Wind-farm simulation over moderately complex terrain

Antonio Segalini¹ and Francesco Castellani²

¹STandUP for Wind, Linné FLOW Centre, KTH Mechanics, Stockholm, Sweden
²Department of Engineering, University of Perugia, Perugia, Italy

E-mail: segalini@mech.kth.se

Abstract. A comparison between three independent software to estimate the power production and the flow field in a wind farm is conducted, validating them against SCADA (Supervisory, Control And Data Acquisition) data. The three software were ORFEUS, WindSim and WaSP: ORFEUS and WaSP are linearised solvers, while WindSim is fully nonlinear. A wake model (namely a prescribed velocity deficit associated to the turbines) is used by WaSP, while ORFEUS and WindSim use the actuator-disc method to account for the turbines presence. The comparison indicates that ORFEUS and WaSP perform slightly better than WindSim in the assessment of the polar efficiency. The wakes simulated with ORFEUS appear more persistent than the ones of WindSim, which uses a two-equation closure model for the turbulence effects.

1. Introduction

In the recent years the number of wind turbines installed onshore increased drastically due to the demand of clean renewable energy. Ideally, it is preferable to install turbines over flat terrains with no roughness, but such ideal sites are rarely available for energy harvesting [1]. However, there are several sites where the terrain is not flat and the roughness affects the wind but the wind resource is sufficient to make the wind-farm project profitable. Such complex terrains have the advantage that they are not very populated and therefore wind farms have a limited social impact. Furthermore, being onshore installations, their cost is approximately half of their equivalent offshore version.

The industrial methods used today to evaluate wind farms were developed for simpler cases such as offshore farms (or onshore over plains) where the inflow profile is approximately homogeneous, with low shear and low turbulence intensity, together with wake models [2, 3] where the wind turbine wakes are superimposed in post-processing to the velocity field estimated over the terrain without the turbines: by means of an assumed wake behaviour (often associated to empirical parameters) and to a law describing how multiple turbine wakes interact, it is possible to estimate rapidly the expected power production. However, a recent study [4] identified that wake models are subjected to significant uncertainty already in offshore cases, while even larger uncertainty is expected onshore since the wakes evolution will be influenced by the terrain condition through vertical displacement and enhanced diffusion. Regarding complex terrain, an interesting test case has recently provided useful indications: in [5], the free flow over the terrain was addressed, while in [6, 7, 8] the combination of wakes and terrain effects
was investigated and the significant amount of wake distortion due to the terrain quantified. Consequently, wake-models physics should be improved to properly estimate the wind resource for wind farms placed in complex terrains, although only few studies have been devoted to this issue despite its importance.

An industrial alternative to wake models is provided by computational fluid dynamics (CFD) where the flow-motion equations are solved in a discretised domain at every grid point. Usually, a Reynolds-averaged approach is used, where turbulence affects the mean wind field through the Reynolds stresses, which are modelled in several ways. A two-equation approach ($k - \epsilon, k - \omega$ with all their variants) is generally considered to be the one that will provide the most accurate results, although there are several evidences where simpler models have been equally successful, if not even better than the more complex two-equations models [9, 10, 11, 12].

Pushed by the growth of the wind-energy sector, a number of international collaborations have begun to determine the accuracy of the currently-used tools and their approximations by comparing predictions with measurements performed offshore or onshore, although the latter cases are quite rare. The present work is aimed at comparing three numerical models (ORFEUS, a recently-developed linearised code for wind-farm assessment in complex terrain, WindSim, a CFD solver based on finite volumes, and WAsP, an analytical solver with the Park wake model integrated for wind turbines) with experimental data measured in a small wind farm located over a moderately-complex terrain.

