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A practical approach in the CFD simulation of off-shore wind farms through the actuator disc technique

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Abstract

In this work a practical approach to Computational Fluid Dynamics (CFD) simulations in wind resource evaluation is proposed in a test case of the IEA project (task 31) "Wakebench" focused on the benchmarking of wind wakes models. The proposed method uses an easy wake model, the Actuator Disc (AD), in a CFD approach, in order to understand the wind behavior in a complex wind farm of 18 turbines sited in the northern part of Netherlands, with a sustainable computational load. In order to optimize the simulation results a useful tool that automates the parameters evolution was developed; such tool is able to improve the control of the engineering parameters and is useful to prepare advanced post processing. The study was mainly focused on the analysis of the single wake; also simulations on the double wake case and other tests on larger wind farm were performed with success using the same automatic approach. Results are in quite good agreement with experimental data and the differences between the predicted and experimental results are to be addressed to: global effect of stability, turbine inferences in the actual wind farm and to some lacks in physical wake model.

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Keywords: CFD; Wakes; actuator disc; off-shore wind energy

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1. Introduction

Numerical wakes simulations play a key role in the offshore wind farm development and a reliable estimation of the complex multiple wakes interaction is fundamental in order to predict with accuracy the power production, hence to optimize the wind farm layout. Many numerical simulation techniques are currently under development for off-shore applications and, among all, computational fluid dynamics (CFD) seems to represent the most promising method compared to the traditional analytical models and it

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is able to give very useful information from the engineering point of view [1, 2]. Among the different CFD methodologies, some (e.g. full rotor simulations with LES) of them requires supercomputing to be applied to large wind farms, some (e.g. DNS) are not even at that stage. Moreover, the possibility to achieve results is strictly related to convergence conditions of the iterative solution process.

Currently, one of the CFD methods that, although not requiring supercomputing, still remains promising for accurate computations of the wind turbine wakes is the Actuator Disc (AD) model implemented in the integration of the Reynolds Average Navier-Stokes (RANS) equations. Anyway, when combining RANS and AD the complex physics of multiple wakes is not fully represented and the convergence of the solution could be critical.

In present work a new practical approach for convergence criteria has been developed for the application of the AD model within the WindSim software package. In order to improve the simulation results the convergence criteria were defined not only in terms of flow parameters (wind speed components and turbulent kinetic energy) but also in terms of more engineering parameters (such as the wind power extracted by the rotor). Despite some modeling issues [3], the AD was discovered to be an affordable engineering tool when dealing with off-shore; the use of such numerical scheme can be accompanied by a smart grid control [4].

A specific tool was developed in MATLAB to manage the WindSim CFD simulations in batch mode; in this way it was possible to monitor the wakes characteristics during the simulation. The tool is used to determine the convergence of the monitored parameters in the rotor areas rather than in the whole domain.

This method was tested and validated using the database available from the Sexbierum wind farm. Comparisons with the experimental dataset are also presented.

This work was carried out in cooperation between the Department of Industrial Engineering of the University of Perugia and WindSim AS; both companies are involved in the IEA project (task 31) “Wakebench” focused on the benchmarking of the wind turbines wakes models.

2. The numerical model

In the last 30 years the role of simulations in the wind potential assessment increased every day, with a lot of different approaches and models. In this work a CFD procedure is applied, in order to evaluate the wake characteristics with a robust numerical tool that can still be launched on a standard PC.

2.1. The CFD model

In CFD approach the principles that govern the flow (mass conservation, Newton’s second law and energy conservation) are expressed in discretized algebraic forms. In this work it has been used the software WindSim, focused on wind analysis, which is based on the more general CFD solver PHOENICS (developed by CHAM).

The wind fields are calculated with the Reynolds Averaged Navier-Stokes equations (RANS) solution with an iterative estimation of the flow variables (pressure, velocity, turbulent kinetic energy and turbulent dissipation rate).

2.2. The Actuator disc model

The wake effects, wind speed deficit and induced turbulence, can be computed with different approaches ranging from simple analytical models [6] to full rotor calculations [13] passing through actuator lines and actuator disc techniques. For the wake overlap some simple models apply the linear superposition scheme [5] but this can lead to an overestimation of the velocity deficit. The PARK model uses the velocity square linear combination [6, 7] but there are also empirical superposition laws [8] or models where the effect of the first row can be stronger than the second and so on like on the

WINDPARK model [9, 10].

