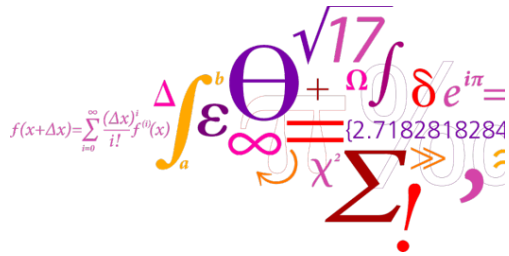
Wake effects

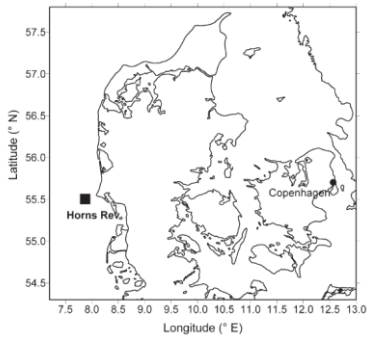


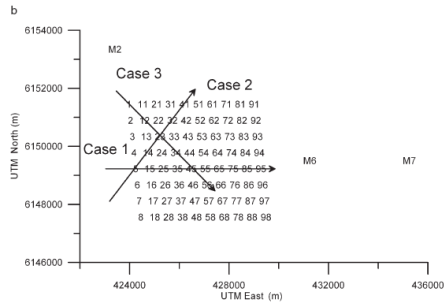
DTU Wind Energy
Department of Wind Energy

What is it – and why is it so important?

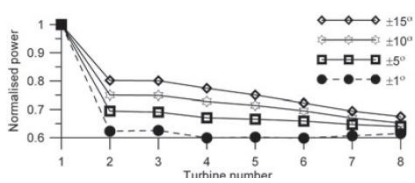
The presence of neighbouring turbines causes:
1. Reductions in windspeed.
2. Increased turbulence – turbine components fails (especially yaw system).

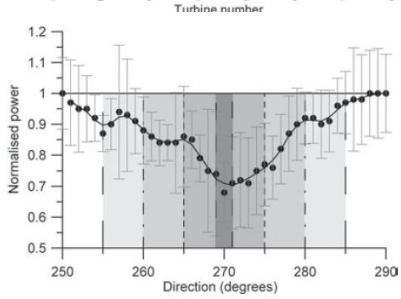
Observations from Horns rev 1





Horns rev



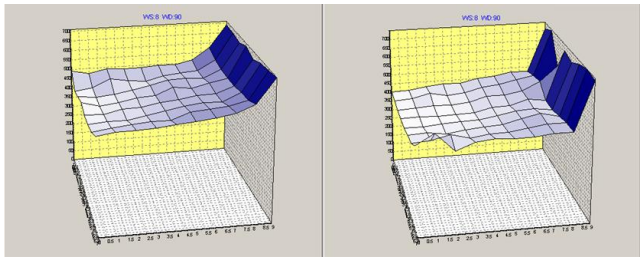


Models for power prediction exist but nearly all only depend on the upwind turbine thrust coefficient. Large uncertainty present.

Background 3: Stability effects

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

Unstable



Neutral

20% reduction in power

40% reduction in power

Example:

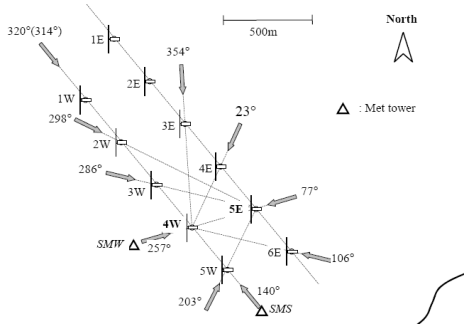
Unstable afternoon

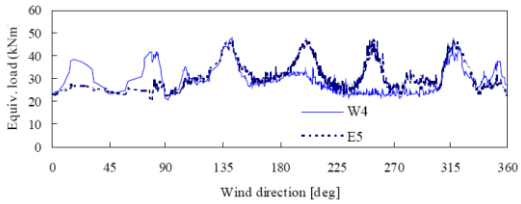
Example:

