Loads in wind farms under non-neutral ABL stability conditions: A full-scale validation study of the DWM model.

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Loads in wind farms under non-neutral ABL stability conditions – a full-scale validation study of the DWM model

G.C. Larsen, T.J. Larsen, Søren Ott and K.S. Hansen

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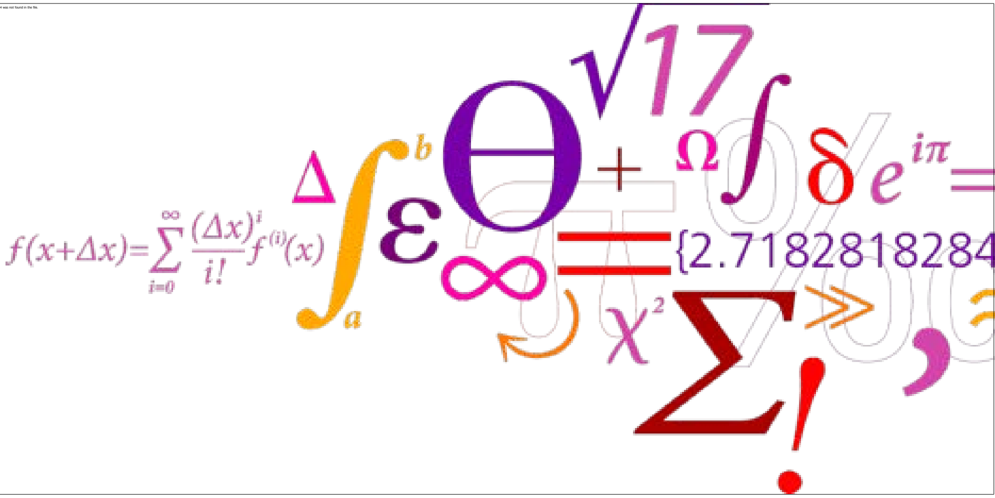
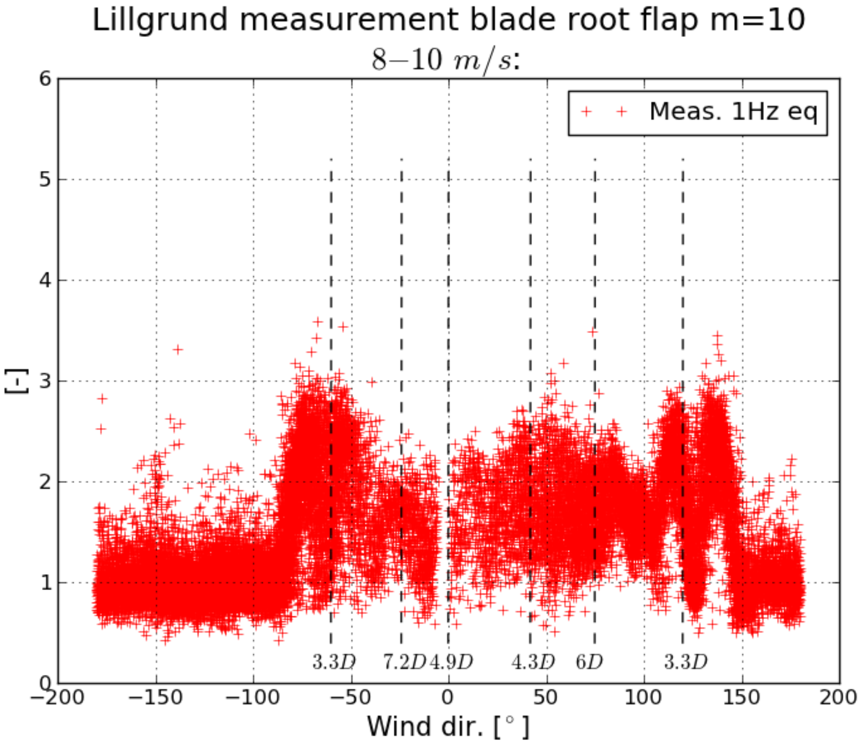