In present work the wake effects are simulated using the Actuator Disc tool; in this way the turbine interference on the flow is represented by porous cells that cover the rotor swept area. These cells exert a force against the wind according with the turbine thrust coefficient.

The distribution over the swept area can be adjusted to study the effect of different boundary conditions; in WindSim there are three possibilities: a uniform distribution, parabolic (max value at hub and zero on the tip) and polynomial (4th order, zero value on the tip). In this work a uniform distribution was used.

The AD model is based on the 1-dimensional momentum theory: the wind turbine is represented as a mechanical system that extracts the kinetic energy from the wind. The flow through the rotor has less energy than the air undisturbed by the rotor presence. Downstream the rotor the tube flow expands, a little upstream the swept area the flow starts to decelerate for the presence of the turbine and the stream tube cross-section grows. Far upstream and far downstream there aren't differences on pressure, but the kinetic energy changes.

The energy previously contained in the mean flow is partially converted into mechanical work at the shaft, a part is instead not converted by the rotor and transferred into the wind turbulence. The use of actuator discs allows to analyze the wind farm aerodynamics with a poor description of the turbine characteristics. In fact there is no need to specify the blades geometry as for calculations of real geometry, neither lift and drag laws for each radial section of the blades as required by the actuator line technique.

2.3. The Test Batteries

In this work a new practical approach to CFD is proposed, with the use of a numerical tool called *test battery* that automates the evolution of some simulation parameters in order to study the dependences of results. Important work was made in order to study the convergence characteristics. Test battery can be useful both for automate the run of simulations as well for calculate flow and wakes parameters with a post processing procedure.

In present work the test battery was applied to reach a target velocity value upstream the wind turbine; this constrain represents the boundary condition requested to compare simulation and experimental data. In the test battery input an approved velocity error is requested. If the difference between calculated and target velocity upstream is greater than the error value, the wind speed over the boundary layer is corrected in order to reach the requested value.

Wake parameters and energy production are calculated in a post processing procedure included in the test battery: ΔP is evaluated at different levels across the swept area so that an estimation of the power P obtained from the turbine can formulated with a discrete approach.

$$P = \sum_{i=1}^{N} v_i \Delta P_i w_i \tag{1}$$

where N is the overall number of considered levels, v_i is the speed on the rotor plane at height i, ΔP_i is the pressure drop and w_i the weight associated to the rotor area corresponding to the height i.

3. The Sexbierum test case

The Sexbierum case is a well-investigated wind farm with a very detailed database of measurements; such case represents a reference case for benchmarking wakes numerical models.

3.1. The experimental dataset

Sexbierum is located in the Northern part of the Netherlands [11, 12], around 4 km from the seashore.

In the site 18 turbines HOLEC machines (with three blades, hub height 35 m, power of 310 kW, synchronous generators with variable speed.) were installed for a total power of 5.4 MW. The wind farm layout is a semi-rectangular grid of 3×6 turbines (fig.1).

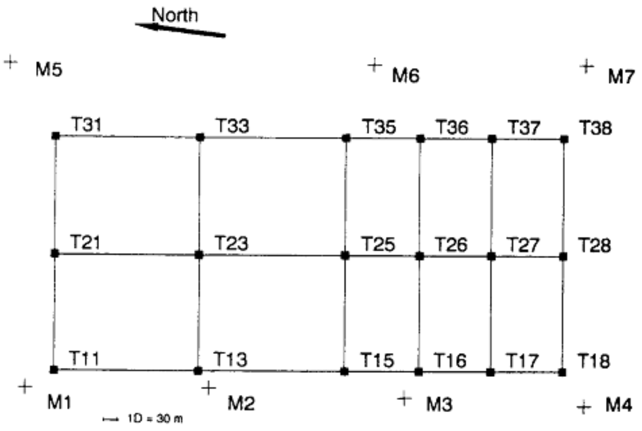

Figure 1: Sexbierum wind farm layout.

For data acquisition 7 meteorological masts were installed in order to measure the undisturbed wind conditions from each direction. In met masts M4 and M6 the sensors are installed at three heights (20, 35 and 50 m). In the other masts the sensors (wind vane and anemometer) are installed at hub height. The T36 turbine is instrumented in order to investigate wake effects. At mast M3 temperature and air pressure are measured. The prevalent wind direction is along the ideal line T18-T36.

