Analysis and validation of CFD wind farm models in complex terrain. Effects induced by topography and wind turbines

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Abstract

Wind farms have been extensively simulated through engineering models for the estimation of wind speed and power deficits inside wind farms. These models were designed initially for a few wind turbines located in flat terrain. Other models based on the parabolic approximation of Navier Stokes equations were developed, making more realistic and feasible the operational resolution of big wind farms in flat terrain and offshore sites. These models have demonstrated to be accurate enough when solving wake effects for this type of environments.

Nevertheless, few analyses exist on how complex terrain can affect the behaviour of wind farm wake flow. Recent numerical studies have demonstrated that topographical wakes induce a significant effect on wind turbines wakes, compared to that on flat terrain. This circumstance has recommended the development of elliptic CFD models which allow global simulation of wind turbine wakes in complex terrain.

An accurate simplification for the analysis of wind turbine wakes is the actuator disk technique. Coupling this technique with CFD wind models enables the estimation of wind farm wakes preserving the extraction of axial momentum present inside wind farms.

This paper describes the analysis and validation of the elliptical wake model CFDWake 1.0 against experimental data from an operating wind farm located in complex terrain. The analysis also reports whether it is possible or not to superimpose linearly the effect of terrain and wind turbine wakes. It also represents one of the first attempts to observe the performance of engineering models compares in large complex terrain wind farms.

Key words: CFD modelling, wind turbine wakes, actuator disk, complex terrain

1. Introduction

Wind farms design involves the need to understand how wakes between wind turbines interact with atmospheric flow inside wind farms. This is a key issue due to it affects not only the output power but also the fluctuating fatigue loads that wind turbines experience during their lifetime. This behaviour is influenced by many ambient factors such as wind speed, turbulence intensity and atmospheric stability, particularly significant at offshore wind farms but also in complex terrain.

Nevertheless, at those wind farms located in complex sites, the variation of terrain has demonstrate to be an important impact on the evolution of wind turbine wakes and consequently on power output.

This phenomenon started to be observed during the early nineties by Taylor and Smith [1], who highlighted the important effect that the topographical wake had over the wind turbine wake, according to wind tunnel measurements. Later on, Crespo et. al. [2] observed that the linear superposition of local speed-ups produced by terrain irregularities and the wind speed deficit induced by a single wake was adequate for moderately complex terrain, with power errors below 20%. This experiment was indeed very appropriate in order to check the assumption of linear superposition of wake and terrain effects [3]. However, they also observed that this hypothesis was less valid when the terrain and two wind turbine wakes were interacting.

In fact, this result was expected as it is known that the merging of wind turbine wakes alone is a not linear phenomenon according to the results of the classical paper of Lissaman et. al [4], who observed that the hypothesis of linear superposition led to overestimation of velocity deficits. This approximation was corrected a few years later by Katic [5], who assumed a linear superposition of the squares of the velocity deficits, deriving the corresponding code named WAsP [6], widely used on wind energy industry for wind farm modelling and design.

Voutsinas et. al. [7] developed a method to take into account non-uniformities in wind velocity and the curvature of streamlines in wind farms with small irregularities, whereas Van Oort et al. [8] proposed second order corrections to the linear superposition. Some years later, Crespo et.al. [9], Günther et.al. [10] and Ansorge et.al. [11] observed the combined effects of terrain irregularities and wind turbine wakes through the commercial code PHOENICS, concluding that the effect was difficult to parameterize. These results were complemented by Hemon et. al. [12], who studied theoretically how terrain complexity could affect turbine loading over the rotor as well as wake deflection in the near wake region of the wind turbine. A similar analysis was made by Helmis et.al. [13] during the same year proposing some guidelines on the influence of complex terrain on the near wake flow validated through large scale and wind tunnel tests.

The models developed up to present day for wind farm modelling do not take into account directly the interaction of wakes with terrain. Among others, Crespo et. al. developed UPMPARK [14] as a parabolic approximation method where atmospheric stability and roughness are used for the simulation of wind flow modelling. Terrain speed up factors derived from WAsP can be included into the code so that they are not calculated directly. Garrad Hassan and Partners Ltd. developed an axisymmetric Navier Stokes solver, named WindFarmer, with an eddy-viscosity closure based on the approximation of Ainslie [15]. Last versions of the solver have been focused on the resolution of big wind farm in offshore or relatively simple terrain sites.

During the last decade, very few developments exist on this topic and since the early nineties some of the models mentioned above have been extensively used and considered as accurate enough for every type of site. With the growing of computational resources, more advanced CFD models have been developed allowing the solution of the elliptic Navier Stokes equations and consequently the solution of combined effects produced by terrain and wind turbine wakes in a reasonable time. Different approaches based on the actuator disk technique for the resolution of wind turbine wakes in complex terrain have been developed during the last years, some of them as part of the European Commission funded project UPWIND [16], with special focus on turbulence modelling.