DTU Wind Energy
Department of Wind Energy

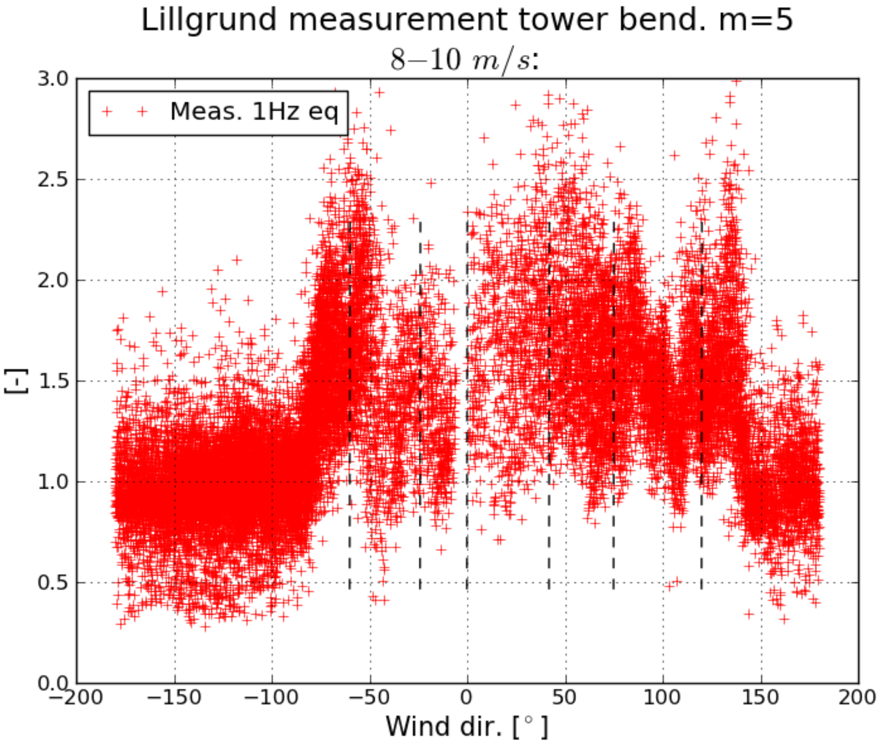
Outline

- Motivation
- Hypothesis … ABL stability
- DWM “classic”
- Approach … DWM under non-neutral stability conditions
- Lillgrund WF case study
  - Layout
  - Stability classification
  - Results
  - Summary
- Conclusions
- Future work
- Acknowledgements

Motivation (1) … why non-neutral?


Lillgrund measurement blade root flap m=10

8–10 m/s:


Lillgrund measurement tower bend. m=5

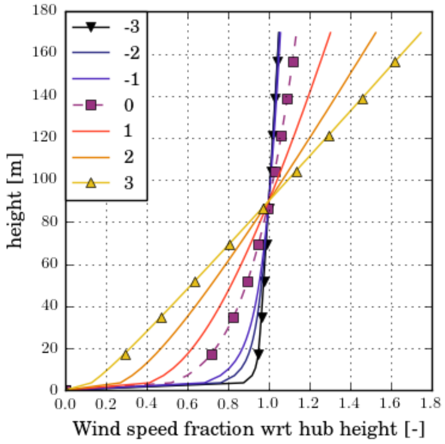
8–10 m/s:

Motivation (2) … why medium fidelity?

- Non-stationary flow fields are required for WT load estimation
- High-fidelity CFD-LES modeling is CPU-costly and challenged by boundary conditions … and a coupled aeroelastic/CFD-LES approach is **not** feasible for a large number of WF simulations!
- Need for medium-fidelity flow field models that
  - Preserves the essential physics of non-stationary wake flows
  - Is (relatively) in-expensive
  - Allow for a straight forward coupling with aeroelastic models