The wind speed frequency is modeled with a Weibull distribution at hub height with a scale factor A=8.6 m/s and a shape factor k=2.1 resulting in an average wind speed of 7.6 m/s.

The available time series are 1-minute data averages, combined in order to obtain 3-minutes average quantities. This choice is due to the consideration that in general a spectral gap for wind velocity is assumed between 10’ and 1 h, and in shorter periods the data can be non-stationary. Another reason is the time of propagation of the wakes that is around 40-45 sec; in order to obtain a coherence between wake and undisturbed data is necessary an averaging period greater than 50”. The averaging time must be short in order to see the details of the variations due to wakes. With these reasons and also for the large amount of data due to the short time step, 3’ averages were chosen.

The frame of reference for the single wake study is based on the line connecting T18 with T27 that is the defined direction 0° (fig. 2).

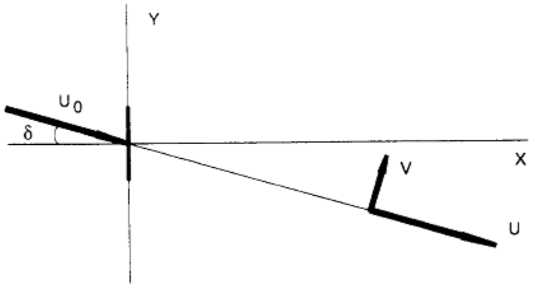

Figure 2: Frame of reference.

Experimental data were treated to be referred to such wind direction: all the following results in term of speed deficit, turbulence etc. are presented and compared against experimental data in the range ±30° [11,12].

The velocity components u, v, w are a right-handed coordinate system where: u is parallel to undisturbed wind, v is perpendicular and w is vertical. In this study the normalized velocity components U/U_0, V/U_0, W/U_0, (U_0 is the undisturbed speed at hub height) and the normalized turbulent kinetic energy k/U^2 (U^2 is the square of the local wind speed) are analyzed. Measurements have been made in the wake of T18 and upstream T27.

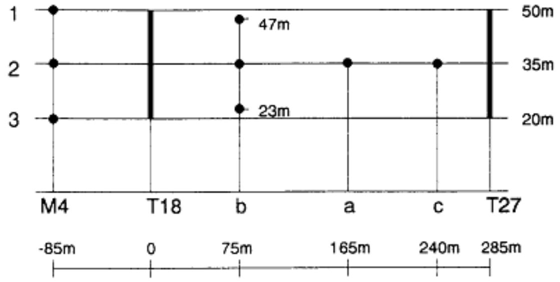

Figure 3: Mobile Met masts disposition downstream T18 in the positions a, b (three heights), c.

The single wake case is studied with the results of the 3 mobile met masts sited at 2.5, 5.5 and 8 rotor diameters downstream the turbine T18 (fig. 3).

3.2. *The numerical setup*

In the single-wake case the test battery was used in order to reach a target velocity of 8 m/s-as requested for the Wakebench project upstream. With the possibility to automate the simulations, the convergence behavior was monitored. The optimal operation conditions for the Actuator Disc tool are when a staggered grid is used with the coupled solver. In this work the accepted speed error was set to 0.1 m/s. In order to obtain the best flow representation a first investigation on the convergence characteristics of the project was performed with the test battery.

With a post processing procedure was possible to analyze the flow field parameters and a comparison with experimental data was possible in the investigated range of flow angles. In present study simulations for the single wake case were performed with a wind direction of 270°. In order to analyze results on the others flow angles the measure sensor was moved on a circular path with a radius equal to the distance from sensor to rotor within the observed angular range. The flow parameters values were interpolated on the observed points with a MATLAB post processing code.

A first test was done with a domain discretized with 788400 cells, simulated wind direction 270° and boundary layer height 800 m. After a first change in speed above boundary layer, the optimal conditions are reached for a speed of 12 m/s: with this boundary condition the upstream speed at hub height is 7.98 m/s, very close to the target velocity.

