Wake modeling with the Actuator Disc concept

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WindSim AS

WindSim AS develops the software WindSim

WindSim is a CFD (Computational Fluid Dynamics) based Wind Farm Design Tool used to optimize energy production and reduce turbine loads

WindSim AS has been within the wind sector since 1997 offering the WindSim software and consulting services
Motivation – wake modelling

Wind farms get bigger and bigger. It has been a trend for several years and future offshore projects will most likely strengthen this trend for cost efficiency reasons.

Optimizing the cost efficiency for large wind farms is a indeed a challenge, where conflicting criteria within areal and resource planning have to be balanced.

In particular the reduced wind speeds and increased loading due to the wakes generated by each wind turbine is an important parameter in this respect.
Wake models – velocity deficit laws

Traditionally the wake models used within the wind industry have been based on so-called velocity deficit laws. These models reproduce reasonably well the reduced velocity in the wake region after one single wind turbine. However, when it comes to large wind farms the wake-wake interaction become important, which is not handled by these models.

Wind deficit: \[ \delta u(x) = U - V \]

The Velocity deficit laws are computational inexpensive, suitable for optimization purposes investigating many layouts.
Wake models – velocity deficit laws

1) Jensen model (Park model)

Oldest and simplest, often said to work well. The wake is supposed to expand like a cone, and the opening of the cone depends on the roughness-length at the turbine location.

2) Larsen model

More complex. It is obtained by integrating the momentum and continuity equations with a mixing-length turbulence model.

3) Ishihara et al. model

It was derived to model a wide range of situations, in theory to model sites with very low (offshore) and very high (complex terrains) turbulent intensities. It seems that the model has only partially achieved this goal, it normally estimates a higher wind deficit than the other two models.
Multiple wakes models

1. Linear sum of wake deficits (LS)

\[ \delta u = \delta u_1 + \delta u_2 + \ldots + \delta u_n \]

2. Root square of sum of squares of wake deficits (RSS)

\[ \delta u = \sqrt{\delta u_1^2 + \delta u_2^2 + \ldots + \delta u_n^2} \]

Where the wake deficits on the RHS of the equations are computed with single wake models.
Wake models – Actuator Disc Concept

Various new modelling techniques based on Computational Fluid Dynamics (CFD) is under development. We present a wake model based on the Actuator Disc Concept, aimed towards capturing the wake losses in large wind farms. Likewise, wake losses in complex terrain will benefit from this new approach with improved handling of the wake-terrain interactions.

Actuator Disc Concept handles:
• wake-wake interaction
• wake-terrain interaction
• thermal effects

Perspective view of the actuator disc, streamlines and iso surface of turbulent kinetic energy ($1.4 \, \text{m}^2/\text{s}^2$, $U_e \, 10 \, \text{m/s at 500m a.g.l.}$)
Actuator Disc Concept – Our first attempt in 2008

The thrust, momentum sink for the axial flow, is supposed evenly distributed on the swept area (uniform pressure drop)

\[ t = \frac{T}{A} = C_T \frac{1}{2} \rho u_\infty^2 \]

\[ T \approx \sum_i t_i = \sum_i \left( C_T \frac{1}{2} \rho u_\infty^2 \text{area}_i \right) \]

\[ t_i = C_{T,i} (u_{1,i}) \frac{1}{2} \rho \left( \frac{u_{1,i}}{1-a_i (u_{1,i})} \right)^2 \text{area}_i \]

Axial induction factor:

\[ a_i = \frac{u_\infty - u_i}{u_\infty} \]

By definition

\[ a = \frac{1}{2} \left( 1 - \sqrt{1-C_T} \right) \] Betz’s theory
Singel wake; comparisons with Wind Tunnel runs

Vertical profiles of normalized velocity from TNO Wind Tunnel tests (solid black lines), from Vermeer et al., predicted by the actuator disc CFD model (coloured lines).

![Graph showing vertical profiles of normalized velocity from TNO Wind Tunnel tests and predictions by the actuator disc CFD model.](image-url)
Singel wake; Comparisons with analytical models

Case a: $C_T = 0.80; z_0 = 0.03$ m (onshore)
Actuator Disc Concept – Status in 2008

• An actuator disc concept was applied to model a wind turbine in RANS simulations of a single WECS wake

• A uniform pressure drop was applied on the disc; the value of the pressure drop was calculated from the thrust coefficient and axial induction factor.

