Wake effects

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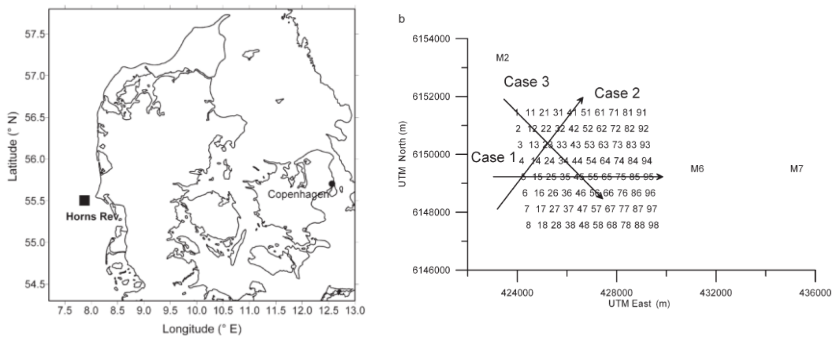
What is it – and why is it so important?

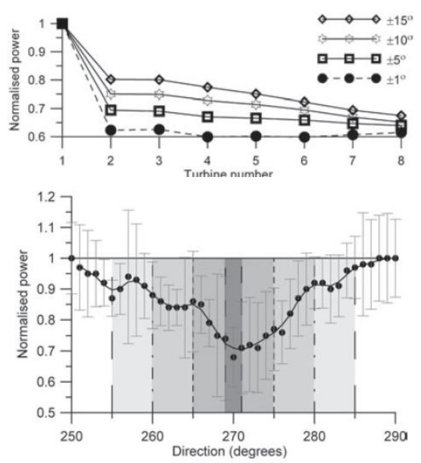
The presence of neighbouring turbines causes:

1. Reductions in windspeed.
2. Increased turbulence – turbine components fails (especially yaw system).

Observations from Horns rev 1



Horns rev

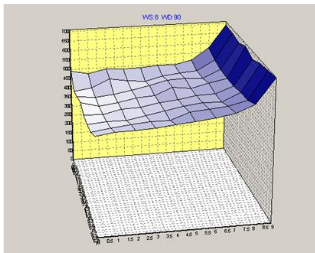


Models for power prediction exist but nearly all only depend on the upwind turbine thrust coefficient. Large uncertainty present.

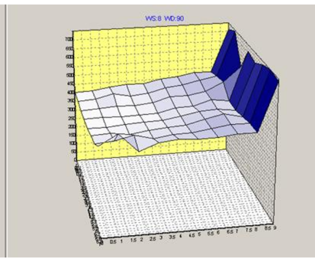
Horns rev: Stability effects

- Measurements from Danish (offshore) wind farms revealed a significant dependence of wake losses on atm. stability conditions.

Unstable



20% reduction in power



40% reduction in power

Neutral

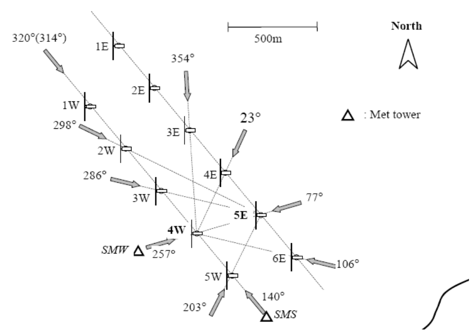
Example:

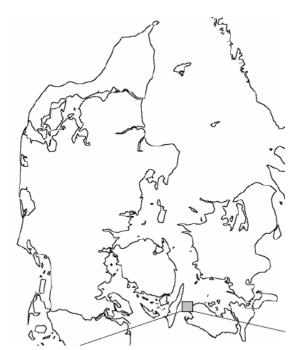
Unstable afternoon

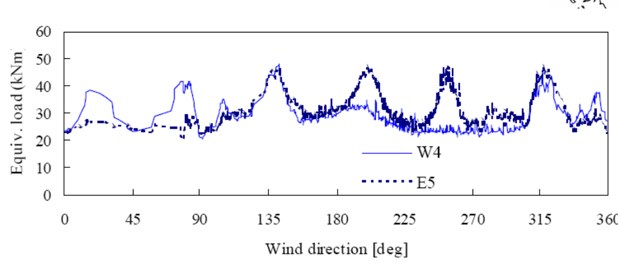
Example:

Stable night

Load measurements on Vindeby 11 Bonus 450kW





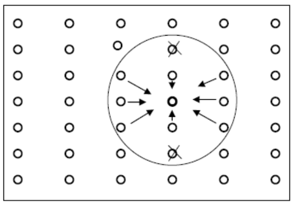


Assessment of turbulence intensity IEC61400-1, Frandsen 2003

For fatigue loads:

$$I_{\text{eff}} = \frac{\hat{\sigma}_{\text{eff}}}{V_{\text{hub}}} = \frac{1}{V_{\text{hub}}}\left[(1-N\,p_{\text{w}})\hat{\sigma}^{m} + p_{\text{w}}\sum_{i=1}^{N}\hat{\sigma}_{\text{T}}^{m}(d_i)\right]^{\frac{1}{m}} ;\ p_{\text{w}} = 0{,}06$$

$$\hat{\sigma}_{\text{T}} = \sqrt{\frac{0{,}9V_{\text{hub}}^{2}}{(1{,}5+0{,}3d_{\text{i}}\sqrt{V_{\text{hub}}/c})^{2}} + \hat{\sigma}^{2}}$$

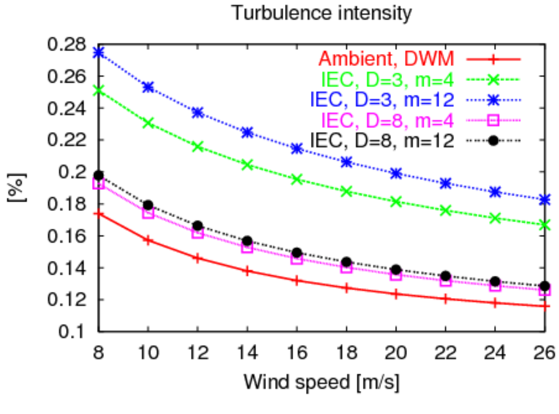


$$\sigma_1 \geq I_{\text{eff}} \cdot V_{\text{hub}} + 1{,}28\,\hat{\sigma}_{\sigma}$$

For extreme loads:

$$I_{eff} = \frac{1}{V_{hub}} \max\{\hat{\sigma}_T\}$$

Used turbulence intensity for the IEC method



Ambient turbulence corresponds to class IC (high wind low turbulence)