A second model was implemented in order to try to reproduce different turbulence levels, with a terrain discretization of 1354017 cells. In order to simulate different turbulence conditions, the boundary layer height is set to 400 m. The wind flow assumes different characteristics with these new conditions and the use of the test battery is needed in order to find the right speed above boundary layer. With a test battery was possible to reach the requested velocity, with a lot of steps. After a first simulation of 2000 iterations, a step of 1500 iterations, 4 steps of 500 iterations, 10 steps of 100 iterations, and a final step of

1000 iterations were performed. The best agreement with target speed was found with a speed of 11,4 m/s: with this boundary condition the upstream speed at hub height is 7.92 m/s.

In Figure 4 the power and upstream speed evolution with the iterations development is shown for the larger model.

The inlet boundary conditions were tuned during the iterative process to match the requested upstream wind conditions; particular attention was addressed to the absolute value of the upstream wind speed: simulations were stopped when such parameter was found very close to the target.

For the three sensors at different heights in the same mast (b1, b2, b3) the behavior of wind speed ratio is in good agreement with experimental results, because the wind shear is well reproduced: the lowest value is a 0° for mast at 35 m, hub height, and far from 0° the flow reaches undisturbed conditions. The global behavior of turbulent kinetic ratio for three heights in the same mast (b1, b2, b3) is in good agreement with experimental results, but kinetic energy shear is not well reproduced: the bigger value is a 0° for mast at 35m for simulated flow, and is at 47 m for experimental data (results not shown).

For the three sensors at different distances at hub height (a2, b2, c2) the speed ratio behavior shows that the simulated wind shear is quite in good agreement with experimental results and the global flow is well reproduced. The simulated results underestimate the speed ratio value. The turbulent kinetic energy near the rotor (mast b, 2.5 diameters downstream) is not well reproduced; better results are obtained far from the rotor (masts a and c).

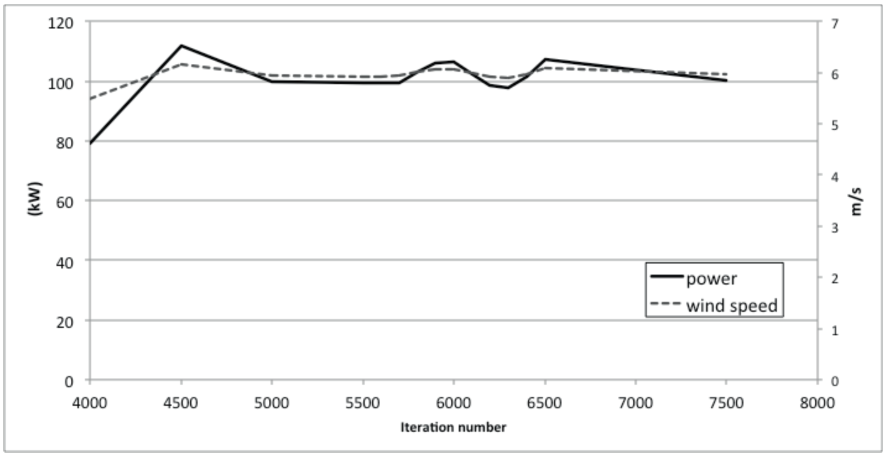

Figure 4: History of convergence for the power output (kW) and the wind speed (m/s) on the rotor disc.

The general behavior of wind speed ratio in wake center is in good agreement with experimental results, but the wind shear is not well reproduced: for experimental data the lowest value at 0° is for sensor at 35 m, hub height, and far from 0° the flow reach undisturbed conditions. In simulated results the lowest speed ratio value is for the sensor at 23 m. These differences can be addressed to the different resolution and the different turbulence level respect to the experimental dataset.

In the single wake test case a deep analysis of the results was done through a specific post-processing tool. The estimation of many wind flow parameters was necessary including all the components of the mean wind speed and the element of Reynolds stress tensor.

In present work all the simulations were carried out using RANS (Reynolds Average Navier Stokes) solutions with the RNG k-ε model. According to this simulation hypothesis the turbulence is supposed to behave isotropically so that all the elements in the principal diagonal of the tensor assume the same value and can be calculated from the estimated value of the turbulent kinetic energy:

$$k = \frac{1}{2}(u'^2 + v'^2 + w'^2) \qquad (2)$$

where u', v' and w' are respectively the fluctuating contributions of the three components of the wind speed.