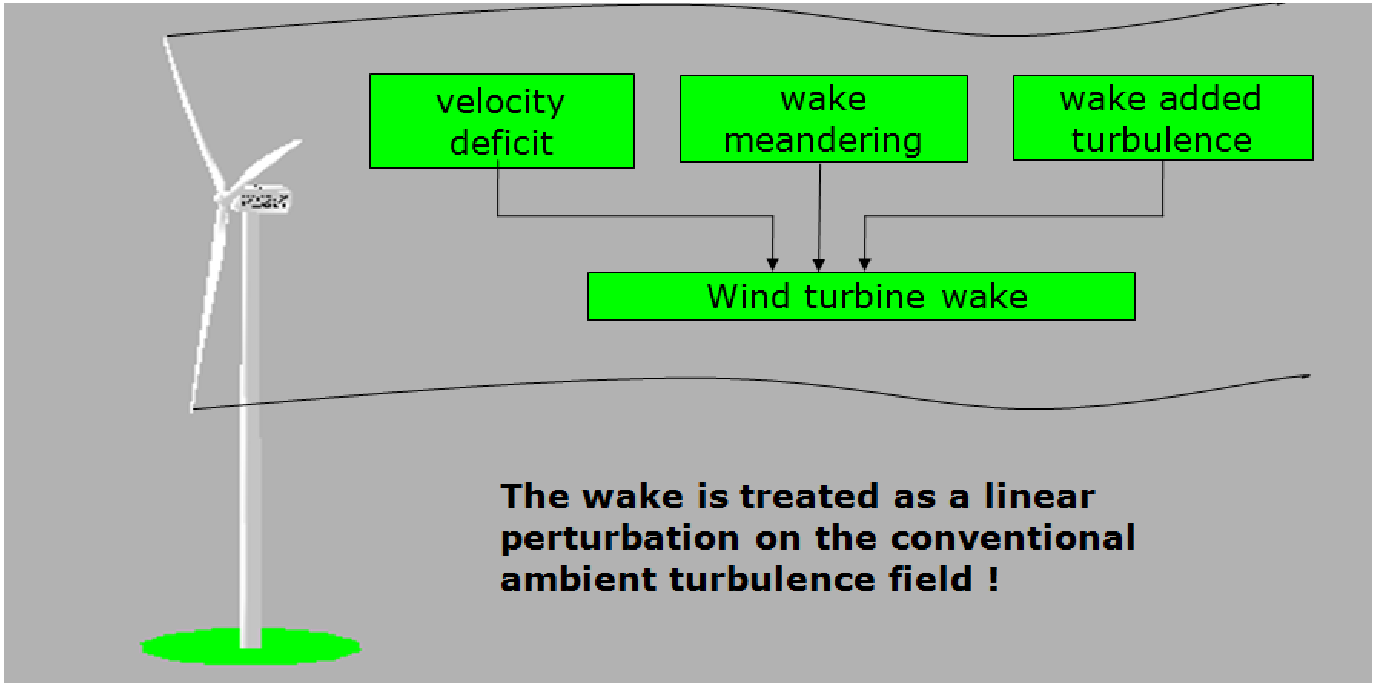
ABL stability

- Mechanical friction is dictating turbulence production in the ABL under neutral conditions
- Buoyancy effects adds to friction when it comes to the turbulence production under non-neutral ABL stability conditions
- ABL stability implications
  - Increased/decreased turbulence intensity for unstable/stable conditions
  - Modified turbulence structure … mainly in the large scale regime
  - Modified shear profile



DWM “classic”

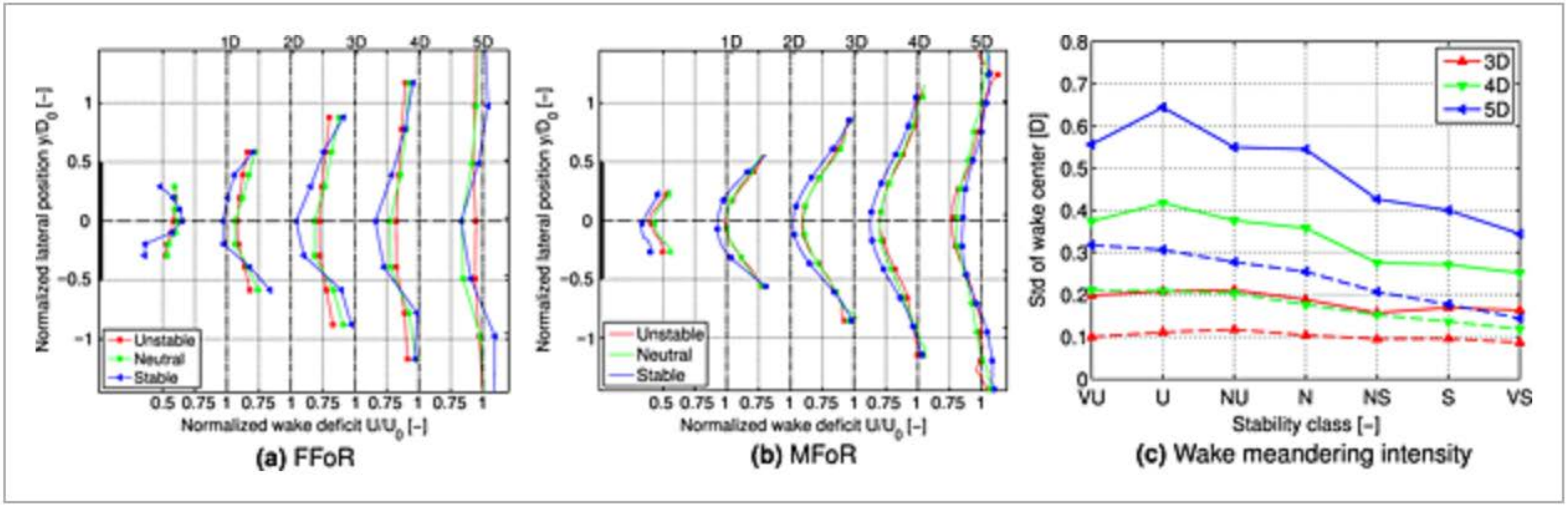
- Included in the IEC-code as recommended practice
- “Poor man’s LES” … based on a passive tracer analogy
  [Larsen GC et al.; Wake meandering – a pragmatic approach; WE]



The wake is treated as a linear perturbation on the conventional ambient turbulence field !