More detailed observations on the NM80

- Full scale experiment in 2003 on an 80 m, 2 MW NEG-MICON turbine in Tjæreborg

Load measurements on an NM80 turbine in 3.3D wake

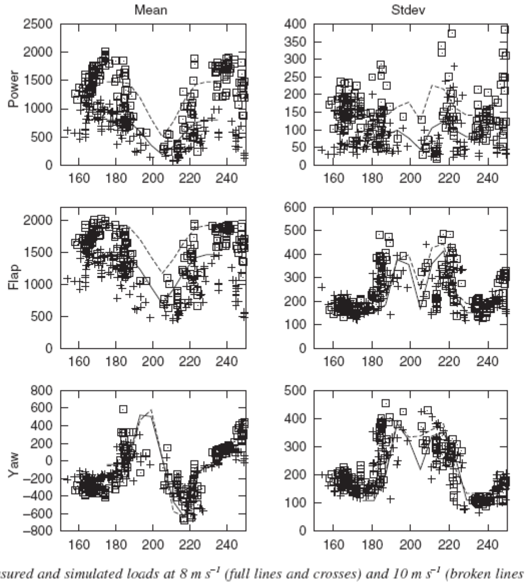


Figure 5. Measured and simulated loads at 8 m s^{-1} (full lines and crosses) and 10 m s^{-1} (broken lines and squares)

Focus on the yaw moment

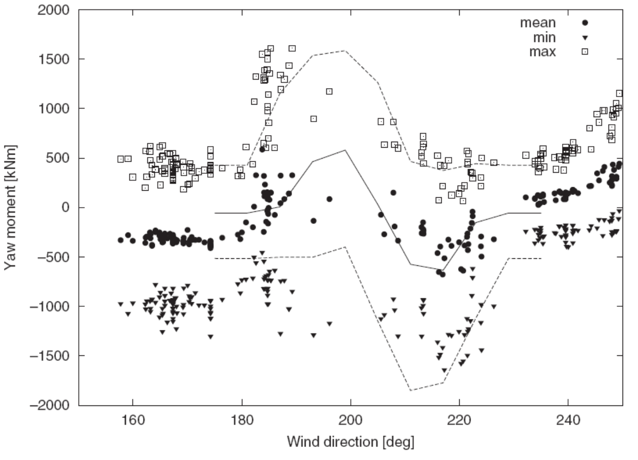
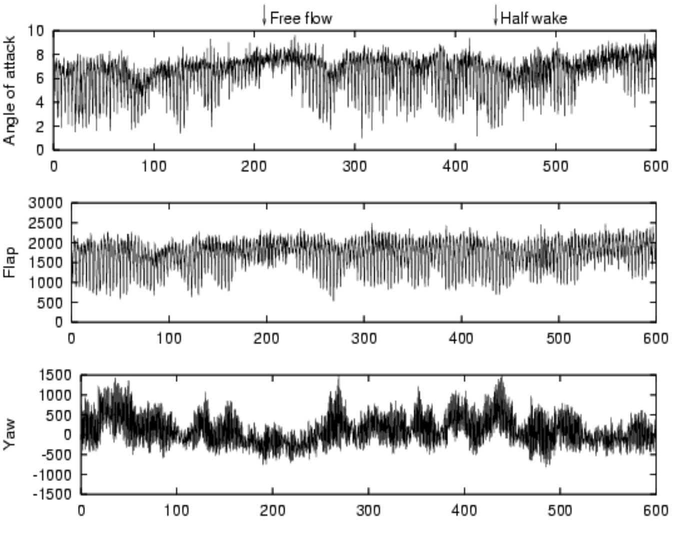


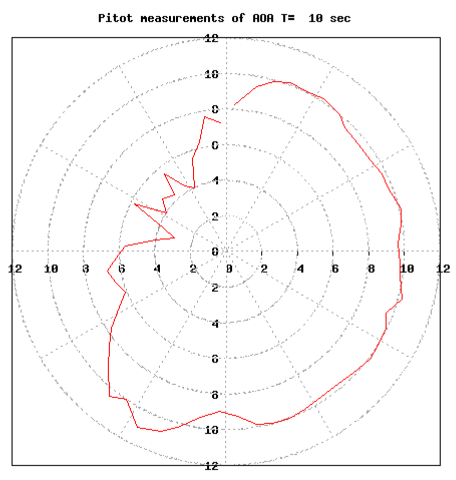
Figure 11. Extremes of yaw moment in a 3·3D wake situation at 9–11 m s^{-1}

Observations on NM80

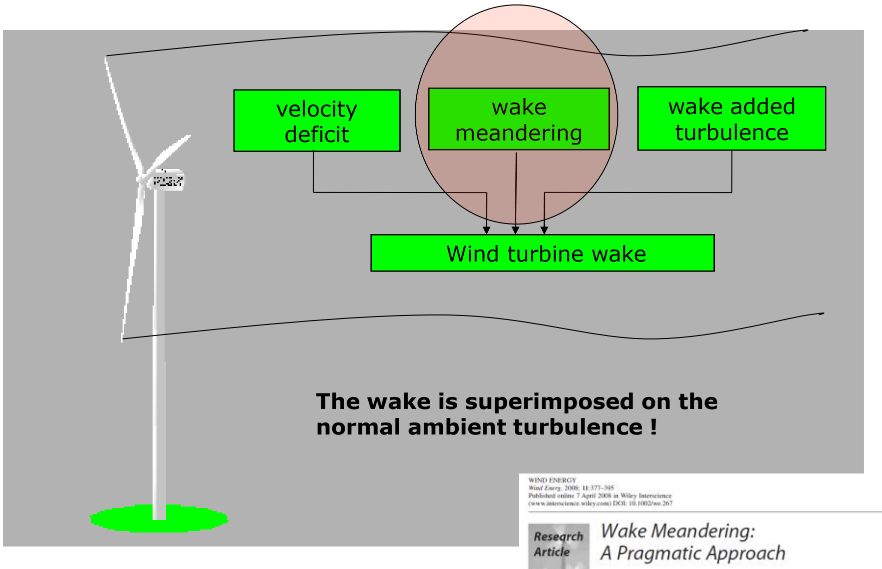


Observations on NM80

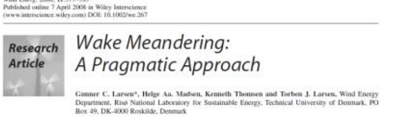
- Wake deficit dynamics illustrated by measured AOA



The basic idea of the Dynamic Wake Meander model (DWM)



The wake is superimposed on the normal ambient turbulence !



WIND ENERGY
Wind Energ. 2008; 11:377–395
Published online 7 April 2008 in Wiley Interscience
(www.interscience.wiley.com) DOI: 10.1002/we.267

Research Article

Wake Meandering: A Pragmatic Approach

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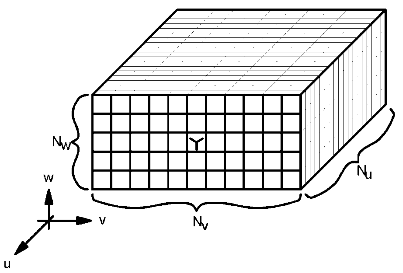
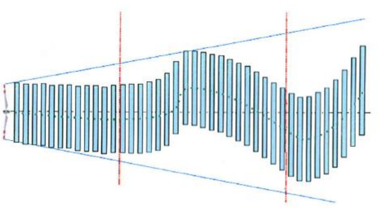
The Meandering

- A cascade of wake deficits are released from the upstream turbine
- Each deficit will be transported dowstream affected only by ambient large scale turbulence (like smoke from a chimney)