Under the isotropic hypothesis the element of the tensor are:

$$u'u' = v'v' = w'w' = \sqrt{\frac{2 \cdot k}{3}} \qquad (3)$$

For the estimation of the elements of the tensor off the main diagonal the calculation of the turbulence eddy viscosity is necessary using the following equation:

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon} \qquad (4)$$

where k is the turbulent kinetic energy, ε is the turbulent dissipation, ρ is the density of the fluid and C_μ is a costant of the turbulence model (in this case its value is 0.0845).

The components of the stress out of the main diagonal can be calculated using the following equation:

$$-\rho u_i' u_j' = \mu_T \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \qquad (5)$$

In present work the partial derivative of the wind speed components were estimated from the numerical results using a discrete approach in the post-processing routine.

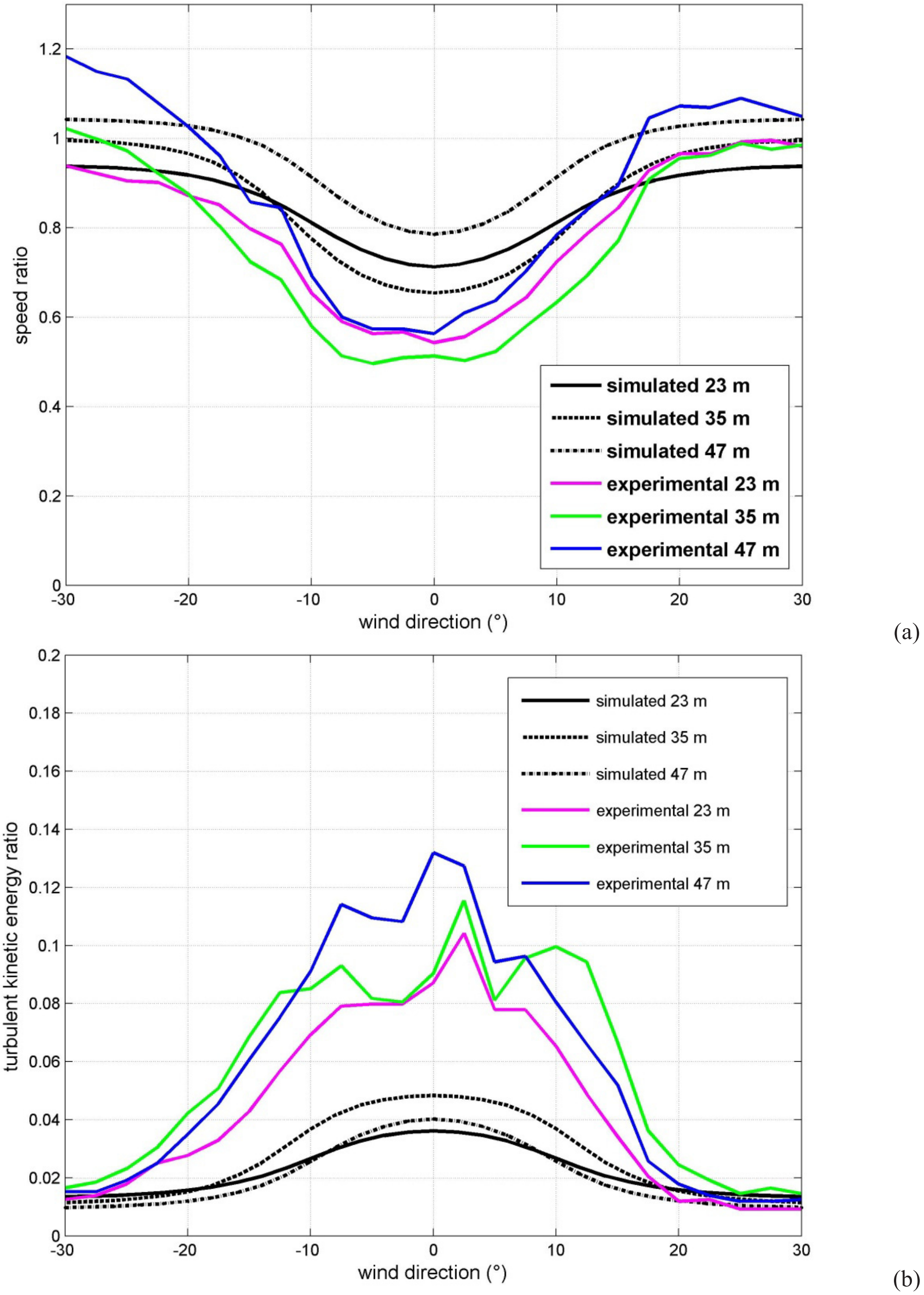

Figure 5: speed (a) and turbulent kinetic energy (b) ratio profiles at different level observed 2.5 diameters downstream.