Stable night

DTU Wind Energy, Technical University of Denmark

Background 1: Load measurements on Vindeby, 11 Bonus 450kW





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

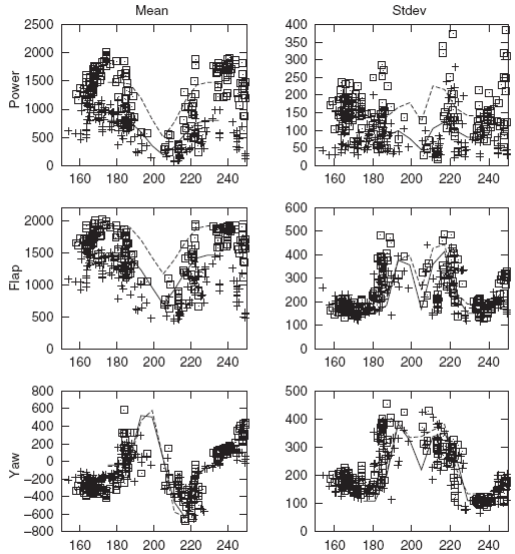


Figure 5. Measured and simulated loads at 8 m s^{-1} (full lines and crosses) and 10 m s^{-1} (broken lines and squares)

Focus on the yaw moment

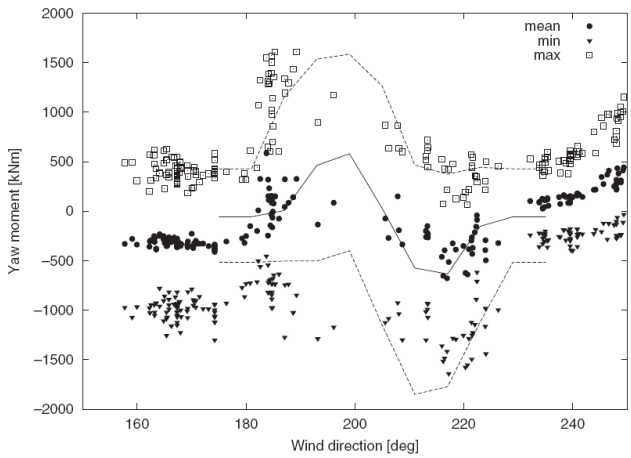
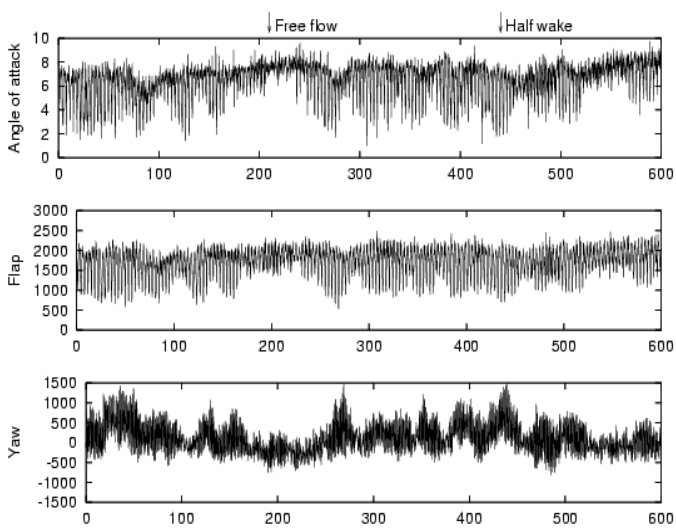


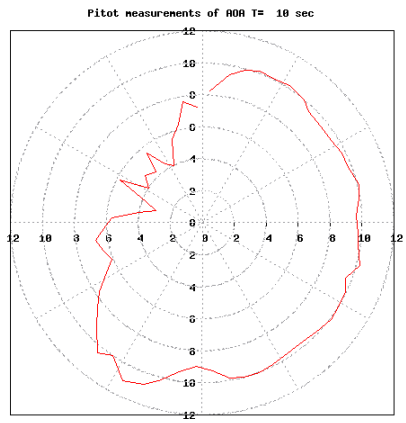
Figure 11. Extremes of yaw moment in a 3·3D wake situation at 9–11 m s^{-1}