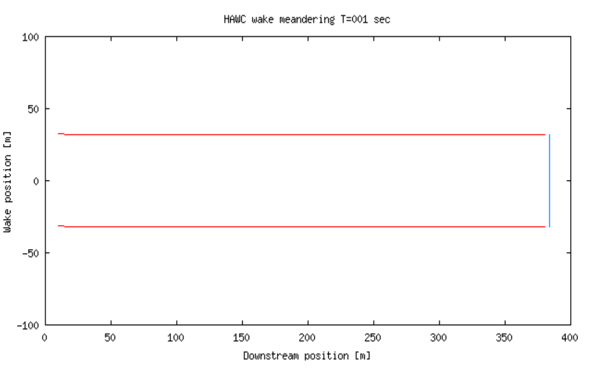
$$\frac{dy(t,t_0)}{dt} = v_c(y,z,t,t_0)$$

$$\frac{dz(t,t_0)}{dt} = w_c(y,z,t,t_0)$$



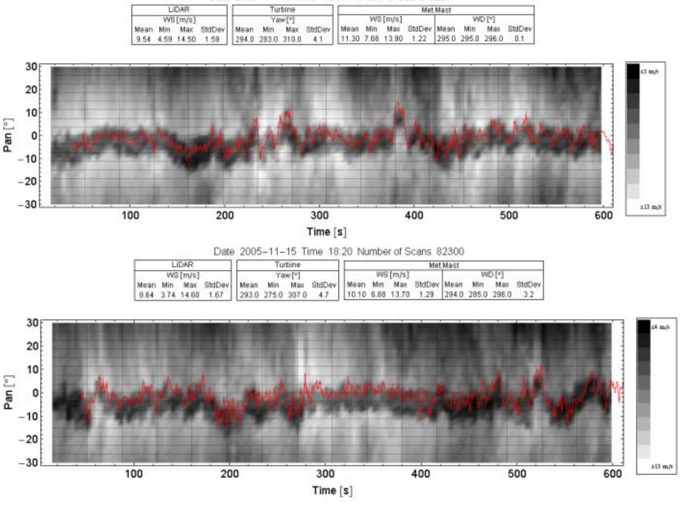


Simulation of wake deficit meandering



The Tellus experiment

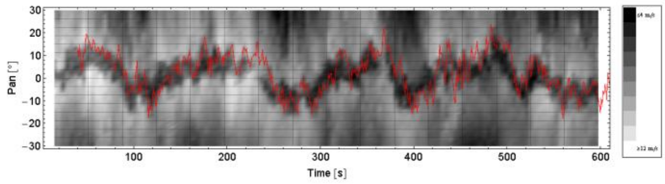
Results -1D line scan (1)



Results -1D line scan (2)

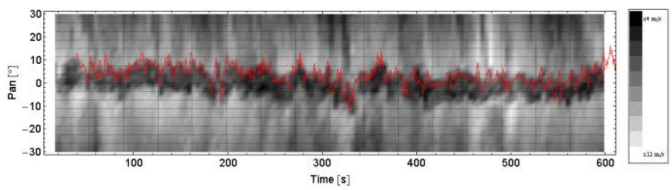
Date 2005–11–15 Time 21:20 Number of Scans 78501

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

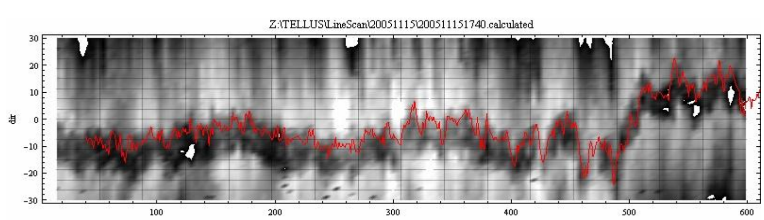


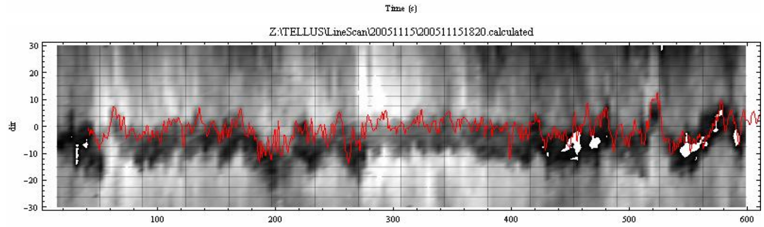
Date 2005–11–15 Time 19:00 Number of Scans 81992

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
8.39	3.58	13.20	1.33	290.0	273.0	302.0	4.3	9.96	7.56	12.60	0.90	286.0	286.0	286.0	0.0

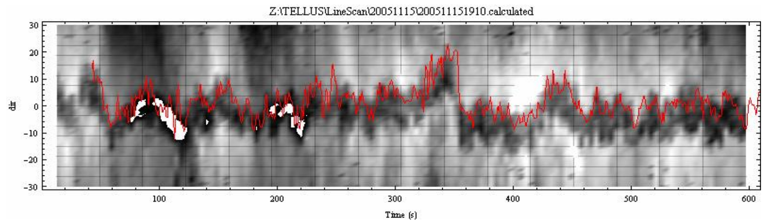


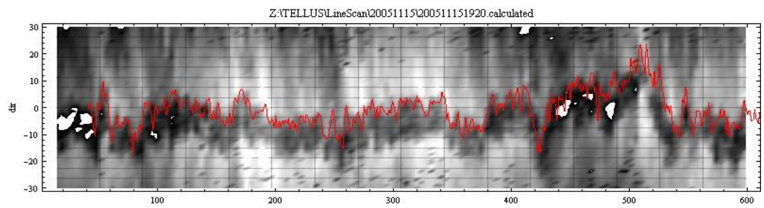
Results -1D line scan (3)



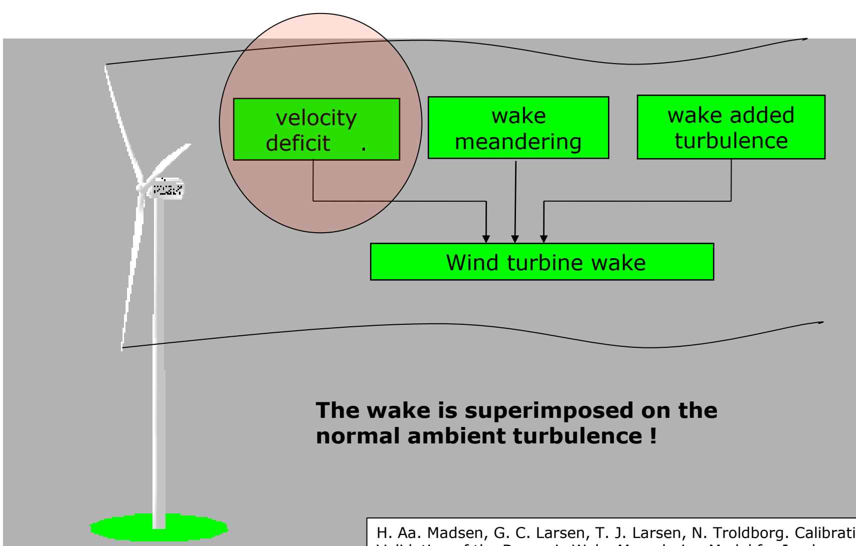


Results -1D line scan (4)





