Wind Farm Flow Modelling Using CFD

2012 Update Webinar

Christiane Montavon, Ian Jones

ANSYS
Agenda

• 15:00 Introduction to the webinar and ANSYS

• 15.10 Presentation
  – Why CFD Simulation?
  – Validation and technical advances
  – Overview of ANSYS CFD tools for wind farm flow modelling

• 15.45 Software Demonstration
  – Automated workflow for wind farm modelling

• 16.05 Question and Answers

• 16.15 Close
Acknowledgements

• Carbon Trust, project CT090-091, Power from Onshore Wind Farms, and partners,
  – RWE, Scottish Power, SgurrEnergy

• Carbon Trust OWA Phase 1 and partners
  – (Dong, RWE, Scottish Power, SSE Renewables, Statoil, Frazer-Nash).

• SSE Renewables

• E.ON

• EU BREIN project

• Loughborough University

• University of Strathclyde...

• and many more
ANSYS: A Comprehensive Simulation Platform

- Blade design
- Generator and shaft design
- Speed Sensor
- Power Electronic
- Wind farm configuration for optimal power generation
- Power Distribution
- Tower design and FSI
- Electromechanical Component
- Offshore Installation and certification
- Site selection, land and sea

- Electric Machine
- Transformer
- Rotor sizing and acoustics
- Electromechanical Component
- Offshore Installation and certification
Background

- More and more onshore sites developed in complex terrain and complex forestry environment.

- Associated risks:
  - Separation, negative shear exponent factors
  - Increased turbulence
  - Implications for turbine longevity and energy output

- On such sites, standard industry tools (linearised models) used outside of the envelope where they are meant to operate

- Large array losses, particularly so offshore
  - Empirical models tend to underestimate the losses for large arrays
  - Atmospheric stability significantly affects array efficiency (e.g. L. Jensen, EWEC proceedings, Milan 2007)

- CFD models increasingly advocated to address these issues.
  - Need for fidelity of solution and reliability → validation!
  - Need for automated solution for users without CFD background
N-S Solvers vs. Linearised models

Advantages of Navier-Stokes solvers as compared to linearized models:

- Accurate prediction of turbulence:
  - flow turbulence is modeled or resolved using RANS/LES

- Better prediction of multiple-wake effects
  - accurate geometry description and wake prediction from multiple installations
  - no limit to number of wind turbines considered

- Separation/shade effects due to complex terrain
  - complex terrain is resolved
  - shading effects, recirculation and separation are captured

Validation material

- **On range of sites**
  - Onshore: Blacklaw, An Suidhe, Nant y Moch, Harestanes
  - Offshore: Horns Rev, North Hoyle

- **On range of issues**
  - Complex terrain
  - Complex forestry
  - Stability
  - Wake interaction

- **Some done by our users**
  - Offshore: Burbo Bank, Gunfleet Sands, Barrow (DONG energy)
  - Forestry: Loughborough University

→ CFD delivers increased accuracy and insight in flow conditions
Example – Blacklaw Power Prediction

- Complex forestry
- Significant wake effects
- Good prediction of normalised power output
- RMSE for power prediction over all turbines and over both masts is 8.5%

Technical Advances

- Forestry model (resistive model)
  - Variable forestry height
  - Variable loss coefficient

- Wake Model, large array losses
  - Horns Rev, North Hoyle

- Atmospheric stability accounted for via equation for potential temperature, buoyancy effect in turbulence model
  - Harestanes, An Suidhe
  - Horns Rev
Resistive ‘Canopy Model’ available:
- Svensson
- Lopes da Costa
- Katul
- Resistance in momentum only

Canopy Input Data
- From roughness data
- CFX Interpolation Table
→ variable tree heights

Forestry loss coefficient
- Constant or variable with height

Horns Rev
Results at Hub Height – Sector 280

$U_{\text{ref}} = 8 \text{ m/s at 70m, } z_0 = 0.0002\text{m}$

Wind direction: sector 280

- Horizontal velocity
- Turbulence intensity
Horns Rev
Normalised Power Down a Row

- Simulations by step of 1 degree, sector 270 – 285, averaged for three different bin sizes.
- Reasonably good prediction
  - Tendency for over-estimation of array losses
  - Good prediction of slope down the row
- Consistent for various bin sizes

North Hoyle
Normalised Power Down a Row

\[ U_{\text{ref}} = 10 \text{ m/s at 67m}, \ z_0 = 0.0001\text{m}, \ \text{upstream TI} = 7\% \]
Wind direction: sector 260

- Very good agreement with power data for both bin sizes
- Absolutely blind test case!

