Simulating wind turbine wake losses under stable atmospheric conditions with steady-state CFD: Challenges and solutions

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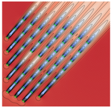
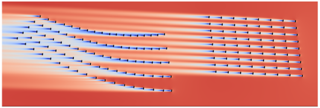
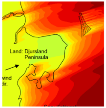

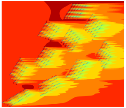

Introduction

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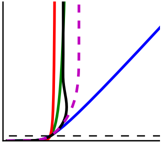
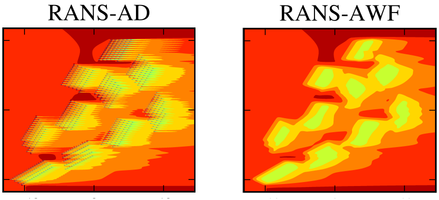
What I do

Atmospheric wind farm simulations using 3D Reynolds-averaged Navier-Stokes (RANS), Actuator Disk (AD) or Actuator Wind Farm (AWF) and terrain:

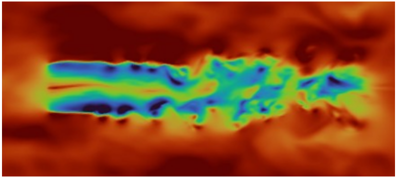




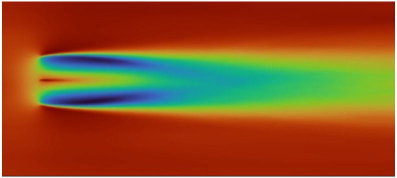
PyWakeEllipSys: https://topfarm.pages.windenergy.dtu.dk/cuttingedge/pywake/pywake_ellipsys/

What is RANS?

Single turbine wake snapshot from large-eddy simulation (LES)



Mean flow from many LES snapshots.

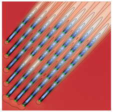


RANS: calculate mean flow directly from RANS equations.

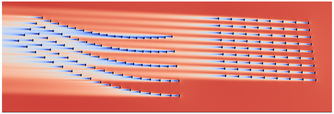
! Requires turbulence model for all scales.

7 Not trivial for multi-scale flow problems!

10^{-3}-10^{2} m



10^{3}-10^{4} m



10^{4}-10^{5} m

10^{5} m

Low- delity: Engineering wake models:

- ✓ Extremely fast (< 1s for an AEP calculation, 1 CPU).
- 7 Need to assume a wind turbine wake shape.
- 7 Need to assume a wake superposition method.

High- delity: Large-eddy simulation (LES):

- ✓ Wind farm ow is solved by mass and momentum eqns.
- ✓ Resolves all relevant large turbulence scales.
- 7 Requires long simulations time to obtain converged statist
- 7 Too expensive for AEP (1 day for 1 ow case, 100 CPUs)

Medium- delity: RANS:

- ✓ Wind farm ow is solved by mass and momentum eqns.
- ✓ Simulate mean ow quantities directly.
- ✓ 1 day for an AEP calculation, 100 CPUs.
- ✓ Suited to isolate atmospheric e ects.
- 7 Need to model all turbulence scales.

In ow & turbulence model

RANS in ow does not exist but could represent a mean:

RANS in ow = idealized atmospheric boundary layer.

In ow model is a solution of RANS model equations:

No downstream development of the in ow.

Turbulence model is often used to enforce this balance:

In ow model = turbulence model.

An active temperature equation cannot be used in most cases:

Active temperature equation) Unsteady RANS. [7]

ASL: Atmospheric surface layer<(100 m).

ABL: Atmospheric boundary layer (1 km).

MO: Monin-Obukhov Similarity Theory (Empirical ASL pro les including atmospheric stability).

k-": A two-equation turbulence model used to calculate the eddy viscosity.

Model	Type	Similarity	Stability	ABL height	Coriolis & veer
k-"	ASL	Re	-	-	-
k-" MO	ASL	Re	✓	-	-
...	...	...	...	...	...
k-" ABLc [1]	ABL	Ro	✓	✓	✓

[1] D. D. Apsley and I. P. Castro. \A limited-length-scale k-" model for the neutral and stably-strati ed atmospheric boundary layer". In: Boundary-Layer Meteorology (1997). doi : 10.1023/A:1000252210512 .