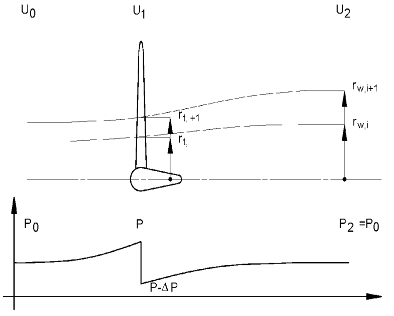
Derivation of the velocity deficit in local meandering coordinates



H. Aa. Madsen, G. C. Larsen, T. J. Larsen, N. Troldborg. Calibration and Validation of the Dynamic Wake Meandering Model for Implementation in an Aeroelastic Code. ***J. Sol. Energy Eng.*** 2010. Vol. 132, Issue 4, 041014 (14 pages) doi:10.1115/1.4002555

Calculation of the velocity deficit at given downstream distance

- Combination of BEM and thin shear layer (TL) method chosen.
- BEM handles expansion due to pressure rise in the near wake region.
- TL handles the turbulent mixing in the far wake region.



$$\dot{m}_i = \pi\,\rho U_0\left(1-a_i\right)\ \left(r_{t,i+1}^2 - r_{t,i}^2\right)\ ,\quad i=1,\ldots,N-1$$

$$\dot{m}_i = \pi\,\rho U_0\left(1-2a_i\right)\ \left(r_{w,i+1}^2 - r_{w,i}^2\right)\ ,\quad i=1,\ldots,N-1$$

$$r_{w,i+1} = \sqrt{\frac{1-a_i}{1-2a_i}\left(r_{t,i+1}^2 - r_{t,i}^2\right) + r_{w,i}^2}$$

Development of the deficit in the far wake region

Thin shear layer approximation of the axissymmetric Navier-Stokes equations with the pressure term disregarded and including the eddy viscosity concept for the Reynolds stresses.

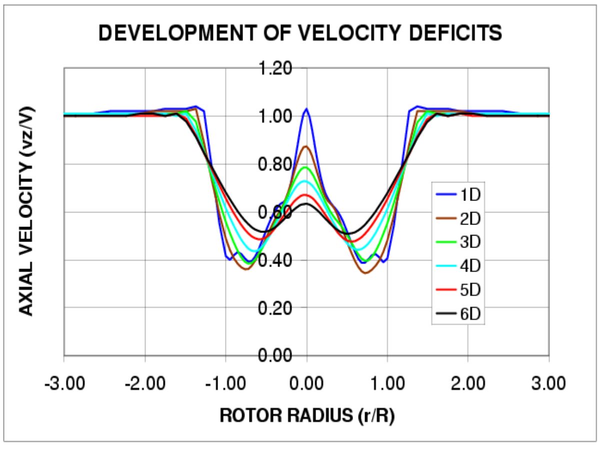
$$U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial r} = \left(\frac{\upsilon_T}{r}\right)\frac{\partial}{\partial r}\left(r\frac{\partial U}{\partial r}\right)$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rV\right) + \frac{\partial U}{\partial x} = 0$$

The eddy viscosity handles turbulent mixing by small vortices due to the deficit itself and mixing from ambient turbulence.

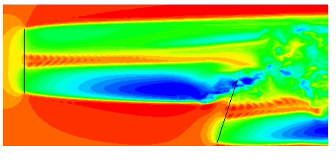
$$\upsilon_T = F_2 k_2 b\left(U_0 - U_{def,\min}\right) + F_1\upsilon_{TA}\quad ,$$

Shear profiles for different downwind positions

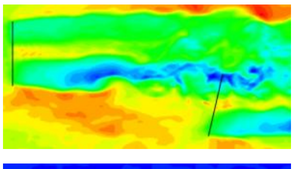


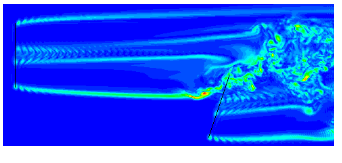
Simulations with the ACL model

no ambient turbulence **3% ambient turbulence**

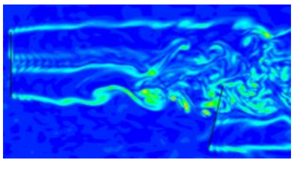


a)



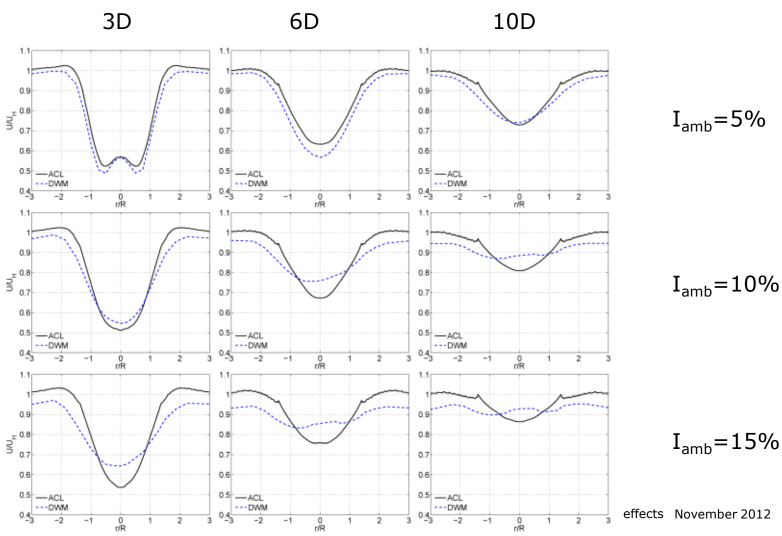


b)

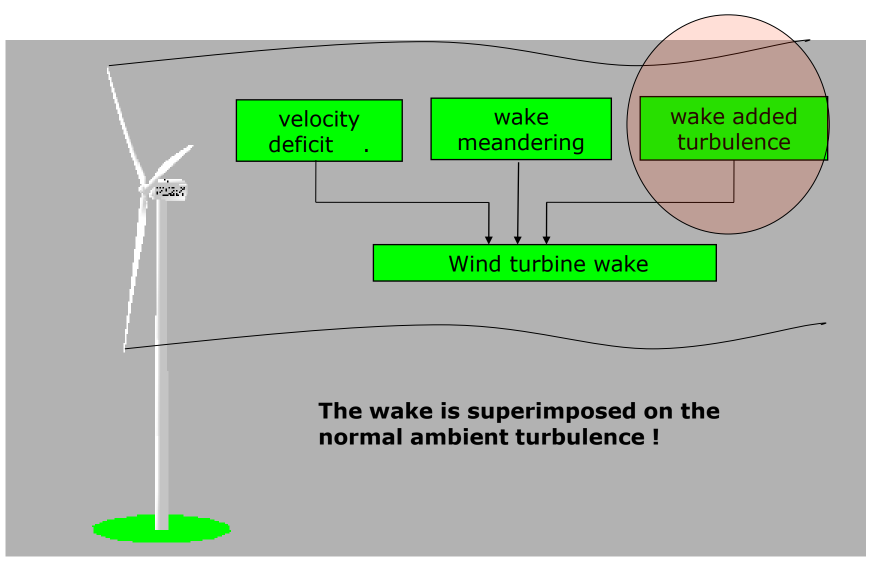


Visualization of flow field in a horizontal plane located in hub height. The rotors are indicated as black lines; a) Stream-wise velocity; b) vorticity

Comparison of AD and DWM effective deficits including meandering.