Improved results with atmospheric stability

- Atmosphere on average stable above boundary layer
- Including this effect
  - Changes the relative distribution of the wind speed between hill tops and valleys → improves mast to mast cross prediction when masts located in different type of positions (i.e. hill tops vs valleys)
  - Improves the prediction of the relative TI on site

Including surface stability effects significantly affects the prediction of array losses

C. Montavon, C. Staples, C. Weaver, 2011, Simulating the flow conditions over complex terrain with RANS models: sensitivity to a selection of parameters including atmospheric stability, EWEA 2011, Brussels.
Harestanes, Masts on site

- 4 masts on site, 3 near hill tops, 1 in a location with difficult flow conditions (valley, proximity to forestry)

- Cross prediction done for 3 masts with long concurrent time series

All masts with data at 70m, 60m, 40m, 30m

Hill top masts:
  - Holehouse Hill
  - Hareshaw Rig

Valley mast:
  - Bran Rig
Harestanes
Mast to Mast Cross Prediction (wind speed)

Maximum relative errors in wind speed cross predictions for three model configurations:

1. Purely neutral
2. Conventionally neutral i.e. stable conditions in free stream, with potential temperature gradient of US standard atmosphere, and neutral conditions at ground (adiabatic).

<table>
<thead>
<tr>
<th>Model</th>
<th>3 masts (70m only)</th>
<th>3 masts (all heights)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BRAN-HOL</td>
<td>BRAN-HAR</td>
</tr>
<tr>
<td>neutral</td>
<td>11.8%</td>
<td>13.3%</td>
</tr>
<tr>
<td>stable</td>
<td>0.4%</td>
<td>4.1%</td>
</tr>
</tbody>
</table>

→ Improved results with atmospheric stability
Validated Tools

- Ongoing validation exercise together with end users, see e.g. our joint EWEA publications at

Copenhagen 2012, available from:

https://docs.google.com/open?id=0B6Cp_fvx8o5Dei0tenVqeIgZQzQ

Brussels 2011, available from:

https://docs.google.com/leaf?id=0B6Cp_fvx8o5DMjBkMzQxNWMtOTk

Previous years, available from:

https://docs.google.com/leaf?id=0B6Cp_fvx8o5DZmEzYxMDAtZGYxZi

00Yml0LWlwMjYtZWM3NmVjYWM2NDI3&hl=en_GB


WindModeller: set of tools wrapped around ANSYS standard CFD products:

- Allow non-CFD experts to perform wind farm analyses in automated way
- Drive ANSYS CFX or FLUENT flow solver
- Allow advanced user to encapsulate their own expertise (access to customised setup and post-processing scripts which can easily be altered by the user to further develop the tools)
Tools for Automated Solution

Objective

- Automation of Analysis and Data extraction
- Map → Mesh → CFD → Report in one step

CFD solution + automated post-processing

Wind data transposition module (cross prediction and energy assessment)
WindModeller: Simulation Process

- Wind farm simulation process from user perspective
  - Set up analysis on desktop computer (either via GUI or command line)
  - Submit job to:
    - Run possible large number of cases on the local machine or on a remote server
    - Postprocess results to automatically generate reports/summary data files
  - Possibility to perform additional post-processing on individual results files using CFD Post

Setup on desktop → Run on local or remote computer → Report as html file
Meshing Approach

- **Current recognised terrain format**
  - SRTM, Shuttle Radar Topography Mission, freely available, 90m resolution (finer resolution in the US)
  - NTF, National Transfer Format, contour data (UK)
  - .map files (WAsP format)
  - Generic point data file (.csv)

