Technical University of Denmark

# The impact of atmospheric stability on wake losses

**Larsen, Gunner Chr.; Larsen, Torben J.; Hansen, Kurt Schaldemose; Chougule, Abhijit S.; Mann, Jakob; Aagaard Madsen , Helge**

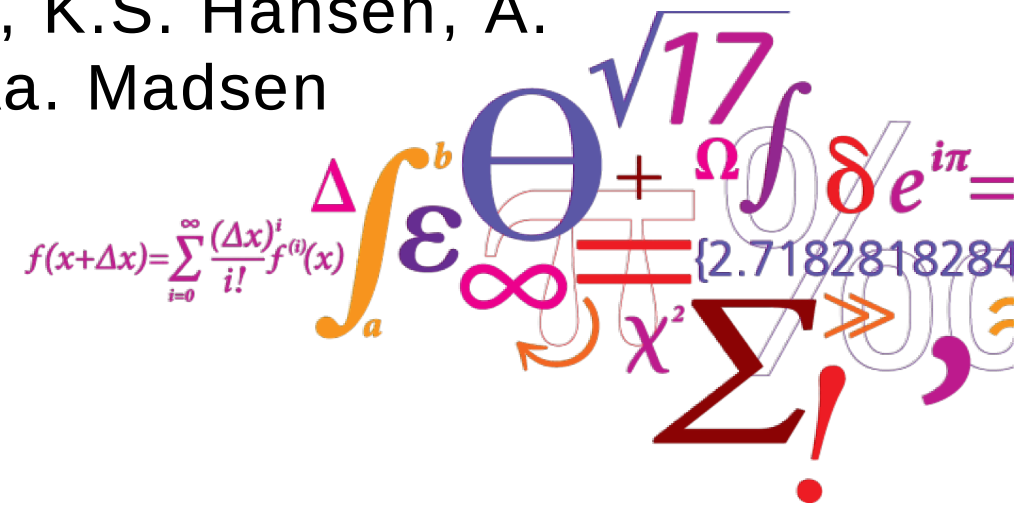
*Publication date:*
2013



*Citation (APA):*
Larsen, G. C., Larsen, T. J., Hansen, K. S., Chougule, A. S., Mann, J., & Aagaard Madsen , H. (2013). The impact of atmospheric stability on wake losses [Sound/Visual production (digital)]. International Conference on aerodynamics of Offshore Wind Energy Systems and wakes (ICOWES 2013), Lyngby, Denmark, 17/06/2013

# The impact of atmospheric stability on wake losses

G.C. Larsen, T.J. Larsen, K.S. Hansen, A. Chougule, J. Mann, H. Aa. Madsen



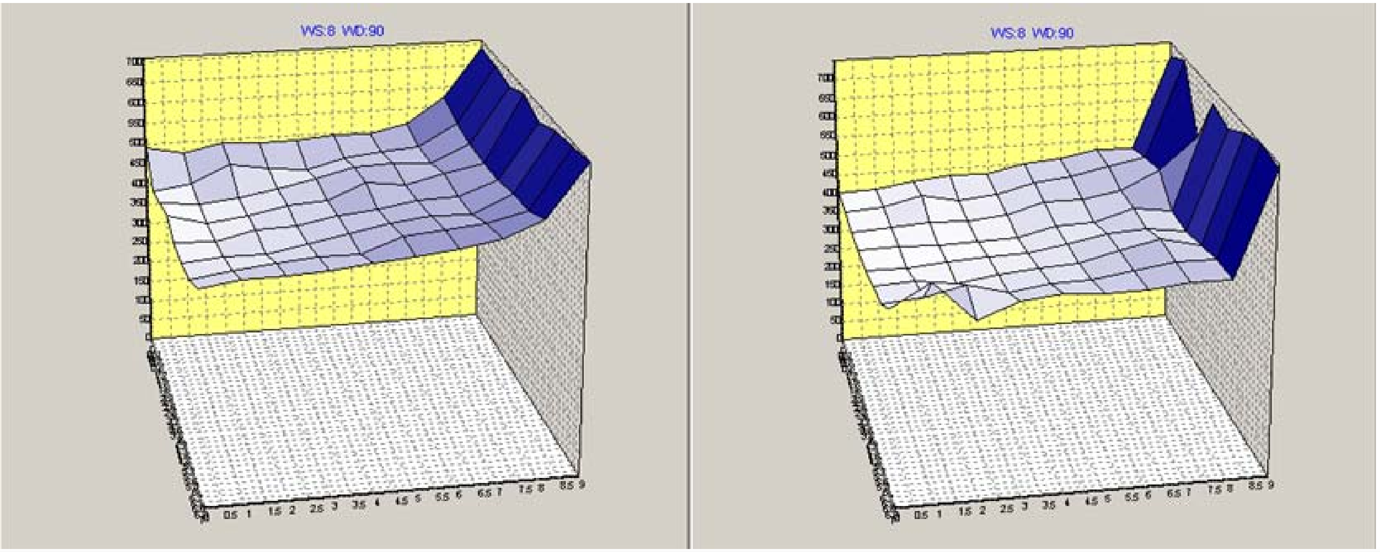
DTU Wind Energy
Department of Wind Energy