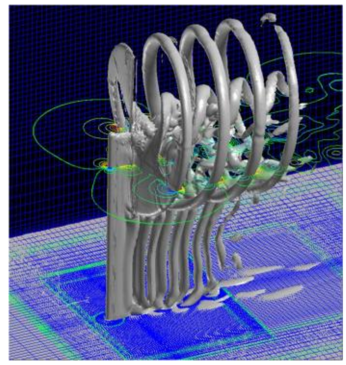


The basic idea of the Dynamic Wake Meander model (DWM)



Added wake turbulence with micro structure

A change in turbulence is present in the wake region, mainly caused by tip and root vortices:



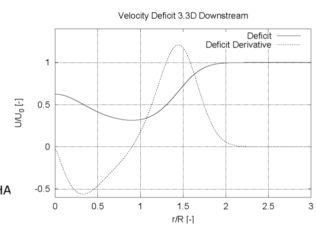
First approximation:

• Isotropic turbulence

• Reduced length scale compared to ambient turbulence. $L_M \approx R/10$

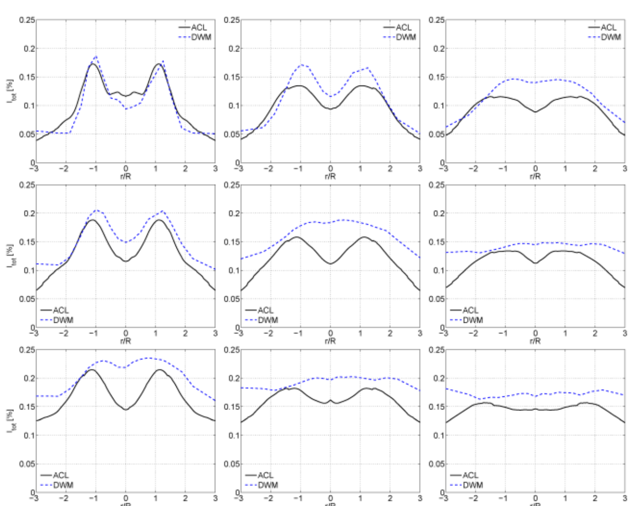
• Intensity proportional to depth of deficit and radial gradient of axial velocity. $k_{m1} \approx 0.6$, $k_{m2} \approx 0.35$

wake added turbulence intensity factor $\longrightarrow$ $$k_{mt}(r) = \left|1 - U_{def}(r)\right| k_{m1} + \left|\frac{\partial U_{def}(r)}{\partial r}\right| k_{m2}$$



Comparison of AD and DWM effective turbulence intensity.

3D 6D 10D

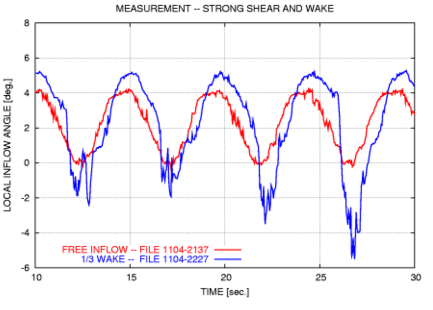


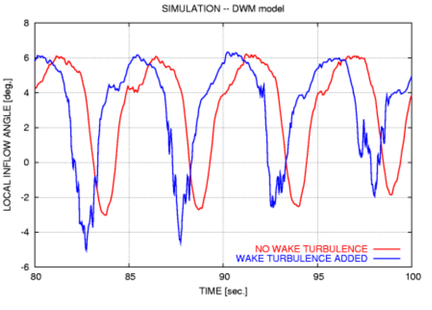
I_{amb}=5%

I_{amb}=10%

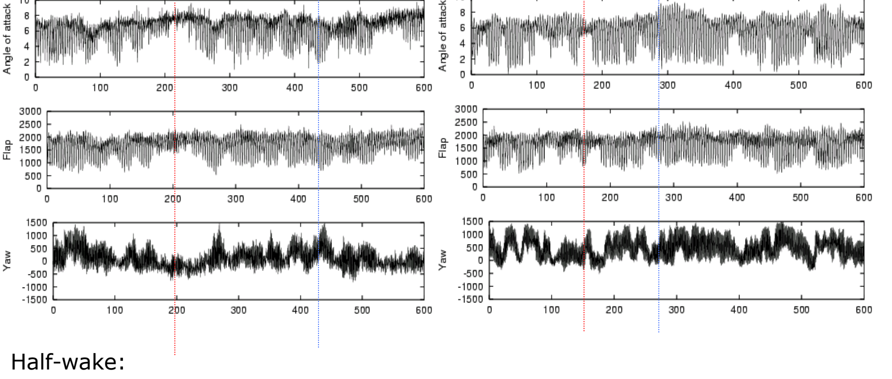
I_{amb}=15%

Influence of added wake turbulence





RESULTS NM80 3.3D spacing



Half-wake:

- large *variations* in angle of attack and flapwise load
- large *mean* yaw moment

Input parameters

```
begin wakes;
   nsource 5;
   source_pos  0.0       -640 -59.89;  X D
   source_pos  640 -640 -59.89;  X D
   source_pos -640 -640 -59.89;  X D
   source_pos  640 0.0 -59.89;  X D
   source_pos -640 0.0 -59.89;  X D
   op_data      1.8 0 ;1.87 0.0 rad/sec, pitch [grader] opstrøms;
   begin mann_meanderturb ;
     filename_u    .\wake-meander\meander_8D_56u.bin ;
     filename_v    .\wake-meander\meander_8D_56v.bin ;
     filename_w    .\wake-meander\meander_8D_56w.bin ;
     box_dim_u   8192 2.06299 ;
     box_dim_v     32 80 ;
     box_dim_w     32 80 ;
end mann_meanderturb;
;
   begin mann_microturb ;
     filename_u    .\wake-turbulence\wake-l08_6u.bin ;    wake-turbulence
     filename_v    .\wake-turbulence\wake-l08_6v.bin ;
     filename_w    .\wake-turbulence\wake-l08_6w.bin ;
     box_dim_u   128 1.5625 ;
     box_dim_v     128 0.78125 ;
     box_dim_w     128  0.78125 ;
end mann_microturb;
 end wakes;
```

An example is also presented in the last part of the manual (version 4.1)

WIND ENERGY
Wind Energ. (2012)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/we.1563