DWM under non-neutral stability conditions (1)

- Full-scale LiDAR experiments [Machefaux et al., WE; Larsen et al., Journal of Physics] have justified:
  - *ABL stability impacts mainly the “large” (meandering) turbulence scales*
  - “small” scale turbulence regime can be considered invariant with respect to ABL stability conditions



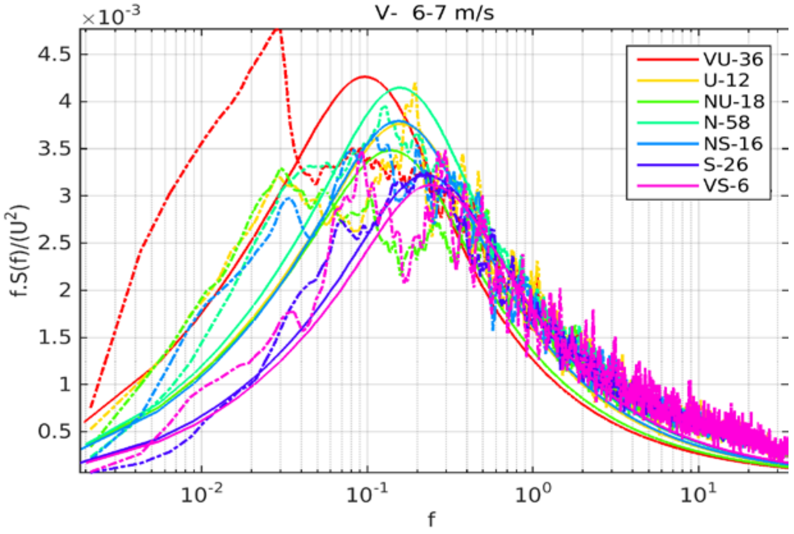
(a) FFoR

(b) MFoR

(c) Wake meandering intensity

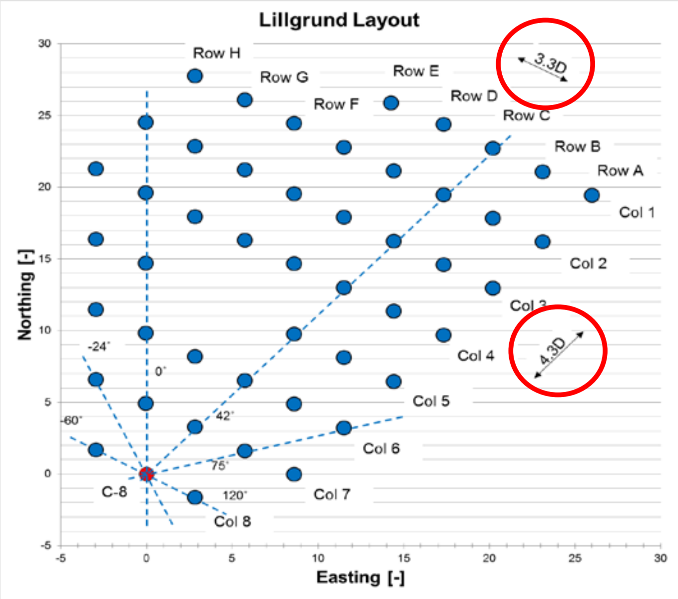
DWM under non-neutral stability conditions (2)

- Synthetic turbulence fields are generated using a generalization of the Mann spectral tensor
  [Chougule A, Mann J, Kelly MC and Larsen GC; JAS]
  - Buoyancy included!
  - Homogeneous velocity and temperature fields
  - Turbulence production driven by vertical shear and a vertical temperature gradient



Case study – Lillgrund WF

- Blade flap and tower bottom moments
- Turbine C-8
- 2008-06-03 to 2013-03-19 … almost 5 years of data
- Un-stable, neutral and stable ABL conditions in focus … but met. mast is missing ☹



Case study – the Drogden supplement

- Offshore light tower … a few km. WNW of the WF (about the characteristic scale of the WF)
- Available 10-min recordings
  - U and T_a at h = 22m
  - T_w at h = -1m
  - Appr. 15.600 hours of measurements (2008–2013)