Observations on NM80

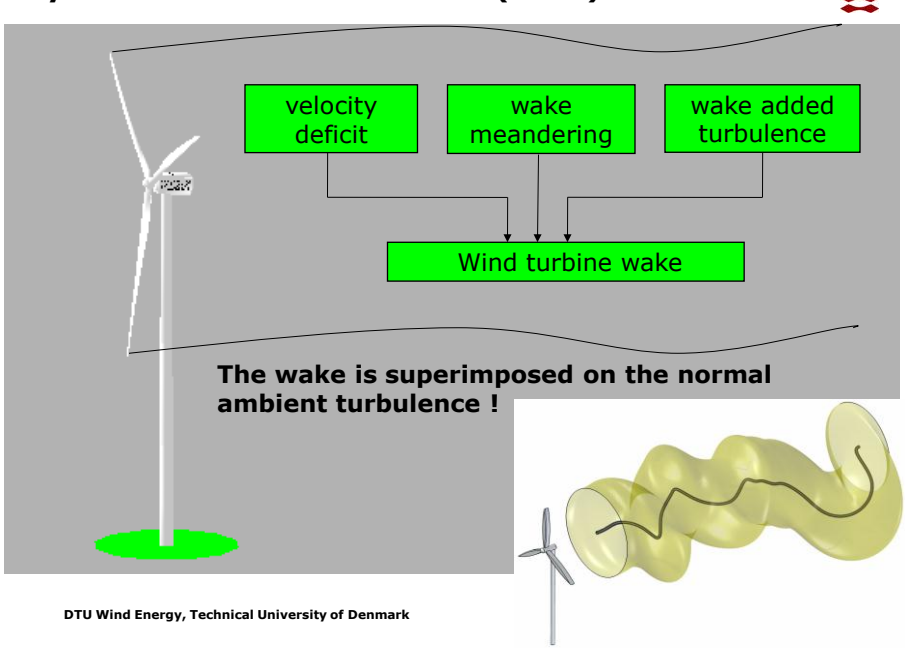


Observations on NM80

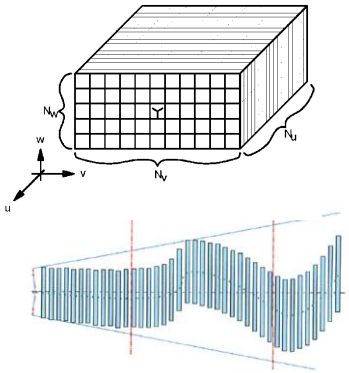
- Wake deficit dynamics illustrated by measured AOA

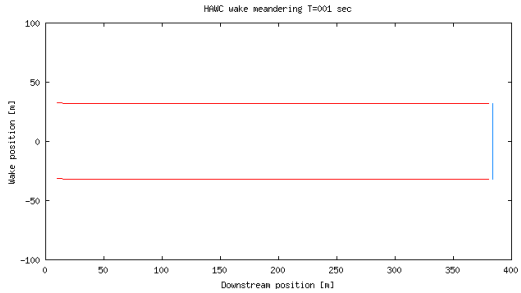


The basic idea of the Dynamic Wake Meander model (DWM)



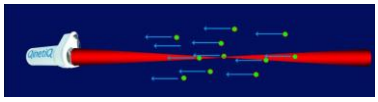
The meandering motion is essential



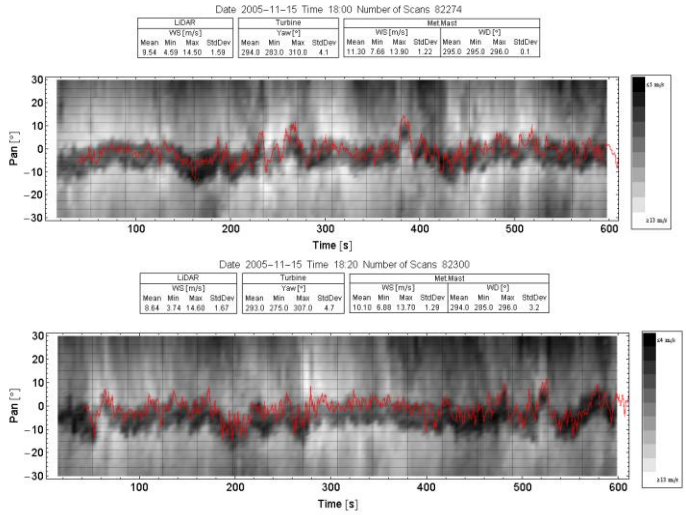


The main principal in the meandering modelling is that the main wake motion is caused by the large and low-frequent structure of the ambient turbulence! Deficits are transported as a cascade of passive tracers.