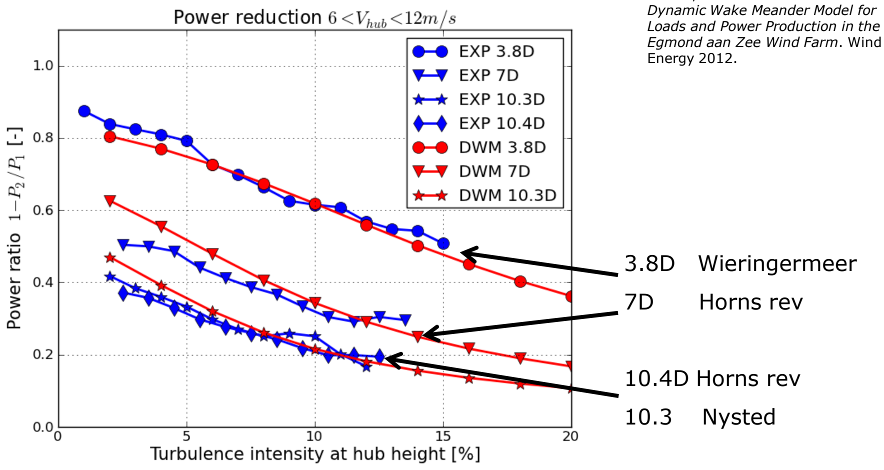
RESEARCH ARTICLE

Validation of the dynamic wake meander model for loads and power production in the Egmond aan Zee wind farm

Torben J. Larsen, Helge Aa. Madsen, Gunner C. Larsen and Kurt S. Hansen
Technical University of Denmark, Wind Energy Division, Building 118, PO Box 49, 4000 Roskilde, Denmark

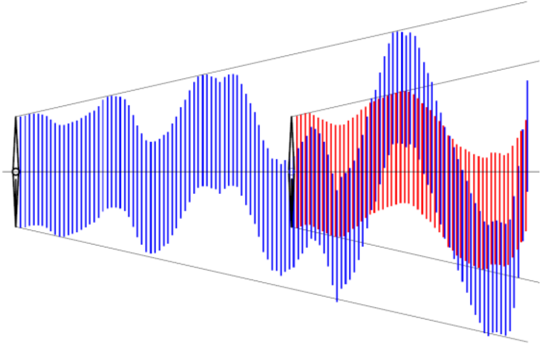
Validation for single wake situation at 3 different wind farms

T.J. Larsen, H. A. Madsen, G. Larsen, K. Hansen. *Validation of the Dynamic Wake Meander Model for Loads and Power Production in the Egmond aan Zee Wind Farm*. Wind Energy 2012.



Increased turbulence causes higher production. The reason is increased turbulence mixing and an increased meandering.

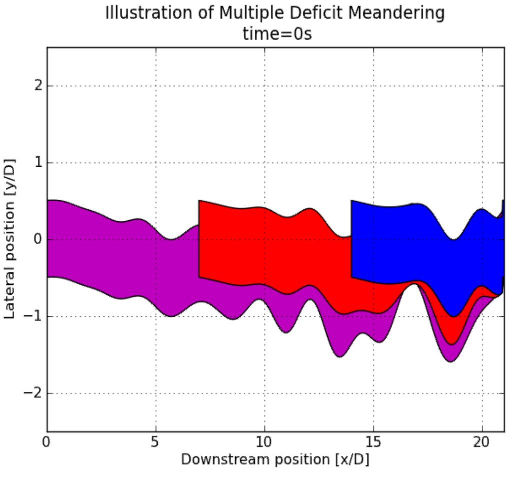
Meander path from multiple turbines - straight forward extension of DWM



The wakes from two turbines (or more) only rarely coincide. Even in full wake direction, the path’s will be different.

It would be convinient if the total wake velocity (when they collide) could be modeled based on individual wake deficits.

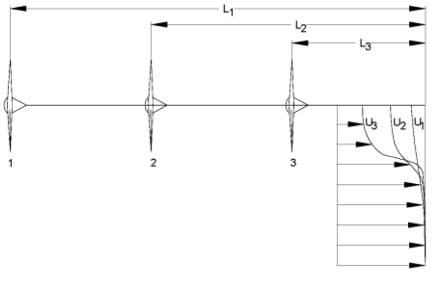
Meander path from multiple turbines - a straight forward extension of DWM

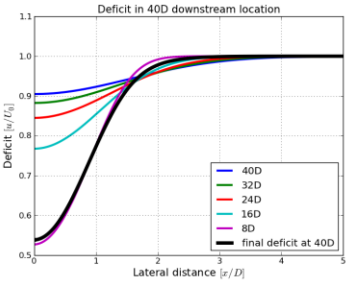


The wakes from two turbines (or more) only rarely coincide. Even in full wake direction, the path's will be different, which further justifies the simple selection proces.

Wakes from multiple turbines

Ambient turbulence is low (1%), meandering is ignored



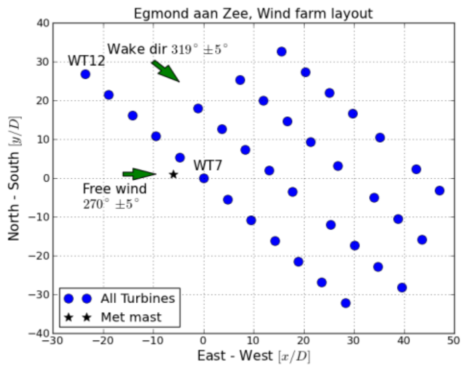


Deficits from individual turbines are compared with a more accurate solution including the wake of the upstream turbines.

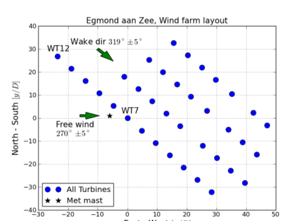
The final deficit seem to be very well aproximated with the deficit of the nearest turbine (where free wsp was assumed)

A good and practical approximation: $u_{def,final}(r) = \mathrm{MIN}(u_{def,i..N}(r))$

Comparison of loads for the Egmond aan Zee windfarm



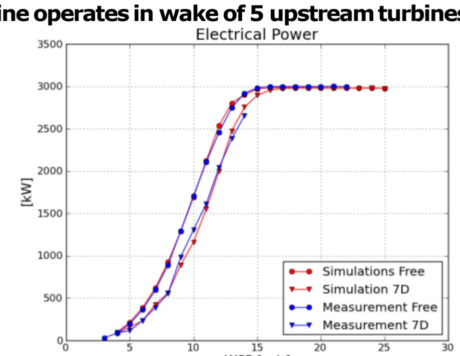
Comparison of power curves in free and wake conditions



Every simulation point represents:

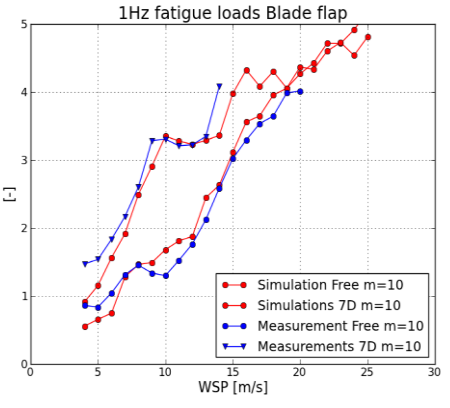
- 3 half-hour time simulations, each with
- Wind direction ±5°, ±2.5°, 0°

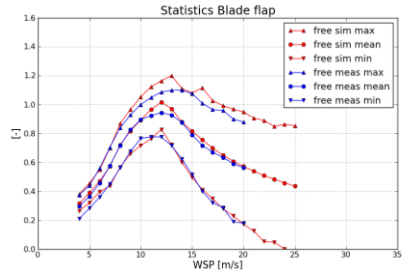
The turbine operates in wake of 5 upstream turbines!