# Outline

- Introduction
- Basic considerations
- Hypothesis
- Model
- Definition of case
- Simulation characteristics
- Results
- Conclusions
- Future work
- Acknowledgements

# Introduction

- Analyses of full-scale measurements from Danish (offshore) wind farms 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



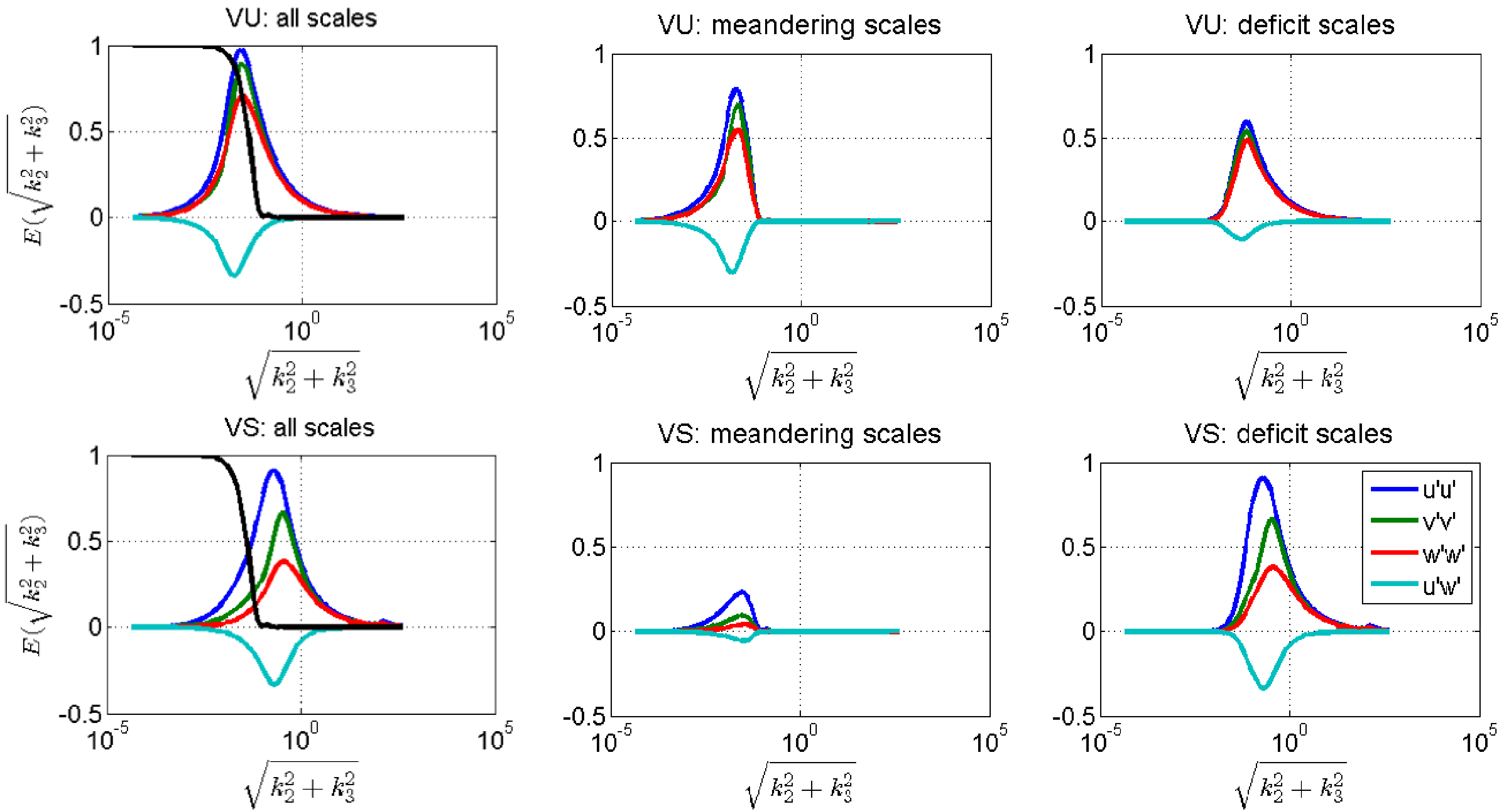
# Basic considerations

- Atmospheric stability affects turbulence *level* and turbulence *structure*
  - *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]