2. Numerical codes

2.1. ORFEUS

The new ORFEUS code, developed in 2016 at KTH, is based on a linearised approximation of the Navier-Stokes equations around the undisturbed incoming boundary-layer profile [12]. The Boussinesq approximation is used to model the Reynolds stresses, where the eddy viscosity is prescribed as a linear function of the height from the ground, similarly to the approach of Ott et al. [10]: the model does not require the boundary-layer approximation and can indeed account for turbulent diffusion in all directions. Wind turbines and forestry are introduced in the simulation by means of body forces related to the thrust coefficient and to the leaf-area density, respectively. The terrain topography is introduced by means of a coordinate-mapping approach, similarly to Jackson & Hunt [9]. The linearised equations are solved through a spectral approach in a Cartesian grid by means of the Fourier transform in the horizontal plane and Chebyshev polynomials in the vertical non-homogeneous direction, providing a fast and accurate numerical solution of the linearised partial differential equations. Additional details on the equations and the numerical implementation can be found in [13]. In contrast with what claimed in [12, 13], here no thrust enhancement correction has been adopted: the latter was originally proposed in [12] to cope for the discrepancy between linearised and non-linear actuator disc by forcing a higher thrust force to get the same disc velocity. Since the power estimated by ORFEUS was much lower than what measured by the four turbines, it was decided to perform the simulations by using the actual thrust coefficient, so that the applied force is globally the same as in the real farm. This appeared as an easy fix to the problem as the wakes would become weaker and decay faster, although other possibilities might explain the negative bias of ORFEUS, such as the neglect of the wake-meandering phenomenon, discussed in [10].

2.2. WindSim

The numerical CFD simulation of the wakes was implemented using the WindSim model, namely a numerical code based on PHOENICS which solves the Reynolds Averaged Navier-Stokes
(RANS) equations [14]. The General Collocated Velocity method was preferred for the solution of the momentum equations while the RNG-\( k-\epsilon \) model was used for turbulence closure. This setup was preferred to have a good convergence but the time for calculation was longer (more than 3 hours for each direction). The turbine wakes are simulated with a simple actuator-disc model, where the axial force applied on the disc surface depends on the wind speed, according to the thrust-coefficient curve of the turbine. Since PHOENICS works on a Cartesian orthogonal grid, the rotor surface could be interpolated only using squared elements.

Wake models could be also used in WinSim, although here the actuator-disc approach was preferred, simulating wind turbines together with the terrain in order to improve the accuracy of the simulations: although the implementation of the actuator disc in WindSim is constrained by the grid orientation (as only body forces orthogonal to the grid can be imposed), the flow field is expected to be well captured in the far wake. This problem does not exist in ORFEUS since the grid is automatically rotated according to the incoming wind direction, and the turbine forces are imposed in a generic volume before the Fourier transformation.

2.3. WAsP

The WAsP (Wind Atlas analysis and application Program [15]) model was additionally used for wakes calculation with the standard Park model [2]. The wake calculations were performed with the standard wake decay constant \( k = 0.075 \) that is considered appropriate for onshore cases.

3. Wind-farm description

The wind farm studied in the present work is located in the south part of Italy and it is characterised by mild elevation changes, as depicted in figure 1 where the terrain elevation (normalised by the rotor diameter) and the turbines position are reported. Table 1 lists the position of the turbines and their name: the turbine T1 is here used as the origin of the adopted reference frame. The ground is covered by olive trees with an equivalent roughness height of \( z_0 = 0.3 \) m.

The four turbines have a rated power of 2 MW and a rotor diameter of \( D = 100 \) m. The thrust coefficient in the investigated range of wind speeds is \( C_T \approx 0.81 \). SCADA (Supervisory, Control And Data Acquisition) data is available for the wind turbines for more than one year, where the wind speed and direction are measured at the nacelle of every turbine. A SCADA system is collecting and storing measurements on a 10 minutes basis. Thanks to the availability of such operational data, a comparison and validation of the numerical results is possible. Nevertheless, filtering of the database is necessary in order to have a fair comparison with the models. Data filtering was done through the following steps:

(i) data were at first selected when all the four turbines were running for more than 90% of each 10 minute interval.