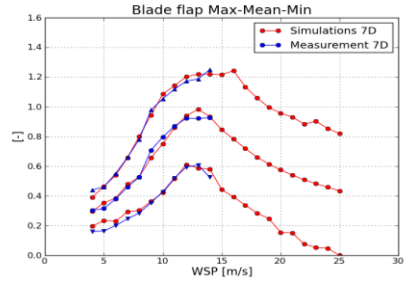


Load comparison at Egmond aan Zee

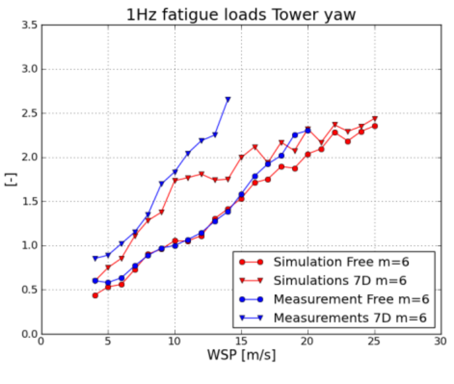
- Fatigue and mean loads

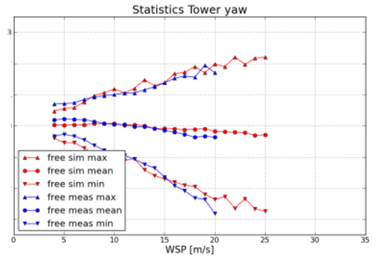


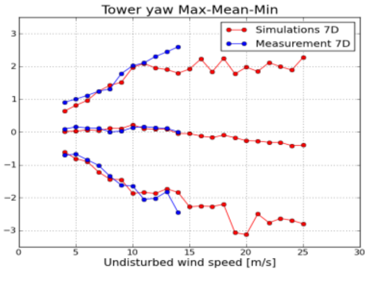




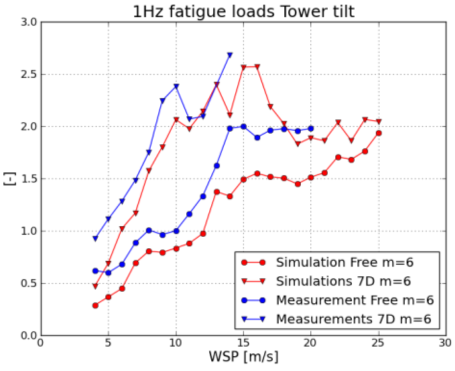
Yaw moment comparison

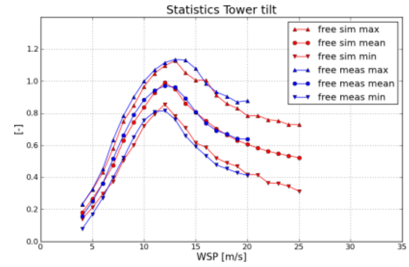


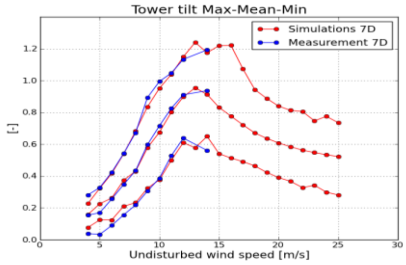




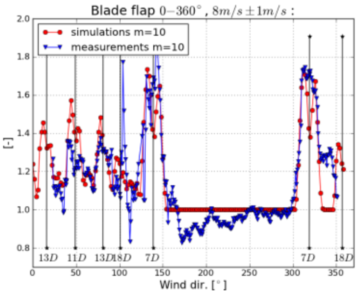
Tower moment comparison

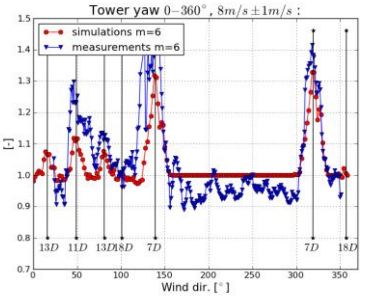


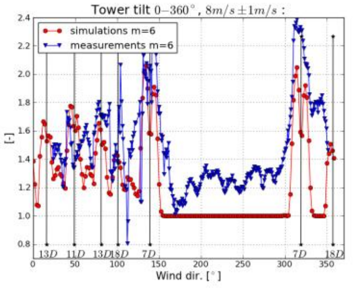


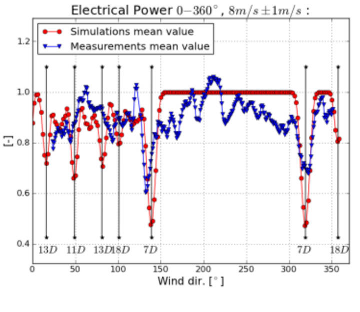


Loads for 0-360°, 8m/s

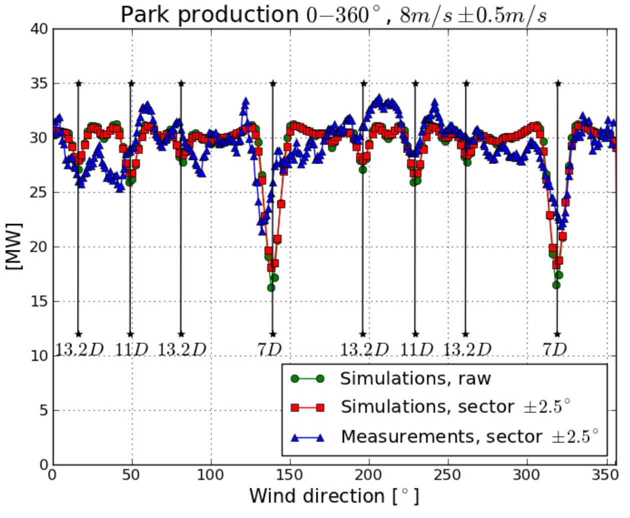








Park power production for 0-360°, 8m/s



Atmospheric stability: Hypothesis

- Free shear flows as wakes are usually ”narrow”, and we believe that major factors in the observed wake loss dependence on stability conditions are:
  - o Wake meandering drived by large-scale turbulent eddies;
  - o Stability impacting primary the low frequency part of the atmospheric turbulence and thus the large-scale turbulent structures (driving the meandering).