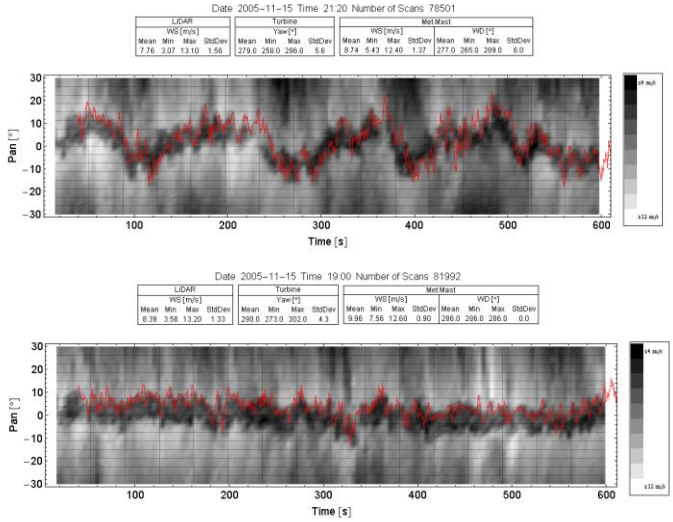
The Tellus Experiment



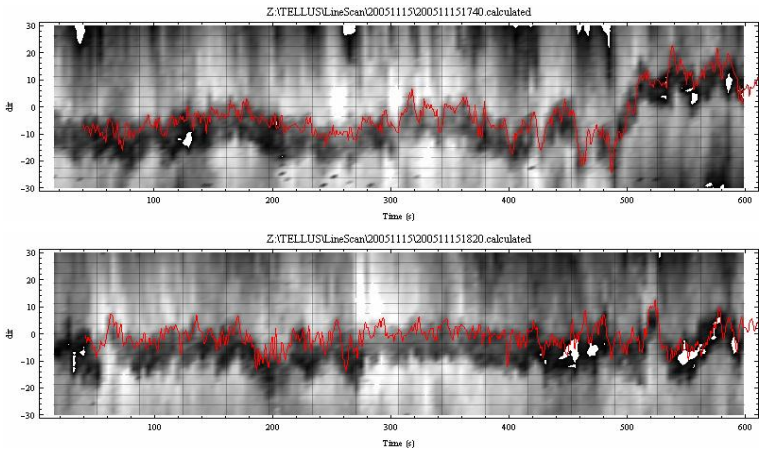
Results -1D line scan (1)



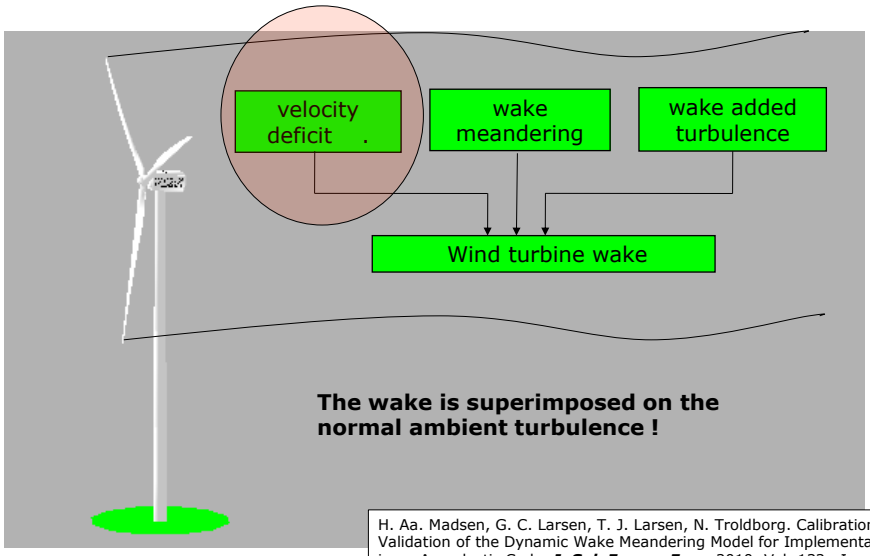
Results -1D line scan (2)