  - 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

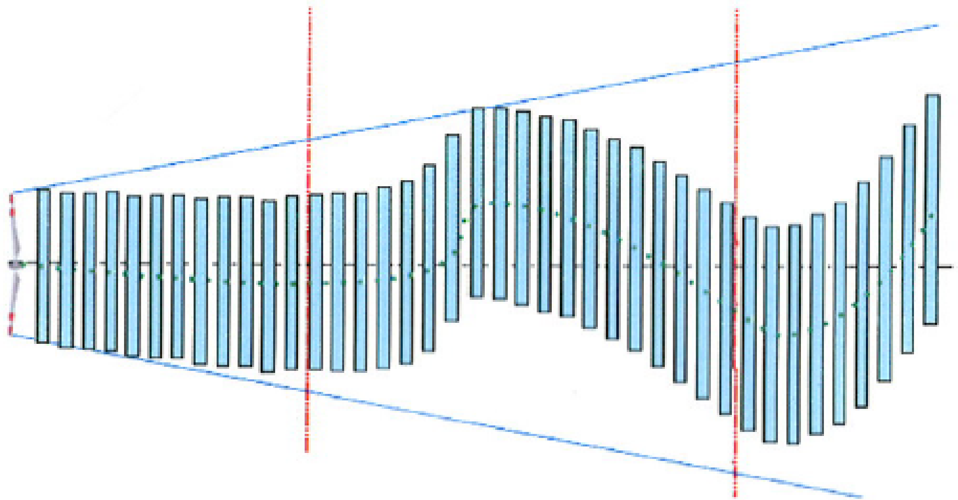
# Hypothesis (2)



# Model (1)

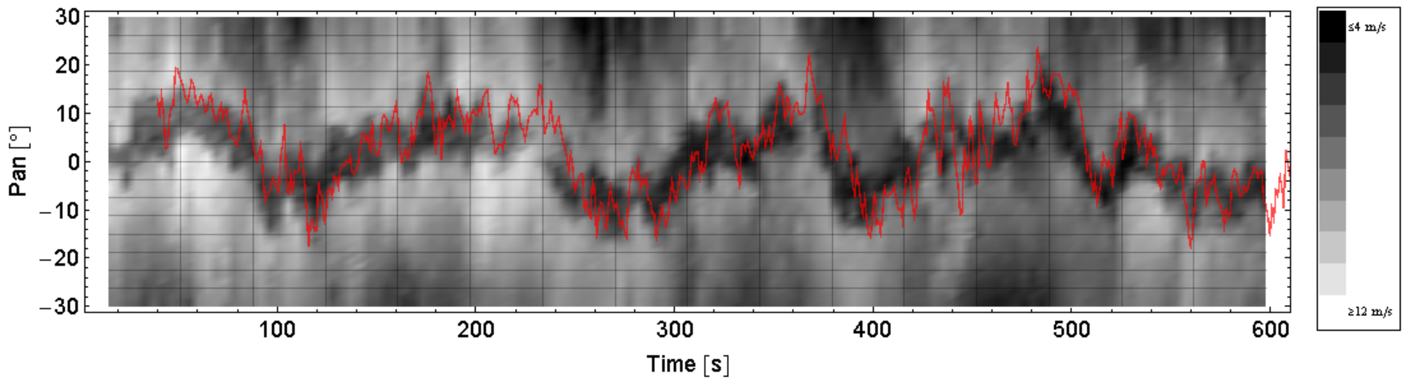
- Dynamic Wake Meandering (DWM) model approach for the wake flow field; i.e. based on a split in turbulent scales … with
  - Small scales being responsible for wake *attenuation* and expansion; and
  - Large scales being responsible for stochastic *wake meandering* by moving wake "releases" as passive 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)