Example:

Unstable afternoon

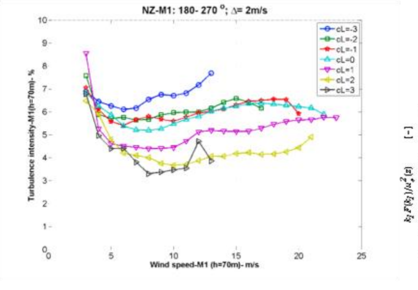
Example:

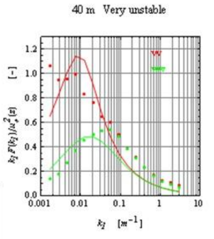
Stable night

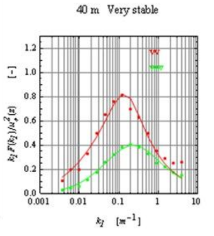
Influence of atmospheric stability

- The level of stability affect both the level of turbulence as well as the structure of turbulence

Unstable condition causes higher turbulence in combination with an increase in the low frequent contribution

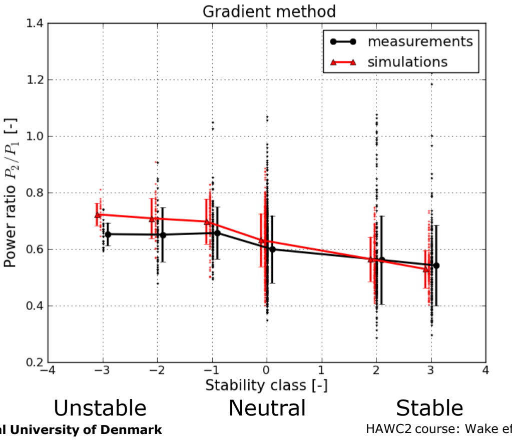






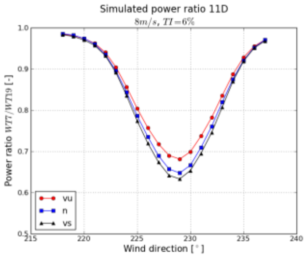
Stability effects modelled with DWM and compared to measurements on Horns rev wind farm.

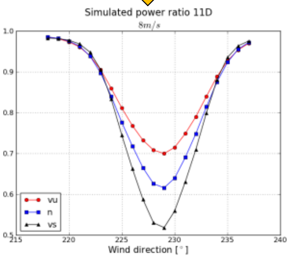
- **Ratio between turbine production in row 1 and 2 is compared and classified based on stability level.**
- **Situation is with wind alond the row, so the turbine operates in full wake condition with a spacing of 8D.**
- **Trend is captured well as well as variation, but absolute level is slightly off.**

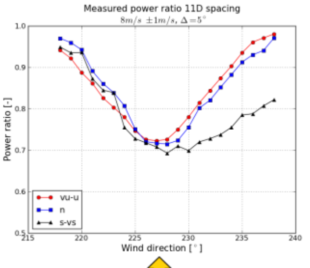


Results of stability study, Egmond aan Zee

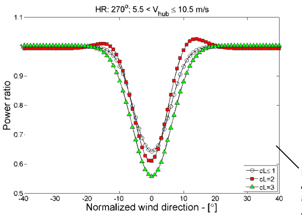
Turbulence intensity matching measured levels







Turbulence intensity constant at 6%



Measurements extracted

- Too little data for final conclusions

T.J. Larsen, H. A. Madsen, G. Larsen, K. Hansen. Wind farm production estimates. In scientific proc. of EWEA 2012, Copenhagen 16-19 April 2012, 9p.

K. Hansen et. Al, *The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm. Wind Energy 2011*

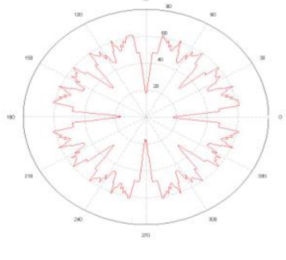
Production sensitivity to wind direction and ambient turbulence level, simulated with the DWM model.

A Wind farm configured in a cartesian 5x5 grid with a spacing of 8D.

The total wind farm power output is shown for 8m/s as function of wind direction. A huge decrease can be seen for certain wind directions when the ambient turbulence intensity is low.

The decrease is from 60MW to 20MW for the worst situation.

DO NOT PLACE TURBINES IN STRAIGHT ROWS!



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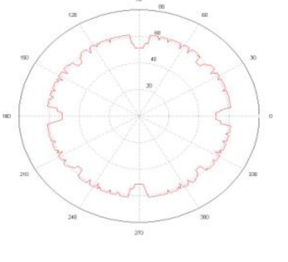
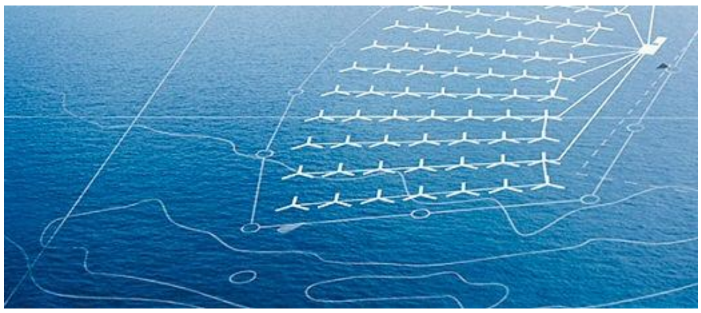
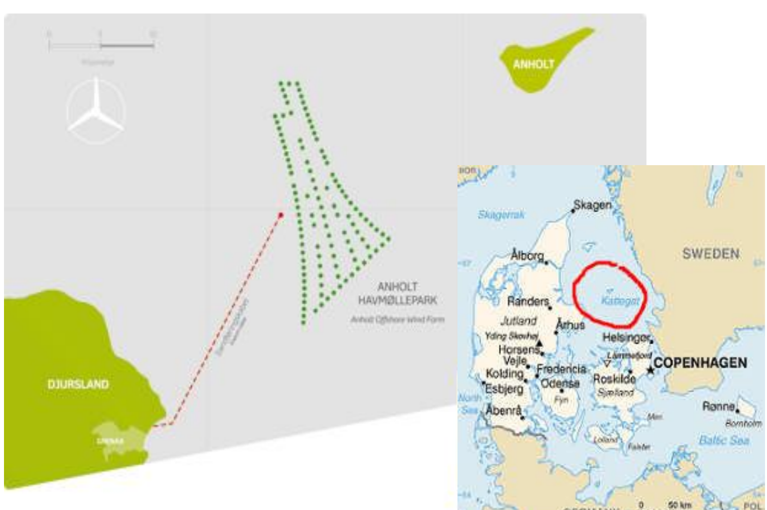


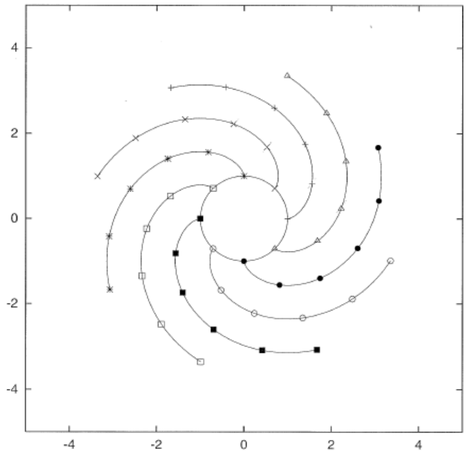
The new layout of Horns rev2



The new layout of the Anholt wind farm



A different possible outcome -based on evolvente expressions



Torben J. Larsen 10. Dec. 2008