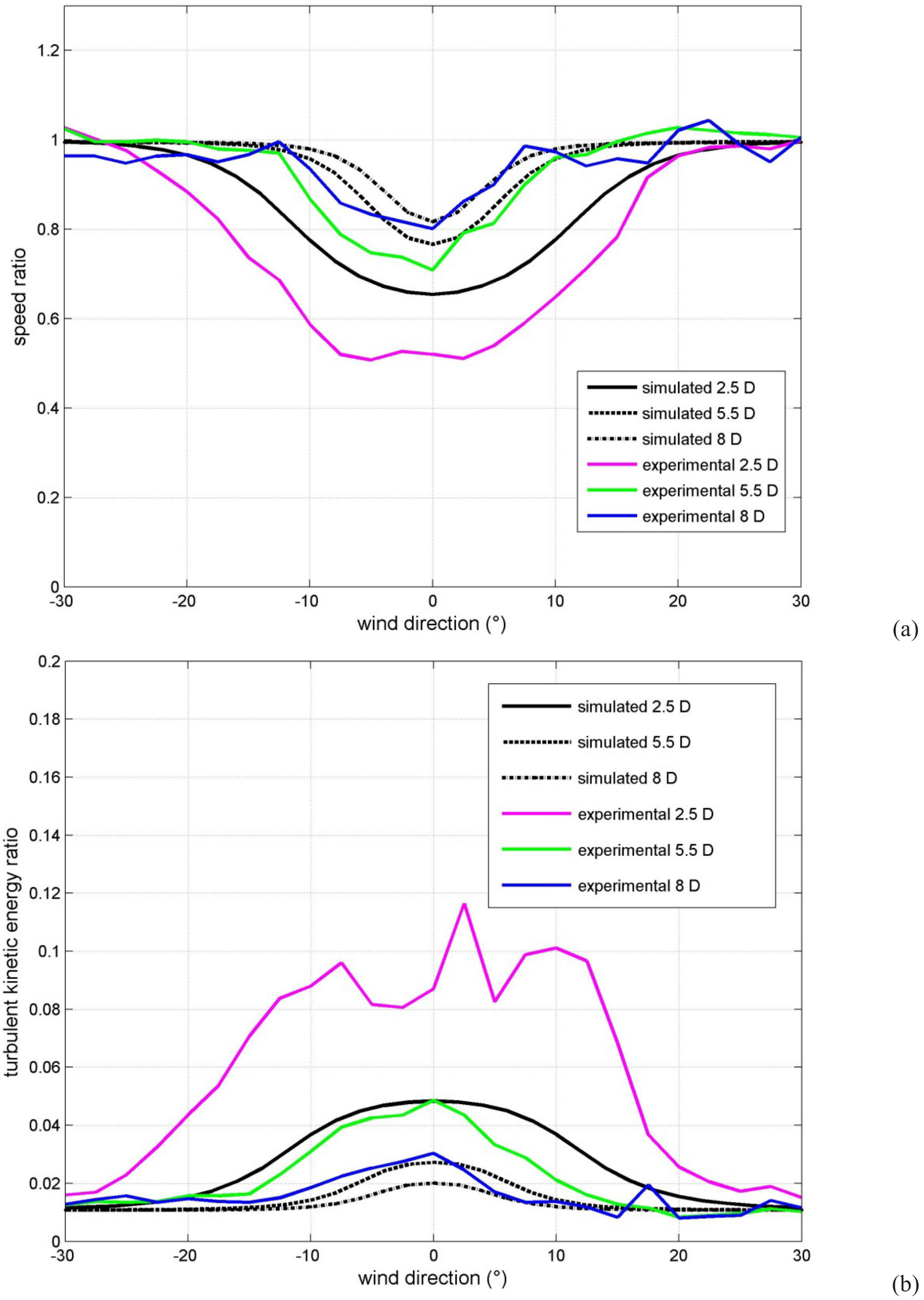

Figure 6: speed (a) and turbulent kinetic energy (b) ratio profiles at hub height observed 2.5, 5.5 and 8 diameters downstream.