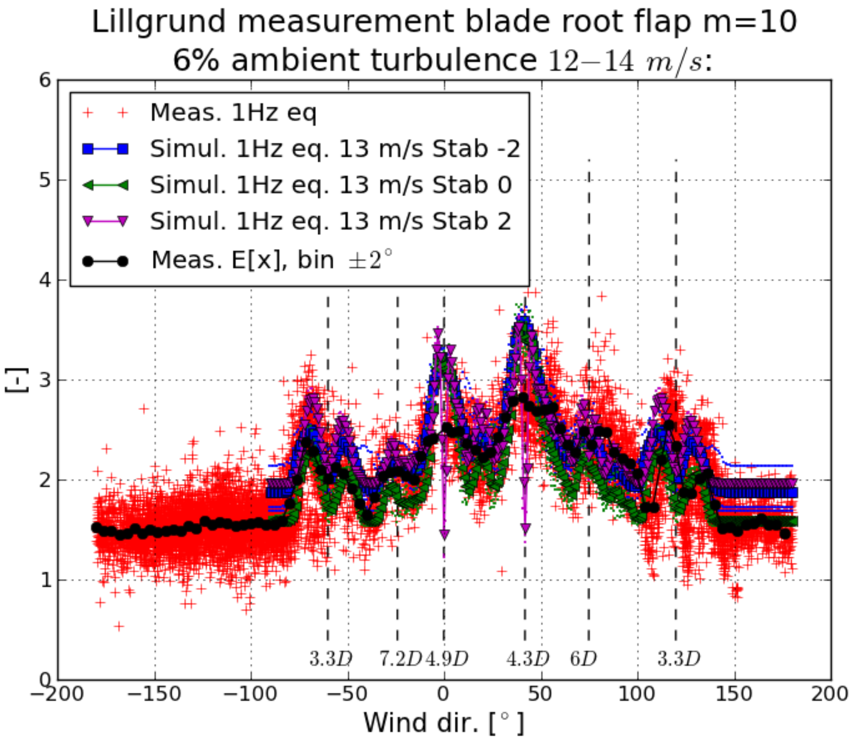
Case study – stability classification

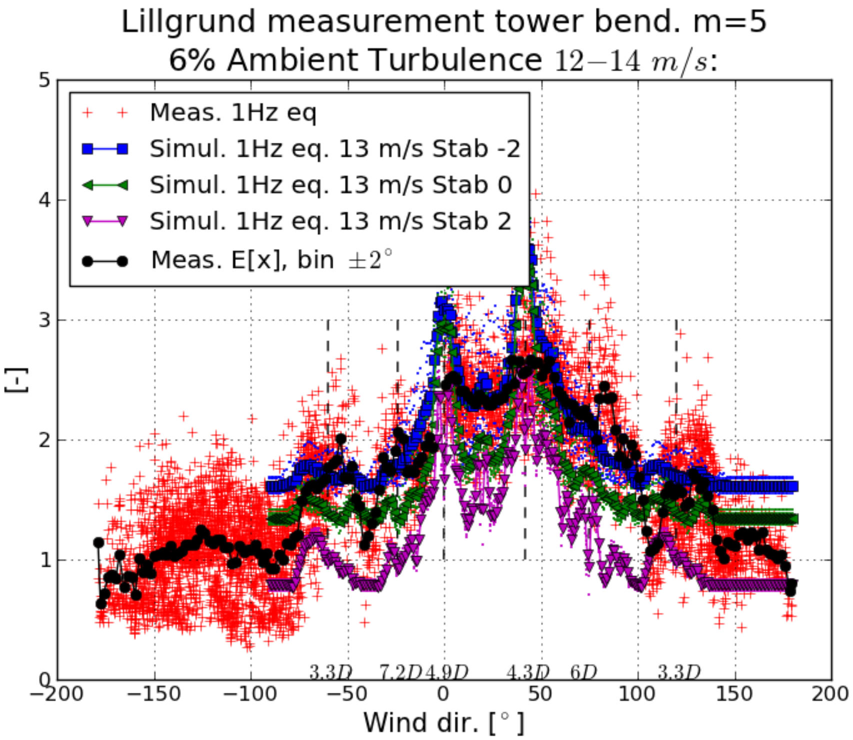
- AMOK approach for offshore sites [Larsen GC et al.; Impact of atmospheric stability conditions on wind farm loading and production; DTU report]
  - Based on a newly developed version of the M-O theory suited for ‘tall’ profiles
  - Profile functions $\psi_m(z/L,\mu)$ and $\psi_h(z/L,\mu)$ are complex with an unstable branch for $z/L < 0$ and a stable branch for $z/L > 0$ … μ Monin-Kazanski parameter
  - Needs: T_a, U, T_w … e.g. from different heights
- Stability classes (1/L) [Gryning et al.; BLM **124**]

Stability Class iC	Description	Condition
-2	unstable	$-200\text{m} < L < -100\text{m}$
0	neutral	$500\text{m} < \lvert L \rvert$
2	stable	$50\text{m} < L < 200\text{m}$