(ii) a second filter was applied on the wind speed in order to have a nacelle wind speed for each machine below 9 m/s. The SCADA data were therefore filtered within the region in which the thrust coefficient is \( 0.81 \pm 0.08 \) (below the rated wind speed), ensuring that a consistent statistics of farm efficiency can be observed in similar conditions;

(iii) finally, the database was prepared for the directional analysis by filtering on twelve sectors with an overall width of 15 degrees, as a good compromise between statistical convergence and direction sensitivity. The direction signal of the vane mounted on the nacelle of the most-upstream wind turbine was used as the reference flow direction.

Since no information was available on the atmospheric stratification condition, the incoming boundary layer was assumed to be neutral.
Figure 1. Topography of the investigated terrain and position of the four turbines present. The colorbar indicates the terrain elevation normalised by the turbines diameter.

Table 1. Position of the available turbines.

| Name | X/D | Y/D | Z_{hub}/D |
|------|-----|-----|-----------|
| T1   | 0   | 0   | 0.8       |
| T2   | 6.05| 2.90| 0.8       |
| T3   | 3.52| 4.94| 0.8       |
| T4   | 0.88| 6.98| 0.8       |

In ORFEUS the terrain is discretised by 1024 × 1024 grid points distributed over an area of 160D × 120D. 80 logarithmically spaced grid points were used in the vertical direction up to 50D. For the sake of simplicity, a homogeneous roughness of z_0/D = 0.003 was assumed, neglecting the slightly roughness variation of the real terrain. The simulation of one wind sector took less than 5 minutes. WindSim had a grid composed by 1.9 million cells (197 × 214 × 45 in the streamwise, spanwise and vertical direction, respectively) with a minimum horizontal grid spacing of 5.5 m.

For each of the three software, the output of the simulation for each direction sector was used to estimate the polar efficiency as well as the normalised power for each turbine.

4. Results

The efficiency of the farm is one of the most important parameters to be quantified for a given layout. For an onshore wind farm it can be defined as [16]

\[ \eta(\theta) = \frac{1}{N_t P_{\text{max}}} \sum_{i=1}^{N_t} P_i, \]

where \( P_i \) is the power of the \( i^{\text{th}} \) turbine, and \( P_{\text{max}} \) is the maximum power of the \( N_t = 4 \) turbines. \( \theta \) indicates the wind direction. The advantage of this definition is that the efficiency remains a number below 1 for any terrain and wind-farm arrangement. It can be expected that the
polar efficiency should weakly depend on the wind-speed magnitude, facilitating the averaging process of the SCADA data and reducing the number of simulations needed: this might not be the case if one or more turbines operate above rated speed, as the thrust coefficient might reduce significantly, but these events were removed by the adopted filtering procedure.

Figure 2 shows the polar efficiency obtained from the three available codes against the filtered SCADA data. The experimental data indicate that the polar efficiency is nearly constant to \( \eta \approx 0.85 \), although two deeps exist at \( \theta \approx 120^\circ \) and \( 300^\circ \), corresponding to the wind directions where the turbines T2, T3 and T4 are aligned and, consequently, affected by significant wake effects. All codes identify correctly these two deeps, although with large errors for \( \theta = 120^\circ \) while the specular case with \( \theta = 300^\circ \) does not show such large discrepancies. WindSim seems to be more pessimistic than ORFEUS and WAsP in the polar-efficiency estimation. The overestimation of WAsP is a consequence of the wake-model approach, since the upstream field is not affected by the turbines presence, and no blockage effect is accounted for. The opposite happens for WindSim and ORFEUS that are elliptic codes and can account for upstream effects.

In order to quantify the systematic error, table 2 reports the relative error in the estimation of the polar efficiency of the three investigated software against the available SCADA data. Interestingly, it is generally observable that both ORFEUS and WAsP perform better than WindSim, although the discrepancy might also be due to uncertainty in the processing of SCADA data. In any case, an average error of 3.5%, 5.0% and 4.7% affects ORFEUS, WindSim and WAsP, respectively.