4. Discussion

The simulated and experimental data in the single wake seem to be in good agreement. In the different heights comparison the sensors are located 2.5 diameters downstream of the rotor T18.

The AD model implemented in WindSim is designed to predict wake losses and wind speed deficits in a very fast way and does not include all the complex physics of the wakes expansion.

The simplicity of the model does not allow to achieve reliable results in the near-wake zone (0 up to 3 D downstream). The order of magnitude of simulated values is correct and the general behavior is well reproduced, but the actual values are not well reproduced.

The speed deficits reproduced by AD model are too focused in the wake core; this can be due to the lack of turbulent momentum exchange. Outside the wake center the turbulence diffuses and its effects decrease. If there are ambient turbulence effects the turbulent kinetic energy balance can be very different causing the smooth of the speed deficit profile. In the real case of the Sexbierum wind farm is possible that the roughness, the presence of the other turbines and stability effects induced ambient turbulence effect that can be very difficult to reproduce in the numerical model.

Exact aerodynamics interactions can't be reproduced by Actuator Disc model. The 1-dimensional formulation can be successfully used to simulate the turbine presence and its wake effect in the global wind farm context, where the inter-turbine distances are greater than 2.5 D and some of the physics can be disregarded.

Anyway present work demonstrates the potential of all the simulation chain that can be automatized using the test batteries. Apart from the simple Sexbierum single wake case with WindSim and the test battery can be very easy to simulate the wake interaction of a quite large wind farm on a real terrain context. In figure 7 the first results of a test case with 9 wind turbines are shown. In this case the numerical model was quite large (approximately 8 million of cells) and the test battery was very useful to verify the convergence by monitoring the power extracted by each actuator disc.

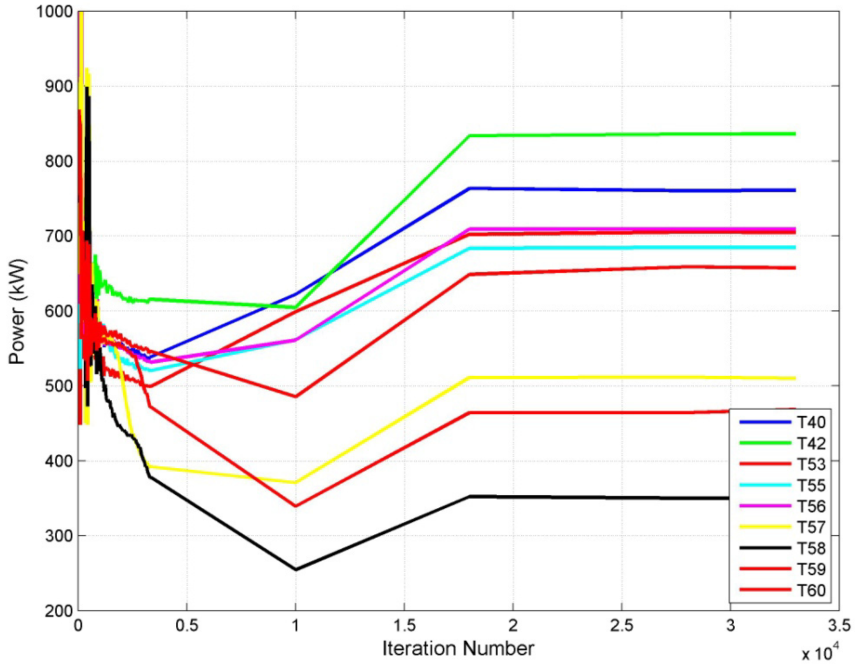

Figure 7: evolution of the power extracted from each rotor of an onshore wind farm on real terrain case.

5. Conclusions

In present work the possibility to use the AD model to simulate the wakes of wind turbines was investigated both for research as well for engineering applications. The Sexbierum single wake case was interesting for benchmarking the physical model and to develop the automatic numerical procedure. The first tests on larger wind farm demonstrate that the proposed method, despite the simplification of the physical model, can give a very useful contribution for understanding the complex aerodynamics of large off-shore wind farm. In this context the power output of each rotor as well the wind speed and the turbulent kinetic energy represent key parameters to be supervised in the modeling activity.

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