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

F. Castellani, A. Gravdahl, G. Crasto, E. Piccioni, A. Vignaroli

Presenter: Dr. Giorgio Crasto, WindSim AS
Contact author: Prof. Francesco Castellani, University of Perugia
THE WindSim MODEL

Key features

- WindSim (WS) is commercial software package for wind flow simulations based on Computational Fluid Dynamics (CFD)

- WS provides a user-friendly interface for the CFD core PHOENICS (by CHAM)

- The code solves automatically the Reynolds Average Navier Stokes (RANS) equations (steady solution) on different direction sectors

- Very easy to setup a simulation on a real terrain case
- Easy grid control
- Quite fast solution

- Strictly Cartesian orthogonal grid
- Solution with RANS and quite standard turbulence models
Using an orthogonal Cartesian grid WS is designed to operate on rectangular domains. This introduce different boundary layers conditions between orthogonal and skewed direction sectors.

Orthogonal flows:
- 1 inlet
- 1 outlet
- 2 frictionless walls

Skewed flows:
- 2 inlet
- 2 outlet
- 2 frictionless walls

Vertical distribution
TURBULENCE MODELS

The RANS equations are closed with different versions of the k-ε model or the k-ω model:

- k-ε Standard
- k-ε Modified
- RNG k-ε
- k-ε with YAP correction
- k-ω

There is a fundamental lack of physics when using RANS and the k-ε/k-ω model with relevant adverse pressure gradients (Réthoré et al., 2010).

Applying some small changes on a open part of the code (Q1 file) it’s possible to test even more solutions for turbulence models.

WAKES MODELLING

WindSim provides two different ways to consider wakes in the numerical solution:

1. **Using analytical models in the post-processing of the CFD/RANS calculations**
   a. Jensen model (momentum deficit theory)
   b. Larsen model (turbulent boundary layer equations)
   c. Model with a turbulent depending rate of wake expansion

2. **Use the actuator disc (AD) model within the CFD/RANS calculations**
   - Only axial forces are applied on the disc
   - All rotational effects are disregarded
   - The thrust is applied according to the thrust coefficient curve of the wind turbine using the actual speed calculated on the rotor (correction with axial induction).
USE OF THE TESTBATTERIES

• The test battery is a numerical tool designed to be used during the development of each new version of the code.

• With the test battery it is possible to run the model in a batch/silent mode, changing the calculation parameters automatically and check all monitored outputs.

• The test battery can be very useful also for research purpose.

A good part of the development of the test battery was carried-out at the WindSim headquarter in Norway by Emanuele Piccioni, a PhD student from the University of Perugia during his four-months stage within the Erasmus Placement project.
TESTING A NEW SOLVER WITH THE TESTBATTERIES

Adjusting the convergence criteria for the new GCV, a SIMPLE-C solver acting on a collocated, BFC grid.
TESTING A NEW SOLVER WITH THE TESTBATTERIES

Assessing the performance on complex-terrain

Coupled solver with staggered grid

GCV solver with collocated grid
RESULTS FROM THE SINGLE-WAKE CASE

Wind speed (m/s)

Pressure (Pa)
RESULTS FROM THE SINGLE-WAKE CASE

Using the testbattery to reach the upstream wind speed conditions:

<table>
<thead>
<tr>
<th>Iteration number</th>
<th>Power (kW)</th>
<th>Velocity upstream (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>79.58</td>
<td>7.54</td>
</tr>
<tr>
<td>2000</td>
<td>98.61</td>
<td>8.11</td>
</tr>
<tr>
<td>2500</td>
<td>93.87</td>
<td>7.98</td>
</tr>
<tr>
<td>3000</td>
<td>93.86</td>
<td>7.98</td>
</tr>
<tr>
<td>3500</td>
<td>93.86</td>
<td>7.98</td>
</tr>
</tbody>
</table>

Spot Values | Residual Values | Field Value
---|---|---
U1 Max       | 7.000E+03     | 7.000E+03
U1 Min       | 5.000E-01     | 5.000E-01
V1 Max       | 3.000E+06     | 3.000E+06
V1 Min       | 2.000E+03     | 2.000E+03
W1 Max       | 2.000E+06     | 2.000E+06
W1 Min       | 5.000E+01     | 5.000E+01
KE Max       | 4.000E+05     | 4.000E+05
KE Min       | 9.000E-01     | 9.000E-01

Velocity upstream (m/s)