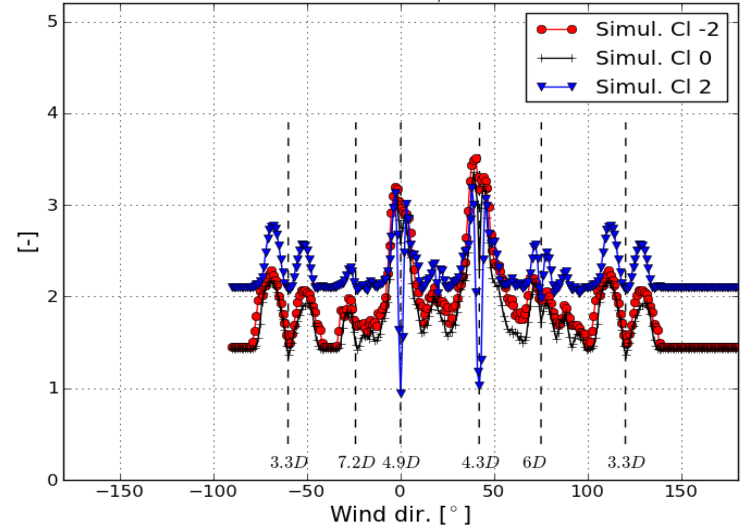
Case study – Results (1)

- Flap and tower bottom fatigue equivalent moments
  - 13m/s:

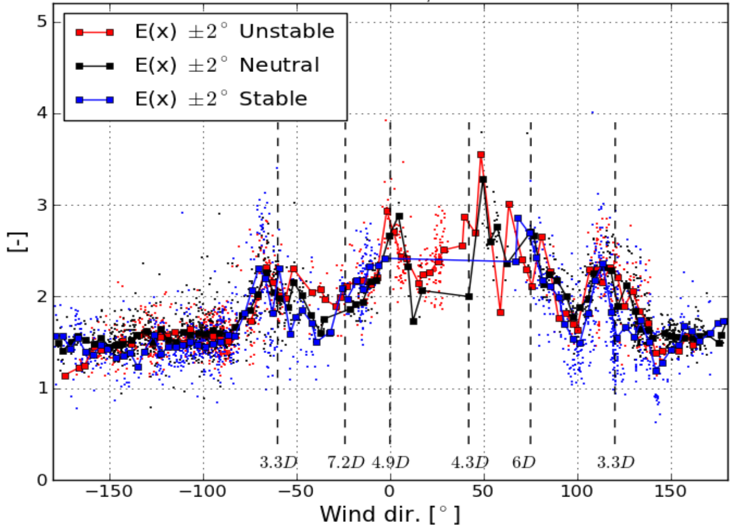




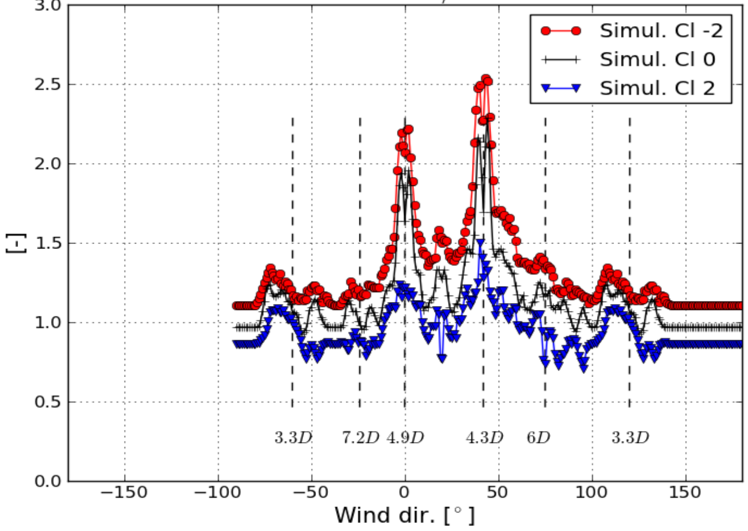
Case study – Results (2)