Model	Type	Similarity	Stability	ABL height	Coriolis & veer
k-"	ASL	Re	-	-	-
k-" MO	ASL	Re	✓	-	-
k-" ABLp [2]	ABL	Re and Ro	✓	✓	-
k-" ABLc	ABL	Ro	✓	✓	✓

[2] M. P. van der Laan, M. Kelly, and M. Baungaard. \A pressure-driven atmospheric boundary layer model satisfying Rossby and Reynolds number similarity". In: Wind Energy Science (2021). doi : 10.5194/wes-6-777-2021 .

- Momentum source representing a balance between a constant geostrophic wind speed (G) and Coriolis force.
- k-ε ABLp: Wind veer is removed by swapping U and V momentum sources and applying the same sign.[3]
- Global turbulence length scale limiter (ℓ_{max}) in the ε-equation, sets an ABL height implicitly.
- Use a numerical 1D inflow precursor (EllipSys1D).
  - Calculate a library of all possible non-dimensional solutions; model only depends on two non-dimensional numbers.
  - Interpolate a desired inflow (WS and TI at a reference height) from the library $\rightarrow$ G and ℓ_{max}, for a chosen roughness length and latitude.

[3] M. P. van der Laan, M. Kelly, and M. Baungaard. "A pressure-driven atmospheric boundary layer model satisfying Rossby and Reynolds number similarity". In: Wind Energy Science (2021). doi: 10.5194/wes-6-777-2021.

- Standardk-" model under predicts the velocity de cit by an overestimation of the wake turbulence length scale.
- k-"-f_P model is developed to overcome this (for neutral conditions) using a local turbulence length scale limiter.[4]

Figure: Nibe neutral single wake case.

[4] M. P. van der Laan et al. \An improved k-" model applied to a wind turbine wake in atmospheric turbulence". In: Wind Energy 18.5 (May 2015), pp. 889{907. doi: 10.1002/we.1736.

We couple the k-"-f_P model with the other in ow models:

- k-"-f_P MO model: modify f_P function to be in balance with MO.
- k-"-f_P ABL models: switch o global turbulence length scale limiter, where f_P function is active (blending function).

Figure: SWiFT (very) stable single wake case.[a]

[a] Paula Doubrawa et al. \Multimodel validation of single wakes in neutral and strati ed atmospheric conditions". In: Wind Energy 23.11 (2020), p. 2027. doi : https://doi.org/10.1002/we.2543 .

Challenges & solutions

Global length scale limiter, ℓ_{max}, sets the in ow ABL height.

- 7 ℓ_{max} can also limit wake recovery unphysically!
- 7 Switch o ℓ_{max} locally with a blending function is not robust.
- ✓ Solution: replace ℓ_{max} by an alternative ABL method: RANSL-.

RANS-N model[5]:

- No global length scale limiter.
- Employs a turbulent buoyancy source: $B = -\frac{\nu_T}{\sigma} N^2$.
  - ν_T: eddy viscosity.
  - σ: constant turbulent Prandtl number.
  - N: Brunt-Väisälä frequency.
- Reality: N varies with height since $N = \sqrt{\frac{g}{\theta_0}\frac{d\theta}{dz}}$
- RANS-N: we use a constant N by assuming a constant temperature gradient, $d\theta/dz$, over the entire ABL.
- This leads to a robust model where N can be used to set the ABL height implicitly!

[5] M. P. van der Laan et al. "A simple steady-state inflow model of the neutral and stable atmospheric boundary layer applied to wind turbine wake simulations". In: Wind Energy Science 9.10 (2024), pp. 1985–2000. doi: 10.5194/wes-9-1985-2024. url: https://wes.copernicus.org/articles/9/1985/2024/.

Horizontal lines: swept area of NREL-5MW turbine.

RANS-N simulations of 100 15 MW turbines (h_T = 268 m).

Waves appear to be numerical, not physical.

Waves grow with downstream distance.

Waves are not caused by the turbulence model equations.

Waves are not caused by oscillations of the Coriolis force.

Waves are not solver speci c.

Waves are probably caused by the momentum equation.
Too low eddy viscosity: RANS Navier-Stokes.

Add additional source terms in turbulence transport equations to arti cially increase eddy viscosity above the boundary layer.

Move the eddy viscosity layer towards the ground far downstream.

Lower ABL heights require stronger damping layers.

Too much damping can e ect the in ow.

Solution II: A damping method for RANS

Damping layer can remove/ reduce numerical waves.
Damping layer is not a solution for turbines operating around the ABL height.

Open questions

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What exactly is causing the numerical waves in RANS?

How to simulate turbines operating outside the ABL?