The impact of atmospheric stability on wake losses

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The impact of atmospheric stability on wake losses

Outline

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Introduction

- Analyses of full-scale measurements from Danish (offshore) wind farms have shown a significant dependence of wake losses on atm. stability conditions [e.g. L. Jensen; EWEC 2007]
- Horns Rev; 8m/s; 90 deg.; un-stable ctr. stable
Basic considerations

• Atmospheric stability affects turbulence level and turbulence structure
  
  o *Field data* from the OWEZ and the North Hoyle offshore wind farms demonstrates the importance turbulence structure only (binning: U; TI; stab. Class). Losses ~10% higher for VS than VUS [Keck et. al. 2012]
  
  o AL-LES *simulations* with OpenFOAM in neutral and very unstable atmospheric conditions and constant TI give similar results as based on WT power curve
Hypothesis (1)

- Free shear flows, as wakes, are usually "narrow" ... and we believe that the observed wake loss dependence on ABL stability conditions is primary dictated by a combination of:
  - Stability impacting the low frequency part of the atmospheric turbulence ... and thus the large-scale turbulent structures (driving the meandering)
  - Wake meandering being driven by large-scale turbulent eddies
Hypothesis (2)

VU: all scales

VS: all scales

VU: meandering scales

VS: meandering scales

VU: deficit scales

VS: deficit scales

$E(\sqrt{k_2^2 + k_3^2})$

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Model (1)

- Dynamic Wake Meandering (DWM) model approach for the wake flow field; i.e. based on a split in turbulent scales ... with
  - Small scales being responsible for wake *attenuation* and expansion; and
  - Large scales being responsible for stochastic *wake meandering* by moving wake “releases” as passive tracers in ABL turbulence
- Aeroelastic simulations (HAWC2) using DWM generated inflow conditions ... thus enabling *full aerodynamic representation* of rotor performance incl. *control* ... thus essentially the “Poor man’s LES ACL”
Model (2)
Model (3)

- Mann “classic” spectral tensor ... and a newly developed generalization including buoyancy effects (i.e. temperature effects) used to model turbulence:
  - One-point fits (i.e. sonic data)
  - Mann “classic” spectral tensor ($\alpha \varepsilon^{2/3}; \Gamma; L$) fitted to Høvsøre data ($vv$, $ww$ ... but excluding $uu$ and $uw$). Violating neutral stab. assumption!
  - Generalized spectral tensor ($\alpha \varepsilon^{2/3}; \Gamma; L; + 2$ additional parameters) fitted to Høvsøre data: Full Reynolds stress tensor ($uu$, $vv$, $ww$, $uw$, $tt$, $ut$, $wt$)
Model (4)
Model (5)
Model (6)

- ABL stability classified into 7 pre-defined stability classes (Obukhov length) [Pena et al.]:
  - Very stable: $10 \leq L < 50$
  - Stable: $50 \leq L < 200$
  - Near neutral/stable: $200 \leq L < 500$
  - Neutral: $|L| \geq 500$
  - Near neutral/unstable: $-500 < L \leq -200$
  - Unstable: $-200 < L \leq -100$
  - Very unstable: $-100 < L \leq -50$
Model (7)

- Spectral tensor parameters depend on height ... in this study the parameters for 60m is chosen
Definition of case (1)

- Nysted wind farm - 72 2.3 MW Siemens WT’s

- Meteorological data (U, direction): MM2
Definition of case (2)

- Relative production of second turbine in a wind farm row considered ... restricted to pairs A04/A14; A05/A15; A06/A16 to reduce large scale effects
- Mean wind speed bin: [8; 10] m/s
- Mean wind direction: Along row; i.e. $277.6^0 \pm 2^0$
- Turbine spacing (in this direction): 10.3 D
Simulation characteristics

• All observed mean wind directions within the selected direction bin simulated ... thus based on MM2 observations within $277.6^0 \pm 2^0$

• All observed mean wind speeds within the selected direction bin simulated ... thus based on MM2 observations in $[8; 10]$ m/s

• Thus, 555 A04/A14; A05/A15; A06/A16 wake cases simulated – each with different turbulence seeds
Results (1)

- DWM using "classic" Mann spectral tensor
Results (2)

- DWM using generalized spectral tensor

![Graph showing power ratio vs. stability class for NYSTED, rows 4-6, using Bulk-Richardson method. The graph compares measurements and simulations.](image)
Conclusions (1)

- Mann spectral tensor can be fitted to atmospheric stability conditions other than neutral ... if only turbulence components $v$ and $w$ is of interest
- However, low frequency part of $U$ and $VU$ spectra should be investigated in more detail ... measured as well as simulated
- The generalized spectral tensor fitted to the full 4x4 Reynolds stress tensor (i.e. $uu$, $vv$, $ww$, $uw$, $tt$, $ut$, $wt$) performs qualitatively as the “restricted” fit of Mann spectral tensor ... although some differences in the case of $U$ and $VU$ conditions are observed
Conclusions (2)

- General trend in power ratio is captured ... but simulated power ratio is less than the measured values, although within the uncertainty band defined by $\pm \sigma$
- Deviation in power ratio level may be related to differences in turbine pitching

- Simulated relative effect of ABL stability also very similar to full scale observations from the OWEZ and North Hoyle studies (i.e. wake losses $\sim 10\%$ higher for VS than VUS)
Future work

- Analysis of production losses of all turbines in a row for the simple along-row flow case
- Analysis of more complex flow cases, where the mean wind direction forms an angle (different from zero) with the direction of the rows – i.e. “oblique” inflow
- Analysis of wind farm production losses integrated over all (mean) wind directions
- Investigation of fatigue load dependence on ABL stability
- Experimentally based determination of meandering pattern’s for various stability conditions as based on the Risø Tellus 2D LiDAR experiment
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