This paper shows the first results on the simulation of complex terrain and wind turbine wakes interaction corresponding to one of these models, named CFDWake 1.0, and its validation against experimental data from an operating wind farm located in complex terrain. These results are compared to the linear wake model WAsP. Special emphasis is placed on the validity of linear superposition of the topographical and wind turbine wakes. Alternative approaches such as simultaneous calculation can be adopted in the CFD model but WAsP uses linear superposition.

2. Test case

Data for validating wake models are generally difficult to find but also to process and interpret. Firstly, a sufficiently long period of data is needed in order to get representativeness of the flow cases of interest and secondly, high quality is also needed so that all spurious data are deleted from the analysis.

The test case used for the analysis and validation of wake models correspond to a wind farm located in a moderately complex terrain and composed by 43 wind turbines organised in 5 rows (row 1 at north and row 5 at south) separated 13 rotor diameters one to each other, as shown in figure 1. Wind turbines are numbered from east to west at each row, being wt101 the reference wind turbine for the definition of the freestream conditions and located at northwest corner of the wind farm. The separation between wind turbines in a row is 1.5 rotor diameters. Rotor diameter is 48.4m. Wind turbines have two different hub heights of 45m and 55m, depending on local elevation of each position.

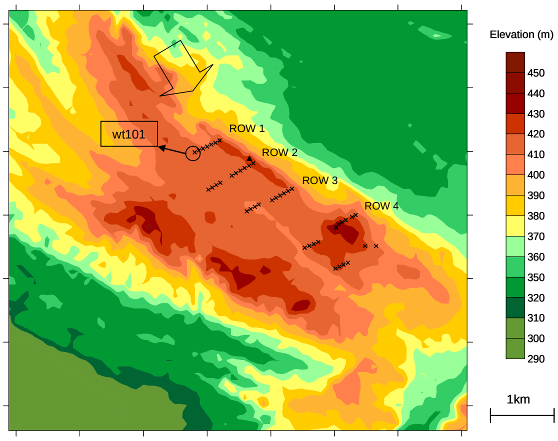

Figure 1. Complex terrain wind farm
X =Wind turbines. ▲ = Meteorological mast

Collected data were filtered and validated in order to define the flow cases to be simulated. A meteorological mast located upstream of the prevailing wind direction registered wind speed and wind direction, in order to define the undisturbed flow conditions. In addition, electrical power output as well as nacelle wind speed, nacelle wind direction and status signal were also collected from the wind turbines SCADA system.

The filtering process provided one significant wind direction (with good coverage of quality data), corresponding to one single flow case, characterized by wind direction values in the range 325º±5º and wind speed values in the range 8±0.5 m/s at wind turbine 101.

3. Wind farm model

3.1 Freestream flow

The flow upstream of the wind farm corresponds to the fully developed vertical profiles in the surface boundary layer, which is a non-uniform shear boundary layer flow. The CFD code CFDWind 1.0 [17] based on the commercial software FLUENT 6.3 is coupled to the CFDWake 1.0 model and adapted in order to solve the mean wind components and turbulence according to the Monin-Obukhov theory. The expressions that describe this flow are derived from Panofsky and Dutton [18]. Turbulent viscosity is assumed to vary linearly with height:

$$\mu(z) = \kappa u_* z \qquad (1)$$

Where κ is the von Karman constant (equal to 0.41), u_* is the friction velocity and z is the vertical coordinate.
Neutral atmosphere is supposed so that thermal and Coriolis effects are neglected. Assuming shear stress to be constant over the surface boundary layer, a logarithmic velocity profile is adopted:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \qquad (2)$$

where z_0 corresponds to the roughness length of the site, which is equal to 0.0082m according to the measurements of turbulence intensity for the freestream sector registered at the meteorological mast of the wind farm.

Assuming equilibrium of production and dissipation of turbulent kinetic energy in the surface boundary layer, the remaining vertical profiles can be derived as:

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}} \qquad (3)$$

For the turbulent kinetic energy (Cµ a constant of the standard k-ε turbulence model) and:

$$\varepsilon(z) = \frac{u_*^3}{\kappa z} \qquad (4)$$

For the dissipation rate of the turbulent kinetic energy.

3.2 Modelling of rotors

From linear momentum theory, it can be deduced that the axial force that the wind turbine exerts over the incoming flow (equivalent to the kinetic energy extracted from the air) is just a function of the local induction factor or alternatively of the thrust coefficient for the corresponding upstream wind speed [19][20][21]. Wind turbines are then considered as actuator disks or momentum absorbers upon which a uniform distribution of axial forces is applied. This force, F, is prescribed over the area of the rotor disk as:

$$F=0.5\cdot\rho\cdot A\cdot C_t\cdot V_{inf}^2 \qquad (5)$$

Where:
A = rotor area (m^2)
C_t=thrust coefficient
V_{inf}=upstream wind speed (m/s)
ρ=air density (kg/m3)

The prescribed force is then applied on a volume of cells (N/m^3) defining each rotor.