Lillgrund simulations blade root flap m=10

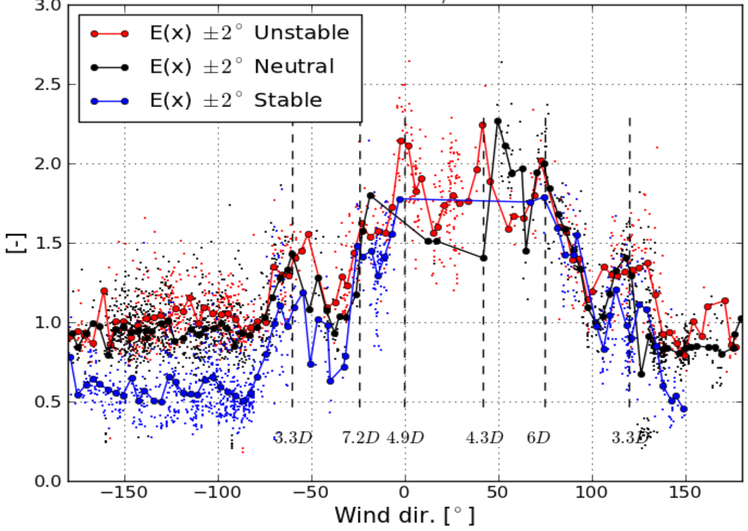
$12-14\ m/s$:


Lillgrund measurement blade root flap m=10

$12-14\ m/s$:

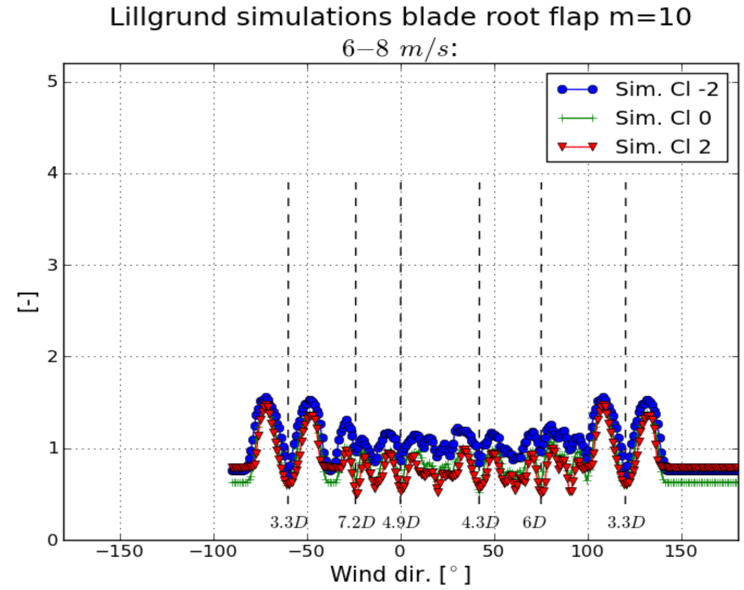

Lillgrund simulations tower F-A bottom m=4

$12-14\ m/s$:

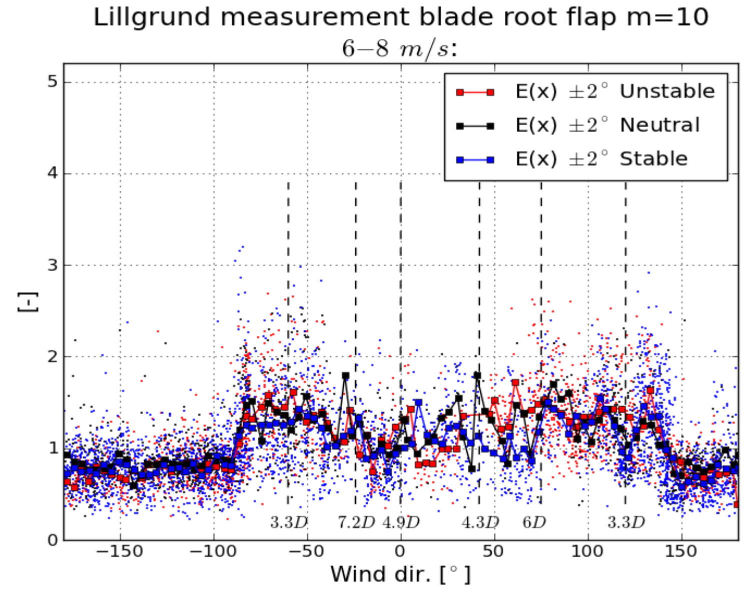

Lillgrund measurement tower F-A bottom m=4

$12-14\ m/s$:

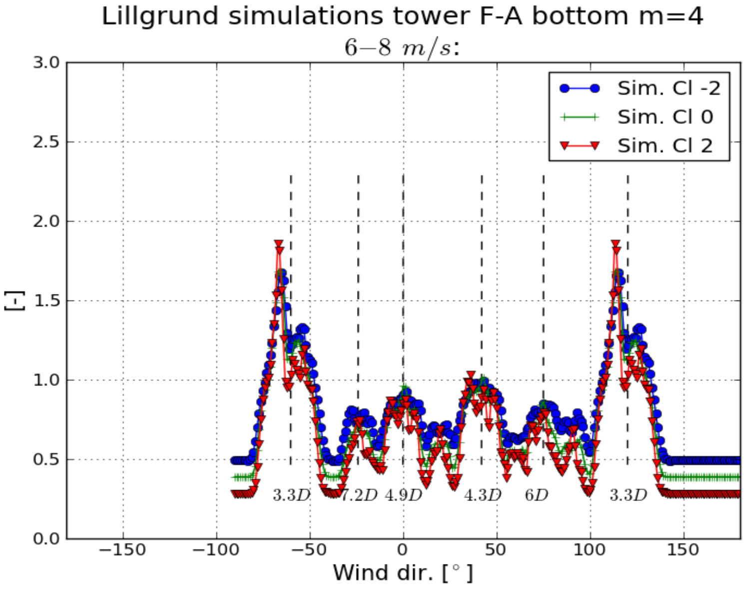
Case study – Results (3)


Lillgrund simulations blade root flap m=10

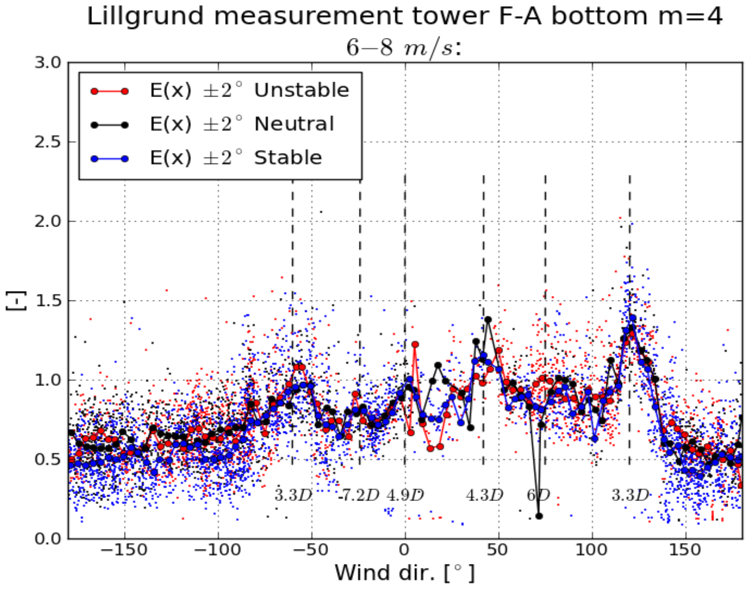
$6\text{–}8\ m/s$:


Lillgrund measurement blade root flap m=10

$6\text{–}8\ m/s$:


Lillgrund simulations tower F-A bottom m=4

$6\text{–}8\ m/s$:


Lillgrund measurement tower F-A bottom m=4

$6\text{–}8\ m/s$:

Conclusions (1)

- A medium-fidelity non-stationary flow field approach for non-neutral ABL conditions is established and coupled with the aeroelastic code HAWC2
- The approach is CPU in-expensive compared to high-fidelity CFD LES ... and is potentially useful for WF layout optimization and WT control design (TOPFARM)
- Simulations:
  - For the rotating WT components the ABL stability impact on shear and turbulence has contra-acting influences on loading
  - Shear is the dominating fatigue load driver for the rotating WT components in the high wind regime ... otherwise turbulence incl. wake meandering

Conclusions (2)

- Simulations:
  - Turbulence incl. wake meandering is the dominating load driver for tower fatigue loading
  - These observations are consistent with a load study of a solitary WT [A. Sathe et al., WE] ... but ABL stability impact on loading further enhanced in WF conditions due to wake dynamics
- Measurements:
  - Agrees reasonably well with simulations ... BUT the significant dependence of blade loading with shear is not seen!
  - Some uncertainty on mean values ... e.g. not “perfect” symmetry of 3.3D cases

Future work

- Replace classic M-O profile functions with profile functions following from the modified version of the M-O theory suited for ‘tall’ profiles … which displays less pronounced shear in the stable regime BUT include veer
- Example quantification of stochastic variability … 20 seeds for one arbitrary wake affected inflow condition
- Mutual comparison of DTU (DWM/HAWC2) simulations, KUL (SPWind) simulations and full-scale Lillgrund measurements … power; flap fatigue loading; tower, fatigue loading
- Consolidate Drogden based stability classification with WRF-simulations
- Inclusion of meso-scale effects in the DWM model approach … the high frequency end of the meso-scale regime

Acknowledgements

The EUDP project “Impact of atmospheric stability conditions on wind farm loading and production”, under contract 64010-0462, is acknowledged for financial support and thus for making this study possible.

Siemens Wind Power is acknowledged for making the Lillgrund full scale load measurements available for this study.