Verification and validation of a real-time 3D-CFD wake model for large wind farms

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Subjective History of Wake Models

1968
Abramovich; Theory of Turbulent Jets; first wind farm representations in large scale numerical models.

1978
Lissaman, Vermeulen, Jensen; Analytical models, axes-symmetrical, empirical superposition; Implementation in PARK, WindPro

1988
Ainslie; 2D axes-symmetric model, verifications with full scale data Implementations: EVFARM, FLAP

1998
Commercial use of Ainslie model, first application to offshore wind farms Implementations in WindFarmer, WindFarm, WindPro and OpenWind

2008
Vindkraftnet: Special Wake Cases - Large wind farm model; Implementations in WindFarmer, OpenWind; Alternative Fuga

2018
Vindkraftnet: Development of 3D wake model; Implementations: WakeBlaster; WindModeller, Equivalent research models at DTU, UOL, ECN, UPM, TUD
The Modelling Challenge

- **Computational intensity**
  - **days**
  - **seconds**
  - **milli-seconds**

- **Fidelity**

- **Large-Eddy Simulation (LES)**
- **3D Reynolds-Averaged Navier-Stokes (RANS)**

Image Source: https://en.wikipedia.org/wiki/Large_eddy_simulation

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The Modelling Challenge

► Reduced wake loss uncertainty
► Increased level of detail and accuracy
► Reduced number of empirical approximations
► Resolve time dependencies (curtailments, ambient changes)
► Model wakes from up to 10,000 turbines in a wind farm
► Real-time operational performance scenarios
► Computational cost efficient even for layout optimisation
► Validation with full scale data
► Ready to deploy for industrial application
Commercial Boundary Conditions

Resources:
- Co-funding from the UK innovation agency, Innovate UK
- Developed during 10 months by team of 5
- Support with data from three major wind farm operators
- Additional data from IEA Task 31 Wakebench

NOT targeted:
- Dynamic representation (meandering, turbine loading)
- Turbine aerodynamics optimisation
WakeBlaster 3D wake model

- WakeBlaster development includes a 3D CFD solver of RANS equations.
- Real-time performance even with large wind farms.
Verification - Scalability

- Target: Practical for wind farms with up to 10000 wind turbine
- Target: Real-time capable for wind farm operation

Method applied: purpose built parabolic RANS solver on structured grid

Verified: Scales linear with number of turbines and can be parallelised
Verified: Cloud based SaaS solution - performance highly scalable
Verification - wake superposition

- Target: Linear arrangement leads to asymptotic solution
- Target: Improved representation of partial wakes
- Target: Weak wakes overlap to momentum deficit addition

Applied method: Model whole wind farm rather than single wakes

Confirmed Solution: Adequate superposition as part of the RANS solution
Verification - single wake

Target - reproduce wake profile for single WT (momentum, width and depth of profile)

WakeBlaster results compared to relative velocity profile at Nibe\textsuperscript{[2]}

Applied method: empirical momentum sink profile, based on turbine thrust coefficient $C_t$

Confirmed Solution: Adequate representation of profile

Simplification: current model not reproduce acceleration outside wake
Validation - overview

- Working with several partners providing historical SCADA data
- > 25 years of wind farm data
- > 15 wind farms
- > 450 wake scenarios prepared
- Offshore and onshore

Wake centreline velocity deficit - development downstream of a wind turbine. Multiple validation cases (+) and WakeBlaster simulation (x)
Validation - larger offshore wind farm

Target: reproduce directional wind farm production

Target: reproduce partial wake superposition at each turbine

Target: reproduce wakes turbine to turbine for linear arrangement

Method: data processed to power matrix and flow case extracted. Model calculation for average ambient inflow conditions. Example: Horns Rev wind farm in Denmark[1]

Solution: Match with full scale data achieved
Validation - compact offshore wind farm

Target: reproduce directional wind farm production

Target: reproduce partial wake superposition at each turbine

Target: reproduce wakes turbine to turbine for linear arrangement

Method: data processed to power matrix and flow case extracted. Model calculation for average ambient inflow conditions. Example: Lillgrund wind farm in Sweden[^1]

Solution: Match with full scale data achieved
Applications

Energy Assessment and Planning
- Fast and accurate wind farm model (stability, turbulence)
- Resolving time dependencies (seasonal, diurnal, hysteresis)
- Reduced uncertainties, curtailment strategies (environmental, technical, market)

Monitoring and Control
- Early detection of issues that require action
- Simulation of scenarios to optimise operation
- Simulate and implement wind farm control strategies

Short term forecasting and electricity trading
- Improved short term forecasting up to 30 min
- Accurate sensitivity scenarios and exceedance
WakeBlaster is developed by the ProPlanEn team: 6 experts with over 55 years experience in wind energy

The WakeBlaster development is co-funded by the UK’s innovation agency, Innovate UK. Additional support in kind is provided by major wind farm operators, thank you.


Contact: www.proplanen.com
Technical Details

Model
- RANS (Reynolds Averaged Navier Stokes) equations, incompressible
- Eddy Viscosity turbulence closure

Resolution
- Advanced actuator disc model
- Details resolved with 100 points over rotor area
- Structured regular grid 0.1D resolution
- > 50 000 000 nodes

Performance
- <10 sec for flow case of 100 turbines
- Delivered as cloud based service
- Open API for easy integration