3.3 Numerical method

The wind farm model is solved in a computational domain of approximately 15 square kilometres leaving 6 kilometres upstream of the wind farm. For that purpose, a structured grid was generated with ICEM CFD Hexa getting a domain of approximately 5 million cells (figure 2).

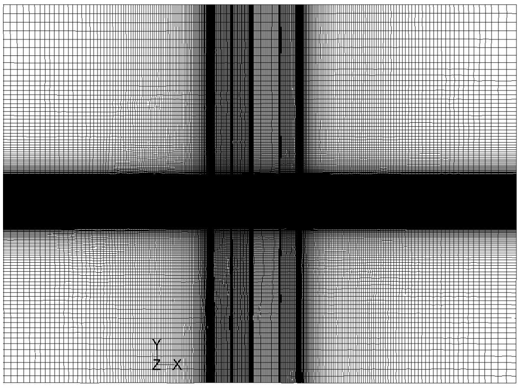

Figure 2. Computational domain

The inlet boundary conditions of the domain are defined by the vertical profiles mentioned above, such that they reproduce the freestream conditions of the flow case at wt101. The outlet and top boundaries are defined as pressure outlet and zero gradient respectively. The ground is simulated as a wall, through an adaption of the standard wall functions setting a link between the turbulent law of the wall modified for mechanical roughness and the surface boundary layer log-law based on the roughness length [22].

The grid is refined at the rotor areas of the wind farm with a spatial resolution of 0.2D in the axial direction and 0.1D in the transversal direction (D=rotor diameters). The height of first cell close to the ground is set to 0.5m.

Once the grid is generated, the steady state 3D Navier Stokes equations in its elliptic mode are solved: the continuity equation, the three momentum equations and the transport equations for k and ε. The standard k-ε turbulence model is then used with modified constants adapted to the characteristics of the surface boundary layer. No additional correction was applied to the standard k-ε turbulence model so that its default configuration was used as a preliminary result. A control-volume technique is used for converting the governing differential equations into algebraic equations that can be solved numerically. Regarding the discretization schemes, a second-order upwind scheme based on multilinear reconstruction approach [23] is used for all dependent variables.

The model is first calibrated for the freestream conditions on the reference wind turbine and then the momentum absorbers representing the wind turbine rotors are activated. This is done in a sequential manner from row 1 up to row 5, such that the free stream wind speed values at wind turbines of row 1 are prescribed and the corresponding sink terms according to expression (1) are estimated and activated. The resulting wind speeds at the positions of row 2 are then used to prescribe the sink terms at their positions. This process is made until the last row is reached. This causes the simulation to operate in a hybrid parabolic-elliptic mode.

Computational time for solving one single simulation in a workstation of 16 Gb RAM (Dual Quad Core Intel Xeon 2.5 GHz processor) was around 4 hours. This makes around 12 hours for solving the complete wind farm.

4. Results

In order to analyze the linearity of wake effect of topography and wind turbines separately, the CFD simulations over the wind farm were carried out in two different ways, named as linear and non-linear methods. All the results are displayed as the ratio of power at every wind turbine normalised to power at the reference wind turbine 101.

Linear method: The first method consists of estimating through 2 different simulations the speed-ups induced by terrain and the wind speed deficits induced by upstream wind turbines (supposing flat terrain) over the incoming flow. The speed-ups induced by terrain and the wind speed deficits induced by wind turbines are added up linearly resulting in a final wind speed deficit, which is transformed into power deficit through the power curve.

Non-linear method: The second method combines the effect of terrain and wind turbine wakes by including both terrain and wind turbine rotors in one single simulation so that wake effects are estimated simultaneously in a non-linear manner. This method reduces computational time due to the lower number of simulations to be run but it has the inconvenience of needing more complete grids that take into account refinement processes at those areas where wind turbine rotors and complex terrain exist.

The results in figures 3 to 6 show the evolution of power ratios along rows 2, 3 and 4 affected by the wake effect of upstream wind turbines. Solving the wind farm by considering a linear superposition leads to an overestimation of power ratios with respect to experiments, as it was expected from previous experience. In general both set of results observe coherently the evolution of terrain with local accelerations particularly intensive at the east corner of rows, where a ridge is present (fig. 1).