Speed vs Iteration number

Sector: 270°
RESULTS FOR THE DOUBLE WAKE CASE
Due to the flow symmetry it is possible to move the sensor rather than changing the wind direction.
In this case it is necessary to rotate the layout (and the sensor positions). If the terrain is not flat also the rotation of the DTM is needed. This is the only possibility to have the rotors exactly facing the wind.
CALCULATING THE REYNOLDS STRESS TENSOR COMPONENTS

The eddy viscosity was estimated according to the chosen turbulence model (RNG k-ε) in order to solve the equations:

\[-\rho u_i' u_j' = \mu_T \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)\]

\[\mu_T = \rho C_\mu \frac{k^2}{\varepsilon}\]

\[C_\mu = 0.0845\]

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

The turbulence is modeled as isotropic; the partial derivative of the wind speed components were evaluated using a discrete approach.
ESTIMATION THE POWER OUTPUT

\[ \text{power} = \int_{A_s} \overline{u} \cdot \Delta p \cdot dA \]

- \( A_s \) is the swept area
- \( \overline{u} \) is the bulk velocity over the swept area
- \( \Delta p \) is the max pressure drop over the swept area
The Sexbierum test-case (1/4)

• 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.

• Sexbierum is located in the Northern part of the Netherlands (Cleijne 1992, 1993), around 4 km from the seashore.

Cleijne J.W., “Results of Sexbierum Wind Farm”, Report MT-TNO 92-388, 1992

The Sexbierum test-case (2/4)

18 turbines HOLEC three-bladed machines, hub height 35 m, power of 310 kW, for a total power of 5.4 MW.

The wind farm layout is a semi-rectangular grid of 3×6 turbines.

Seven fixed met-masts M1-M7 and a mobile met-mast used to measure the wake along the main wind direction T18-T27.
The Sexbierum test-case (3/4)

(a) Speed ratio $U/U_{ref}$

(b) Turbulent kinetic energy ratio $TKE/TKE_{ref}$

Figure 5: speed (a) and turbulent kinetic energy (b) ratio profiles at different level observed 2.5 diameters downstream - position b, 75 m downstream of T18.
The Sexbierum test-case (4/4)

(a) Speed ratio $U/U_{ref}$

(b) Turbulent kinetic energy ratio $TKE/TKE_{ref}$

Figure 6: speed (a) and turbulent kinetic energy (b) ratio profiles at hub height observed 2.5, 5.5 and 8 diameters downstream.
Validation, Horns Rev (first 3 rows)

Production for all eight turbines in each three first columns for case with income wind from 270° and wind speed of 10 m/s at hub height. Variability due to sector division.

Computational characteristics:
Resolution  D/10 (8 meter)
# cells  5.0 M
Lillgrund is an offshore wind farm located in Øresund consisting of 48 wind turbines (Siemens SWT-2.3-93)

The presence of shallow waters caused the layout of the wind farm to have regular array with missing turbines (recovery holes).

- Very close inter-row spacing
- Onshore effects
- Interesting wind farm for wake simulations

Validation, onshore wind farm

For the turbines placed in north-west of the domain (quite far from the met-mast) there is an difference in yawing even larger than 20°.

This misalignment is not fully captured by the actuator disc implemented. Orographic but also metereological effects.
Conclusions

1. WindSim with the Actuator disc model can be a useful tool for simulation of wakes on real cases (offshore and onshore);

2. Using RANS and the k-ε turbulence model can introduce some critical issue for the model not realizable (near wake);

3. Another critical part of the model can be connected with the lack of swirl in the wake (near wake);

4. Comparison with SCADA data is possible but a large uncertainty can be introduced by rotors yaw misalignments (this issue is more critical in onshore wind farms).
FUTURE WORK

1. **ON THE MODEL SIDE**
   a. Complete the simulations with different wind speed conditions using the testbattery
   b. Improving turbulence modeling (realizable models?)
   c. Define the best force distribution on the rotor
   d. Introduce thermal stratification
   e. Introduce swirl of wake

2. **ON THE EXPERIMENTAL SIDE**
   a. Understand misalignments (for onshore application)
   b. Introduce much more information on the actual wind direction
   c. Analyze seasonal behaviors
THANK YOU FOR YOUR ATTENTION

If you want to know more about this tool …

Dr. Giorgio Crasto, WindSim AS (NO)
giorgio@windsim.com

Prof. Francesco Castellani, University of Perugia (IT)
castellani@unipg.it