Date 2005–11–15 Time 21:20 Number of Scans 78501

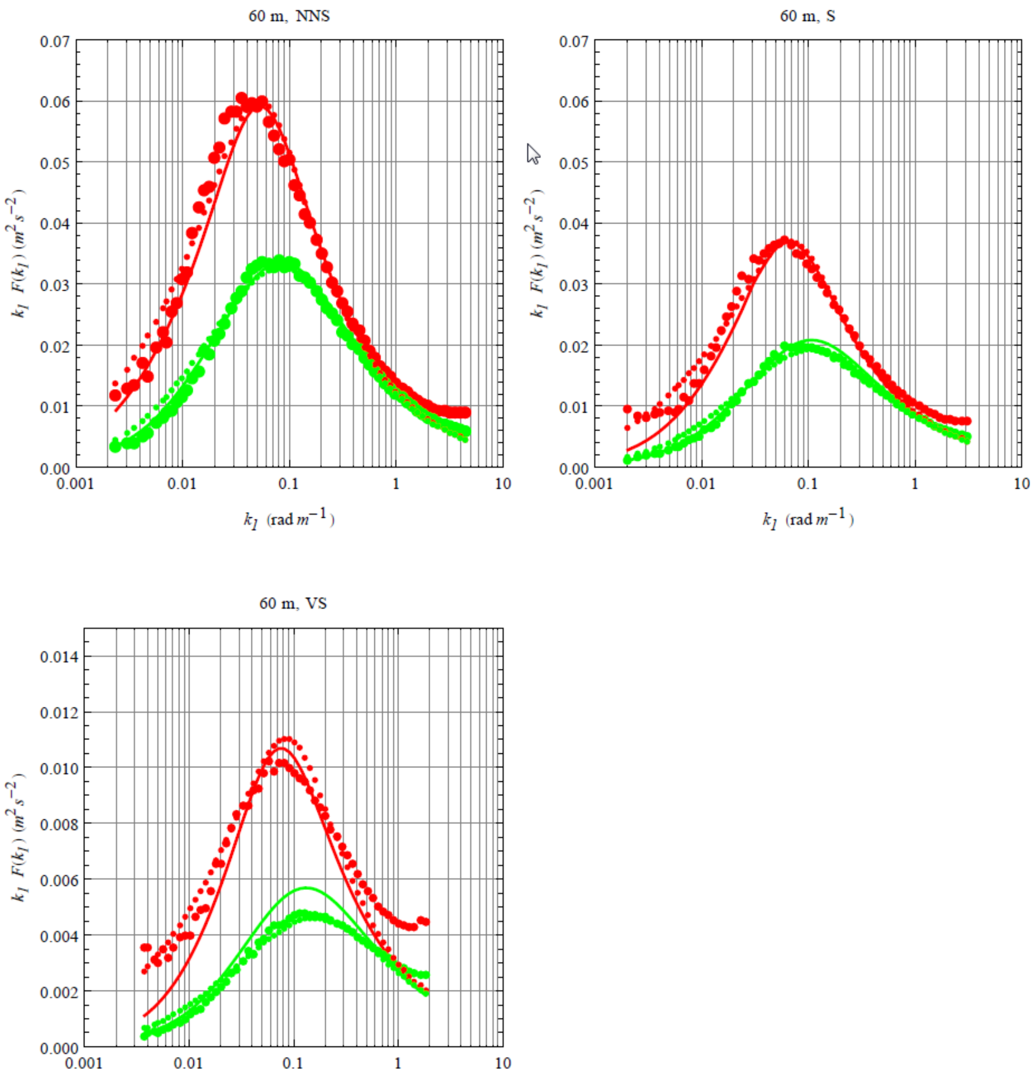
| LiDAR | | | | Turbine | | | | Met.Mast | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WS [m/s] | | | | Yaw [°] | | | | WS [m/s] | | | | WD [°] | | | |
| Mean | Min | Max | StdDev | Mean | Min | Max | StdDev | Mean | Min | Max | StdDev | Mean | Min | Max | StdDev |
| 7.76 | 3.07 | 13.10 | 1.56 | 279.0 | 258.0 | 296.0 | 5.6 | 8.74 | 5.43 | 12.40 | 1.37 | 277.0 | 265.0 | 289.0 | 6.0 |