• Comparison with wind tunnel tests show that the wind deficit predicted by the CFD simulations is under predicted in the near wake at 2D diameters downstream, the level of wind deficit is correctly predicted at 6D downstream while in the far wake the wind deficit is overestimated.

• When comparing the presented actuator disc to some analytical models the best match is found with the Jensen Model.
Actuator Disc Concept – Tasks post 2008

Automatization of the process:
• Reading the wind farm layout from the layout (.ows) file
• Automatic generation of the grid
• Reading of the thrust curve from the power curve (.pws) file

Investigation of:
• Introduction of turbulence sources over the swept area
• Radial distribution of axial forces
• Methods for power extraction
• Rotational effects (swirling wake)
• Stability
• Nesting technique to improve the grid design
Single turbine: neutral cases, grid sensitivity

A grid sensitivity study is performed with 20, 10, 5 and 4 meters cell resolution in the turbine region, which in terms of rotor diameters are D/4, D/8, D/16 and D/20.

Resolution 20 meters, D/4

Resolution 10 meters, D/8

Resolution 5 meters, D/16

Resolution 4 meters, D/20
Single turbine: neutral cases, grid sensitivity

Wind speed, resolution 20 meters, D/4

Wind speed, resolution 5 meters, D/16
Conclusions of the grid sensitivity study:

1. A good level of grid dependency is reached with 16 subdivisions of the rotor diameter (in this case 5m);
2. There is a significant sensitivity on the method used to compute the power extracted by the disc.
Power extraction method – pressure

\[ \bar{u} \text{ is the bulk velocity over the swept area} \]

\[ \bar{u} \text{ is the velocity at the hub} \]

\[ \Delta p \text{ is the max pressure drop over the swept area} \]

\[ \Delta p \text{ is the max pressure drop along the centerline} \]

Power is approximately \( \bar{u} A_s \Delta p \)

where \( A_s \) is the swept area
Power extraction method – power curve

$\bar{u}$ is the bulk velocity over the swept area

Power curve corrected with axial-induction factor and Betz’s theory

Evaluate the power entering in the corrected power curve
Radial distribution of axial forces

Pressure and wind speeds for various radial distribution of axial forces
Generation of turbulence over swept area

Turbulent Kinetic Energy contour map at hub height [m²/s²]

Without source of turbulence (Ck = 0.0)  With source of turbulence (Ck = 0.01)

\[ S \approx \sum_i s_i \quad [\text{W}] \]

\[ s_i = C_k \rho |u_{1,i}|^3 \text{area}_i \]
Validation case: Horns Rev – Model

Horns Rev is an offshore wind farm located 13 km from the Danish coastline consisting of 80 wind turbines (Vestas V80)

Computational characteristics:
Resolution: D/4 (20 meter)
# cells: 1.5 M
RAM: 2-3 GB
Computational time: 2 hrs

Note: Grid resolution D/4 does not give grid independent solutions
Validation case: Horns Rev – Results 274°

Wind speed left (m/s) and turbulent intensity right (%) for case with incoming wind from 274° and wind speed of 10 m/s and TI of 6% at hub height.
Validation case: Horns Rev – Results 270°

Average production for all eight turbines in each column for case with income wind from 270° and wind speed of 6 m/s at hub height.
Validation case: Horns Rev – Model (3 columns)

Computational characteristics:
- Resolution: D/10 (8 meter)
- # cells: 5.0 M

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.
Validation case: Lillgrund

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

Summary

- Tests on single wakes
  - Neutral cases (grid sensitivity study)
  - Sensitivity to roughness (onshore/offshore)
  - Stable case (Monin-Obukhov length 100m)
  - Turbulence source at the rotor

- Tests on Horns Rev
  - Good behaviour in predicting the power ratio for the wide sectors
  - Meandering is not included in the simulations
  - Resolution issues - too coarse model (Resolution 20 meters, D/4)

- The actuator disc approach is promising – still more basic studies will be performed to adjust model constants
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