- **Terrain converted to tesselated format (STL)**

- **Meshing with custom tools**
  - Fixed mesh structure, hexahedral mesh (5 or 9 blocks), aimed at process automation
  - Template mesh morphed onto STL terrain representation
  - Variable mesh topology for elongated/twin wind farms
Varying Mesh Topologies

Compact wind farm

Elongated wind farm

Twin wind farms
User can prescribe:
- horizontal resolution in central region
- Rate of horizontally expansion outside
- first layer cell heights in vertical
  ➔ Good control of mesh resolution in lower heights (ensures appropriate resolution is achieved in forested regions)
  ➔ Smooth vertical expansion above
Mesh Adaption on Wind Turbine Rotor

- Improve resolution by automatically refining mesh around the turbine location, from the specification of the rotor location and actuator disk parameters only
- Automatically enabled if wake model is used.
Setup

- Outer surface divided into 24 regions
  - 12 for inlet b.c. (Dirichlet on velocity)
  - 12 for outlet b.c. (entrainment conditions with prescribed static pressure)

- Setup automated to run for e.g. 12 wind directions

- Selection of surfaces defining inlet/outlet automated in script running cases for various wind directions

- meshing done only once
Flow Modelling in WindModeller

- **Atmosphere modelled as:**
  - incompressible fluid (Air at 15°C)
  - assuming neutral stability
  - solving for steady state RANS

- **Turbulence modelled via two-equation model**
  - Shear Stress Transport (SST) turbulence model or k-ε.

- **Ground modelled as rough wall (spatially variable roughness)**

- **Inlet boundary conditions**
  - Classical constant-shear ABL profiles (Durbin & Petterson Reif):

  \[
  u = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad k = \frac{u_*^2}{C_{\mu}^{1/2}} \quad \varepsilon = \frac{u_*^3}{\kappa z}
  \]

- **Additional physics:**
  - **Forest canopy model** (resistive term in momentum equation + additional source terms in turbulence model)
  - **Multiple wake model** (actuator disk model)
  - **Atmospheric stability** as beta feature
Wake Modelling

- Hierarchy of Wake Models available in ANSYS CFD
- Resolved blade models
- Virtual Blade Models
- Simple Actuator Disk Models
  - Provide practical model for calculations with many turbines
  - Input is turbine thrust curve, turbine diameter, turbine hub height
  - Provides momentum sink in cylindrical volume surrounding each turbine
  - Basis of Models for WindModeller
Simple Wake Model

- Wind turbine represented by
  - momentum sink
  - constant thrust per volume within
  - identified rotor disk.

- Wind turbine orientation parallel to wind direction at inlet

- Works on any type of mesh, although it is expected that the best results will be obtained with resolution that captures the wind turbine disk reasonably well

- User input:
  - Coordinates of hub location
  - WT diameter
  - WT thrust and power curve
As part of the automated approach WindModeller can generate:

- Plots of streamlines
- Identification of recirculation zones
- Plots at constant height AGL and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor
- Exported data tables of similar quantities at wind turbine/mast locations
- Export to Google Earth (.kml files)
- Automated report in html format
As part of the automated approach WindModeller can generate:

- Plots of streamlines
- Identification of recirculation zones
- Plots at constant height AGL and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor
- Exported data tables of similar quantities at wind turbine/mast locations
- Export to Google Earth (.kml files)
- Automated report in html format
As part of the automated approach WindModeller can generate:

- Plots of streamlines
- Identification of recirculation zones
- Plots at constant height AGL and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor, flow angles
- Exported data tables of similar quantities at wind turbine/mast locations
- Export to Google Earth (.kml files)
- Automated report in html format
As part of the automated approach WindModeller can generate:

- Plots of streamlines
- Identification of recirculation zones
- Plots at constant height AGL and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor, flow angles
- Exported data tables of similar quantities at wind turbine/mast locations
- Export to Google Earth (.kml files)
- Automated report in html format
As part of the automated approach WindModeller can generate:

- Plots of streamlines
- Identification of recirculation zones
- Plots at constant height AGL and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor, flow angles
- Exported data tables of similar quantities at wind turbine/mast locations
- Export to Google Earth (.kml files)
- Automated report in html format
As part of the automated approach, WindModeller can generate:

- Plots of streamlines
- Identification of recirculation zones
- Plots at constant height AGL and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor, flow angles
- Exported data tables of similar quantities at wind turbine/mast locations
- Export to Google Earth (.kml files)
- Automated report in html format
As part of the automated approach WindModeller can generate:

- Plots of streamlines
- Identification of recirculation zones
- Plots at constant height AGL and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor, flow angles
- Exported data tables of similar quantities at wind turbine/mast locations
- Export to Google Earth (.kml files)
- Automated report in html format, including the above
Post-Processing in WindModeller

- As part of the automated approach WindModeller can generate:
  - Plots of streamlines
  - Identification of recirculation zones
  - Plots at constant height AGL and profiles at wind turbine/mast locations for quantities such as normalised velocity, turbulence intensity, shear exponent factor, flow angles
  - Exported data tables of similar quantities at wind turbine/mast locations
  - Export to Google Earth (.kml files)
  - Automated report in html format, including the above
Wind Data Transposition Module

Simulations establish **climatological relationships** between wind conditions at mast (reference site) and WTG (predicted site).

Simulations are performed independently from the data collection at the mast.
Energy Assessment/Cross Prediction

- Wind data for input:
  - Time series or Frequency tables
- Allows for multiple masts and with / without wake calculations
- Can deal with heterogeneous wind farm
- Masts data collected before or after wind turbines installed
  → Possibility to do a post-mortem on an existing wind farm to understand performance issues of single WT if mast still measuring when wind farm is operational

Note: masts must be within simulation domain (no MCP)
Output from Data Transposition

- Tables of **Capacity Factors** (by directions and overall) summarising the average annual energy output at each WT.
- Wind speed distributions (**WAsP .tab files**) at WT and masts.
- Resource file (**WAsP .rsf**) at WT locations.
- Summary table with **average wind speed** at masts from cross prediction.
- Summary tables of **mean and representative turbulence intensity** by wind speed classes at masts and WT locations. (When working from time series, including the wind speed standard deviation as input).
Availability of WindModeller Tools

- Customised tools based on standard ANSYS CFD software under continuous development
- Driven by customer and project demands
  - Used on many cases
- Made available to customer on ‘service based approach’ via two stage process:
  - 1st phase: demonstration of capability on terrain chosen by customer
  - 2nd phase: Technology Transfer. Tools made available to customer, also includes one-to-one training, support and maintenance of the tools after delivery.
- Develop features on request.
Ongoing Projects

- **OWA Phase II**: integration of atmospheric stability and associated effects on large array losses

- **Carbon Trust POWFARMM project**: complex terrain, forestry, wakes, comparison with masts and Galion LIDAR data

- **Various consultancy projects recently completed for customers**
  - Pollution transport
  - Integration of buildings
  - More complex stability conditions (e.g. strong inversions, coastal low level jets)

- **Diversification into modelling of marine arrays** (TideModeller)
Summary

• CFD delivers increased accuracy for
  – Complex terrain/complex forestry cases
  – Estimation of large array losses

• Atmospheric stability improves accuracy compared to neutral cases, which tend to be used by other CFD packages in the industry

• ANSYS has a suite of tools (WindModeller) that helps you automate the simulation process, with state of the art models for
  – Forestry
  – Wakes
  – Atmospheric stability

• Validation material available to attest this.
Upcoming ANSYS Events

**ANSYS Events**

- **Webinar - Advanced Multi-body Hydrodynamics and Motion Analysis Using AQWA Software - 2012 Update**
  - Friday, 11th May 2012

- **All Energy in Aberdeen on May 23 & 24 - stand C111.**

**Question, Comments, Inquiries…**

- [ian.jones@ansys.com](mailto:ian.jones@ansys.com)

**Scheduled for 2012**

Information: [http://www.ansys.com/events](http://www.ansys.com/events)