# Model (3)

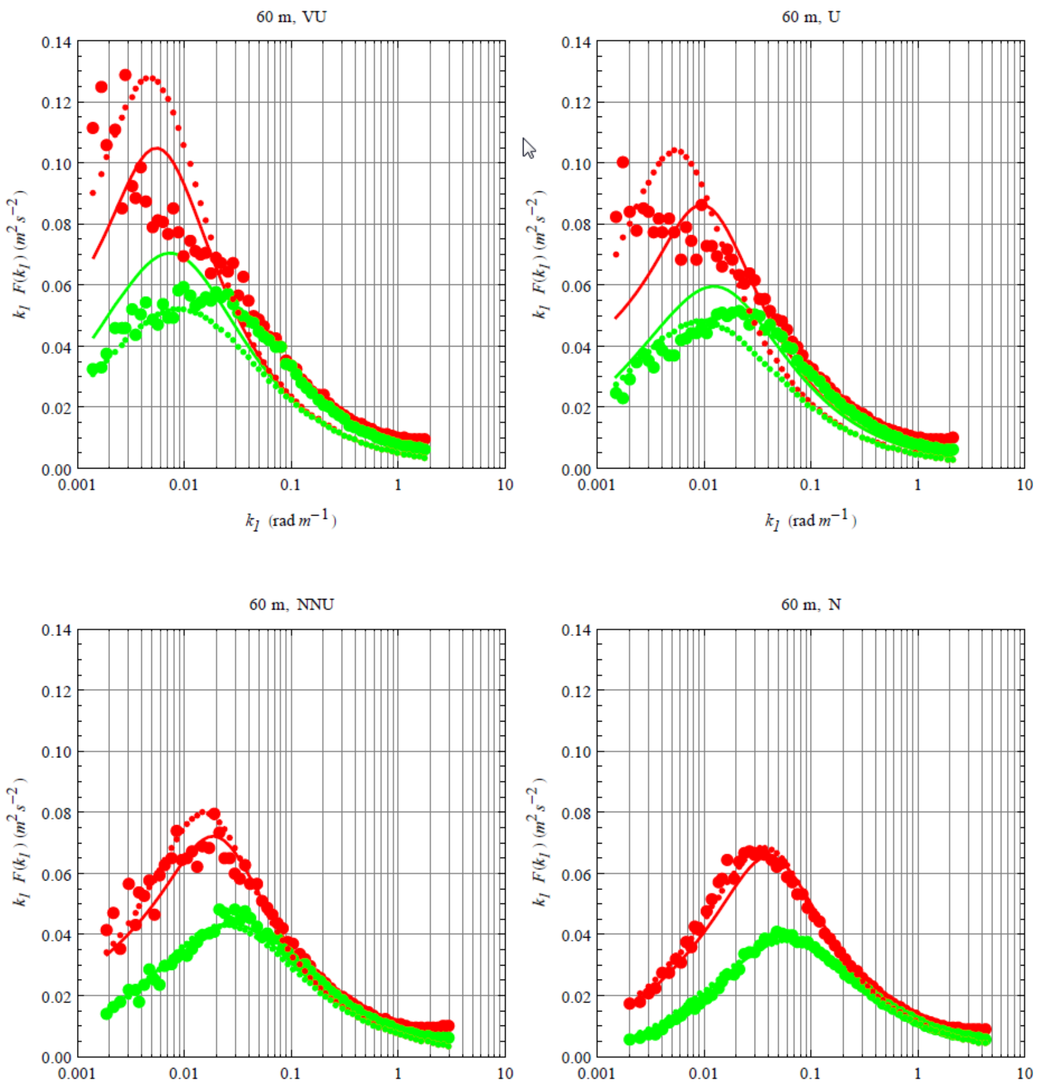
- Mann “classic” spectral tensor ... and a newly developed generalization including buoyancy effects (i.e. temperature effects)  used to model turbulence:
  - One-point fits (i.e. sonic data)
  - Mann ”classic” spectral tensor ($\alpha\varepsilon^{2/3}$; Γ; L) fitted to Høvsøre data (*vv*, *ww* ... but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