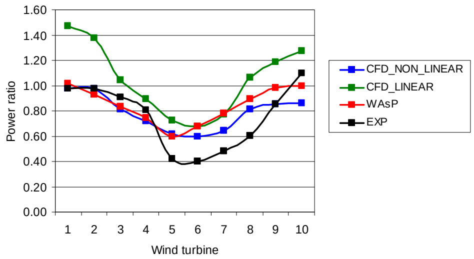

Figure 3. Power ratios at row 2 (power normalized to wt101)

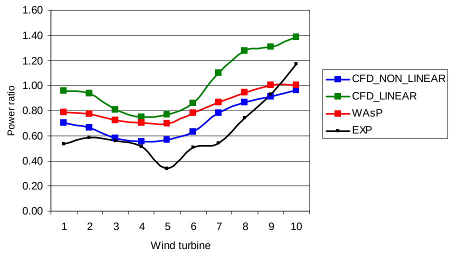

Figure 4. Power ratios at row 3 (power normalized to wt101)

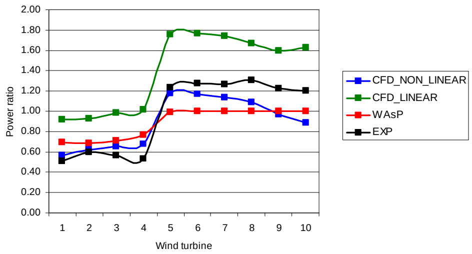

Figure 5. Power ratios at row 4 (power normalized to wt101)

Power at downstream wind turbines decreases up to 40% with respect to its free stream value for the prevailing wind direction according to experimental data. This decrease remains downstream at the central wind turbines of the wind farm but is partially compensated by local terrain accelerations causing power ratios to be increase at some turbines especially at the ridge along the wind turbines located at the east side (wt210, wt310 and the east alignment of row 4).

A comparison to the analytical model WAsP is also included at the analysis. The results from this model are compared in table 1 with the ones obtained from the CFD model for its linear and non-linear aproximation in terms of mean absolute error.

	CFD linear	CFD non linear	WAsP
Row 2	0.30	0.12	0.15
Row 3	0.37	0.13	0.22
Row 4	0.43	0.14	0.22
Total	**0.37**	**0.13**	**0.20**

Table 1. Mean absolute error of power ratios at rows 2, 3 and 4

The non-linear superposition of terrain and wind turbines wake effect through the CFD model is in general more accurate with an average power ratio error of 13%.

The results at those turbines in freestream conditions are in general quite similar due to the fact that both models observe non-perturbed flow at a relatively simple terrain area. Nevertheless, some discrepancies are observed at wind turbines located inside those areas affected by wake effects, as expected. This is the case of wind turbines wt205 up to wt209, immersed in the wake area produced by row 1, so that main differences at those positions come from the wake models. Linear model produces in general an underestimation of the power deficit leading thus to an overestimation of predicted power at those positions.

This tendency remains at the wind turbines of row 3 (figure 4), where most turbines are affected by the wake effect produced by rows 1 and 2, with a constant difference between both models of approximately 10%. The first 4 wind turbines of row 4 (figure 5) are immersed in a wake region, with a combined wake effect well captured by both type of models at these positions.

Power ratios observed at positions wt405 to wt410 increase sharply due the combined effect of accumulated wind turbines wakes and local terrain acceleration. This effect is accurately simulated by the CFD non linear method at wt405, with higher errors at the eastern positions of row 4, as in the rest of rows, due to the low resolution of the digital terrain model, causing local terrain acceleration to be represented less accurately than expected.

5. Conclusions

Elliptic CFD modelling of wakes in complex terrain wind farms based on the actuator disk concept is feasible. From this analysis, it is concluded that linear superposition of topographic and wind turbine wakes leads to an invalid approximation according to the results of the validation process carried out in an operating wind farm located in complex terrain.

Combined wake effects must be thus simulated under integrated simulations that take them into account simultaneously. As a consequence special grids must be generated that are adapted to complex terrain and refined at the areas where rotors are placed. Despite that, the grid density is affordable through high performance workstations.

Both models tend to overestimate power ratios at rows 2 and 3, with more intensive overestimation observed by the linear model (average power error of 13% for the CFD model in comparison to 20% for WAsP), although they are equally able to reproduce the increase in power ratios at those positions where local acceleration of terrain is particularly significant.

Further work will consist of using a high resolution digital map for this test case in order to capture local terrain acceleration accurately in combination with the wake effects induced by wind turbines for continued improvement of the results.

Alternative methods for generating refined grids at wind farm areas as well as the generation of rotor areas for different wind directions have to be developed. In this process, a grid sensitivity analysis is also needed in order to optimize the number of grid nodes and consequently computing time.

Finally, more research has to be done on possible corrections over the standard kε turbulence model or even higher order turbulence models combined with intensive validation analysis in order to take into account the different length scales existing in wind farm environments leading to a better representation of phenomenon such as wake merging or topographical interference in complex terrain. This is considered nowadays one of the key topics in the near future for improving wind farm models and consequently the estimation of power output and fatigue loads at big wind farms in offshore and complex terrain.

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