In order to understand the origin of the various deeps, and to see how the different wakes are simulated by ORFEUS and WindSim, figure 3 shows the comparison for several wind directions between the two software: a reasonably good agreement between the two software is observed both qualitatively and quantitatively. The wakes simulated by ORFEUS appear stronger and more persistent than the ones of WindSim, probably due to the \( k-\epsilon \) closure scheme of the latter software. The sectors \( \theta = 120^\circ \) and \( \theta = 300^\circ \) are characterised by the overlap of the wakes of T2, T3 and T4, although the wake deficit does not increase in WindSim as it does for ORFEUS.

The normalised power produced by each turbine is reported in figure 4 for the same 6 wind directions analysed in figure 3: ORFEUS and WAsP provide in general a good estimation, although slightly positively biased. WindSim appears more conservative with the largest error for \( \theta = 120^\circ \).
Figure 3. Wind speed (normalised by the reference speed of $U_{ref} = 5.9 \text{ m/s}$) on a plane parallel to the ground located at hub height for the wind directions $0^\circ$, $60^\circ$, $120^\circ$, $180^\circ$, $240^\circ$ and $300^\circ$ (increasing from top to bottom of the figure). The positions of the turbines and their radial extension are indicated by the black thick lines. (Left) Field obtained with ORFEUS. (Right) Field obtained with WindSim.

Figure 4. Normalised powers for different wind directions. (bars) SCADA data, (circles) ORFEUS, (asterisks) WindSim, (plusses) WAsP.
Table 2. Relative error (in percent) in the polar efficiency between the three software and the SCADA data.

| θ [deg] | ORFEUS | WindSim | WAsP |
|---------|--------|---------|------|
| 0       | 4.4    | 5.3     | 6.6  |
| 30      | -0.8   | -0.7    | 0.3  |
| 60      | -1.9   | -2.6    | 0.6  |
| 90      | 4.6    | 5.0     | 7.2  |
| 120     | 12.3   | -7.3    | 15.3 |
| 150     | -6.1   | -10.5   | -2.9 |
| 180     | 0.7    | -4.2    | 3.6  |
| 210     | -0.7   | -6.1    | 3.9  |
| 240     | 0.9    | -1.3    | 4.4  |
| 270     | -1.5   | -3.2    | 3.4  |
| 300     | 7.6    | 7.6     | 7.1  |
| 330     | -0.8   | -6.0    | -1.1 |

5. Conclusions

In the present work a comparison between three independent software to assess the energy yield of a wind farm placed over a moderately complex terrain has been performed. Two linearised software (ORFEUS and WAsP) were compared against a non-linear tool (WindSim): being linearised, the first two allow for a faster and numerically-efficient solution (ORFEUS is based on spectral elements, providing a high-accuracy numerical solution of the involved equations, while WAsP is based on an analytical solution) compared to WindSim, that fully accounts for the nonlinearity of the flow-motion equations with a solution performed with the finite-volume method. The turbulence closure schemes of the three codes is substantially different as WAsP is based on the mixing-length approach [15], ORFEUS on a prescribed linear eddy viscosity and WindSim on a $k-\epsilon$ model. WAsP uses the Jensen wake model to account for the turbines, while WindSim and ORFEUS simulate the turbines by means of the actuator-disc approach.

According to the present results, ORFEUS and WAsP perform slightly better than WindSim in the assessment of the polar efficiency, although positively biased. Despite the simplifications, the velocity field estimated by the ORFEUS code is close to the one simulated with WindSim, with wind-turbine wakes that are slightly more persistent (and less diffusive) than what WindSim provides. Interestingly, while all software for almost all wind directions were affected by an error of ±5%, they all showed significant deviations for $\theta = 120^\circ$, corresponding to a waked sector, although the specular waked sector $\theta = 300^\circ$ was not affected by the same error. The reason for this might be due to the processing of the SCADA data or to the different upstream conditions, although more data is maybe required to sort this out properly.

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