# Model (4)



60 m, NNS
60 m, S
60 m, VS
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0.001
0.01
0.1
1
10
$k_1$ (rad $m^{-1}$)
$k_1$ $F(k_1)$ ($m^2 s^{-2}$)

# Model (5)

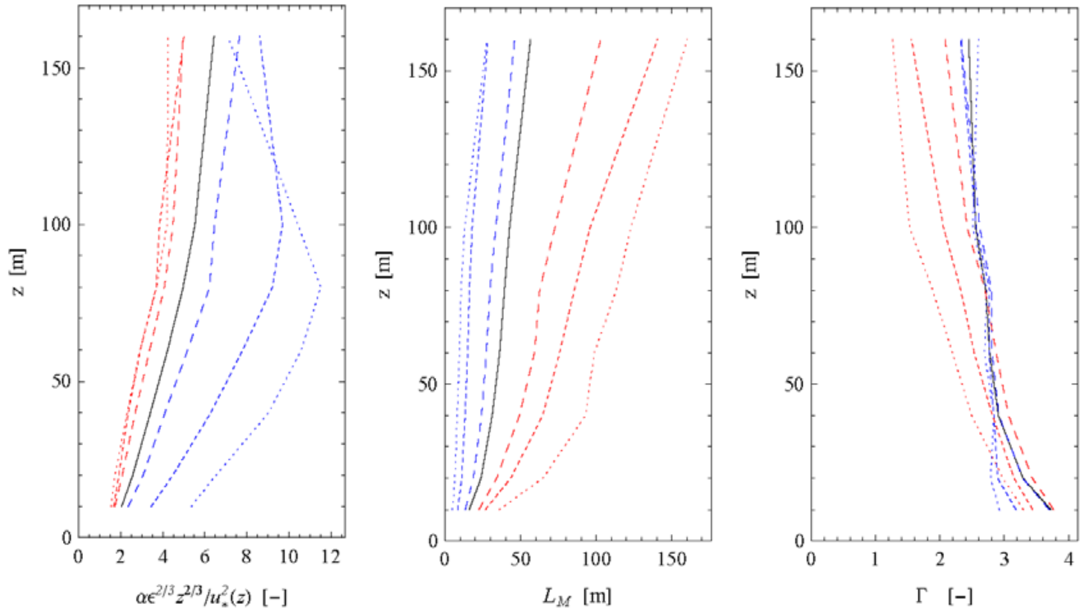

60 m, VU
60 m, U
60 m, NNU
60 m, N
$k_1\ F(k_1)\ (m^2 s^{-2})$
$k_1$ (rad $m^{-1}$)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.001
0.01
0.1
1
10

