited on a very complex terrain is analyzed numerically and experimentally. The conclusions are summarized here on:

- A free flow model is unable to capture the trend of wind intensity on such complex terrain.
- The AD model captures the main features of the trend of wind (and power) along the subcluster. The AD model on flat terrain predicts a decreasing power trend from SGM11

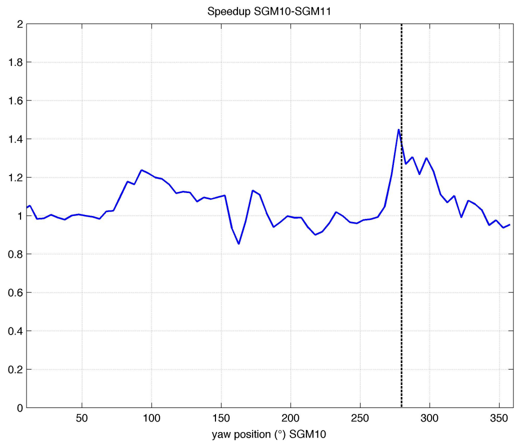

Figure 10. SGM10-SGM11 speed-up ratio against SGM10 yaw position

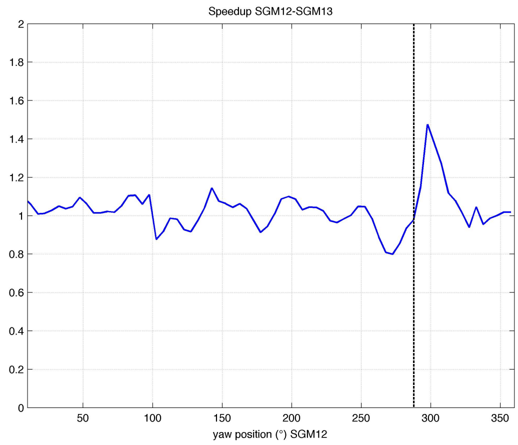

Figure 11. SGM12-SGM13 speed-up ratio against SGM12 yaw position

to SGM12, while on real terrain a plateau is predicted. The experimental analysis reveals even an increase. This provides an indication of how fundamental is the role of the terrain in driving the main stream flow.

- The AD model on the real terrain captures the main features of actual turbine alignment patterns, while instead the AD model on the flat terrain and the free flow model do not capture the amplitude and the trend of northward wind flow distortion.
- An experimental analysis on the speed-up ratios of couples of nearby turbines against yaw orientation reveals that, when wakes are the main speed intensity driver, the alignment is consistent with the idea that maximum (or minimum) speed-up should occur along the connecting line. Significant deviations occur instead when terrain complexity is relevant, as in the SGM12-SGM13 case.

5. Learning Objectives

- The role of numerical modelling for performance interpretation in complex terrains.
- The importance of terrain complexity in intensity and directional distortion of the wind flow.
- The effect of wake interactions and complex flow in capability of the machine in following the wind direction.