# 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: $-100 < L \leq -50$

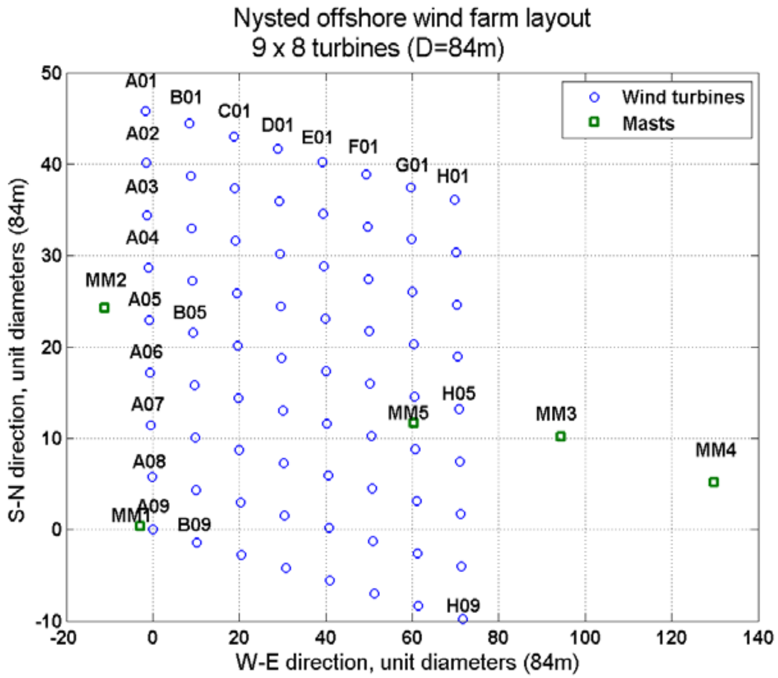
# Model (7)

- Spectral tensor parameters depends 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)

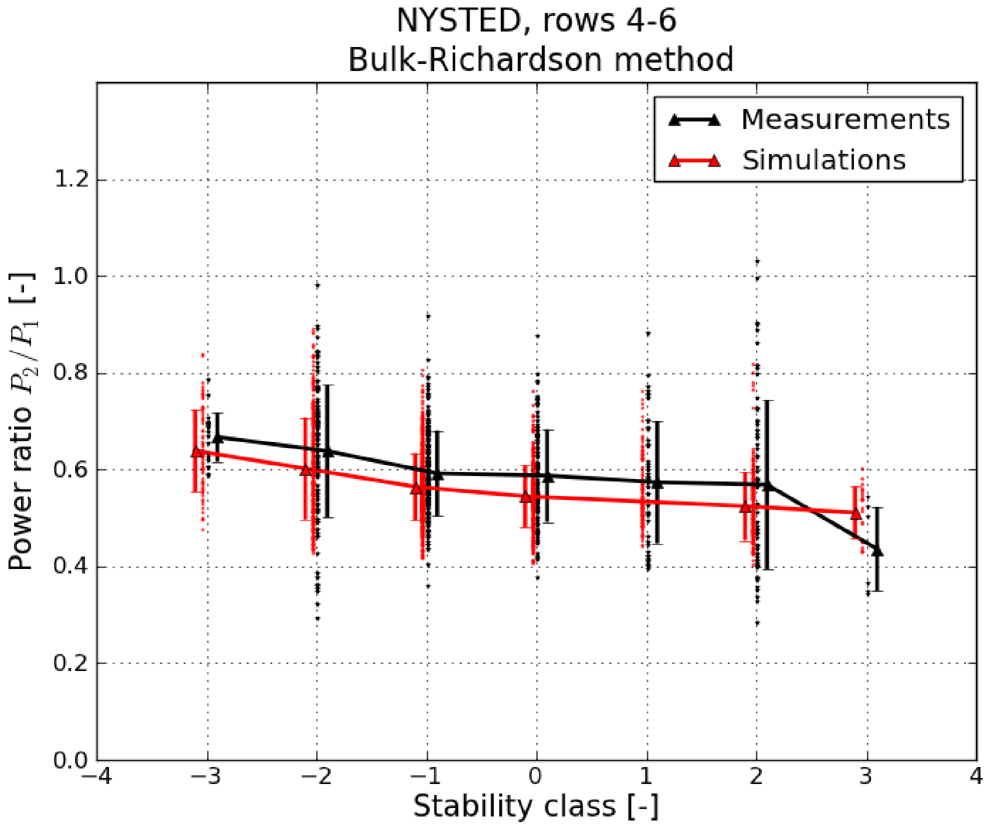
- Relative production of second turbine in a wind farm row considered ... restricted to pairs A04/A14; A05/A15; A06/A16 to reduce large scale effects
- Mean wind speed bin: [8; 10] m/s
- Mean wind direction: Along row; i.e. $277.6^0 \pm 2^0$
- Turbine spacing (in this direction): 10.3 D

# 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

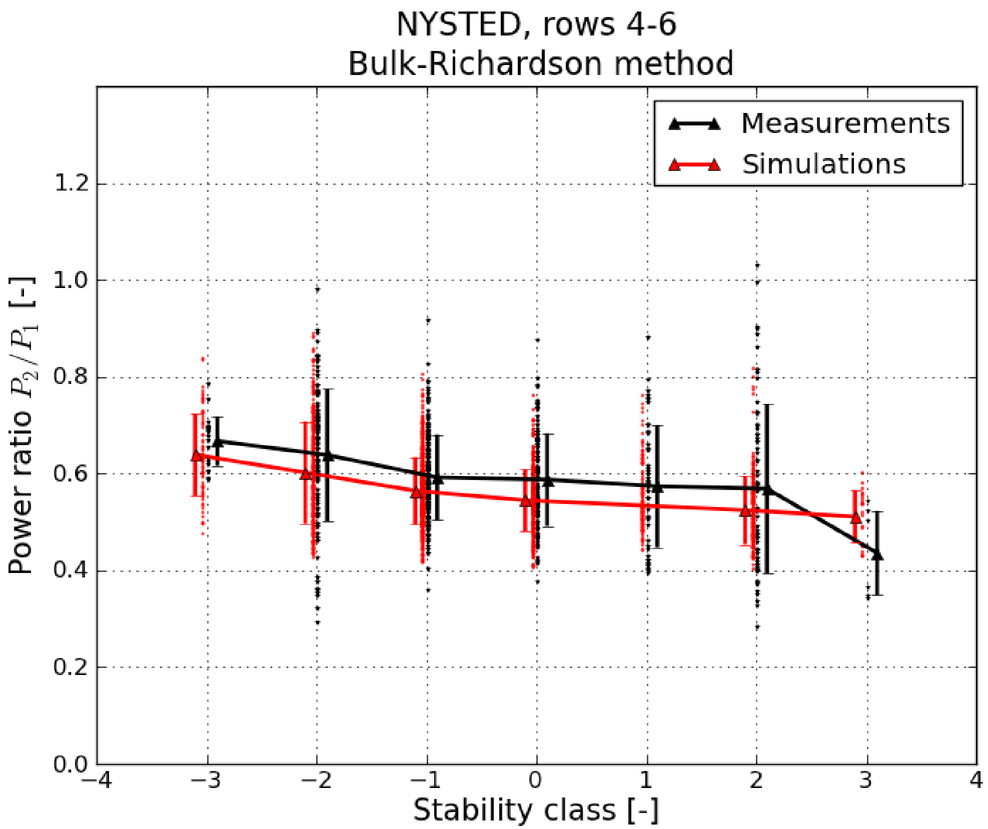
# Results (1)

- DWM using ”classic” Mann spectral tensor



# Results (2)

- DWM using generalized spectral tensor

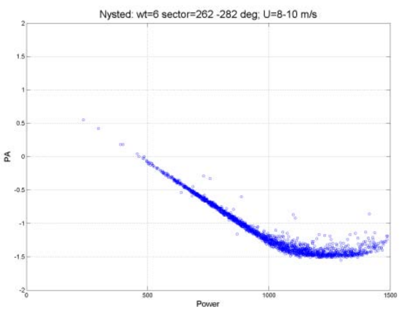


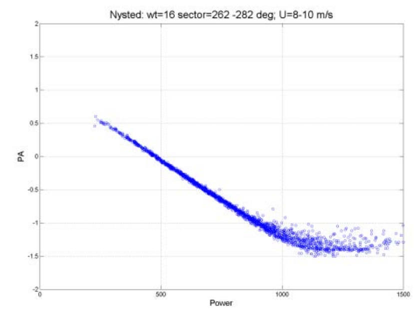
# Conclusions (1)

- 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 ~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

# 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