Results -1D line scan (3)



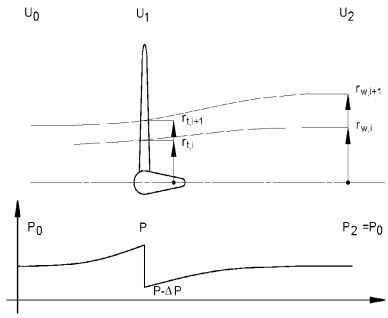
Derivation of the velocity deficit in local meandering coordinates



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.



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

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

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

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.

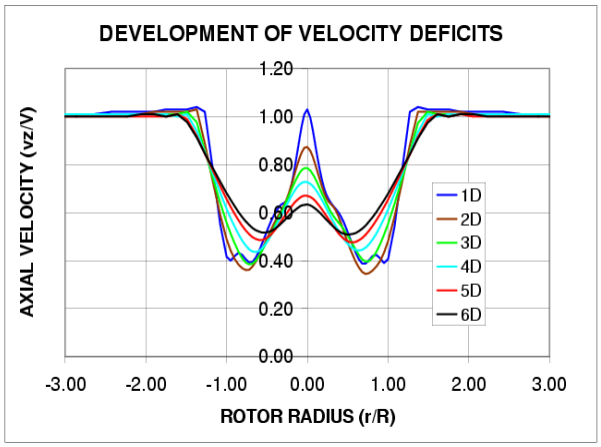
$$U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial r} = \left(\frac{\upsilon_T}{r}\right)\frac{\partial}{\partial r}\left(r\frac{\partial U}{\partial r}\right)$$

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

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

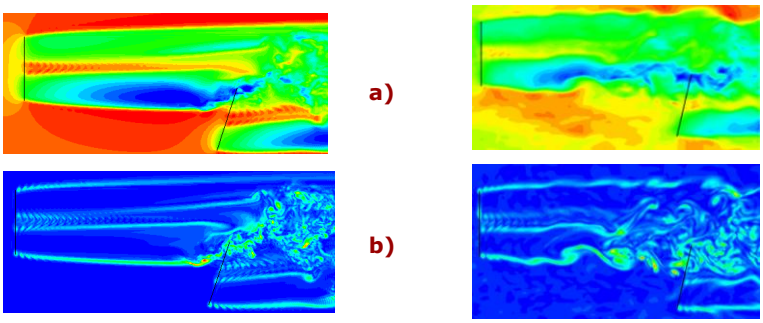
$$\upsilon_T = F_2 k_2 b\left(U_0 - U_{def,\min}\right) + F_1 \upsilon_{TA} \quad ,$$

Shear profiles for different downwind positions



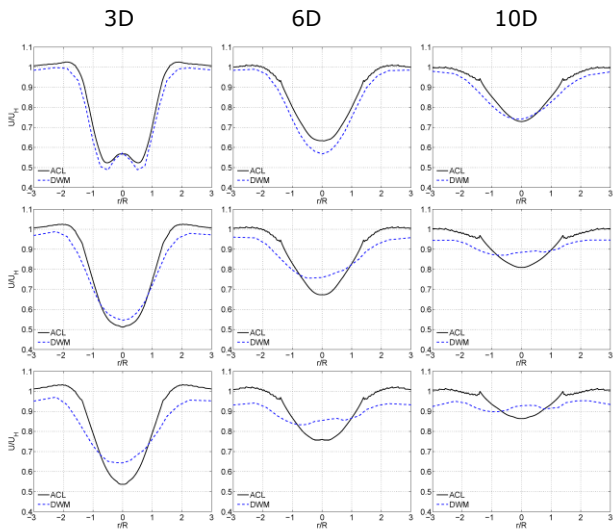
Simulations with the ACL model

no ambient turbulence **3% ambient turbulence**



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.

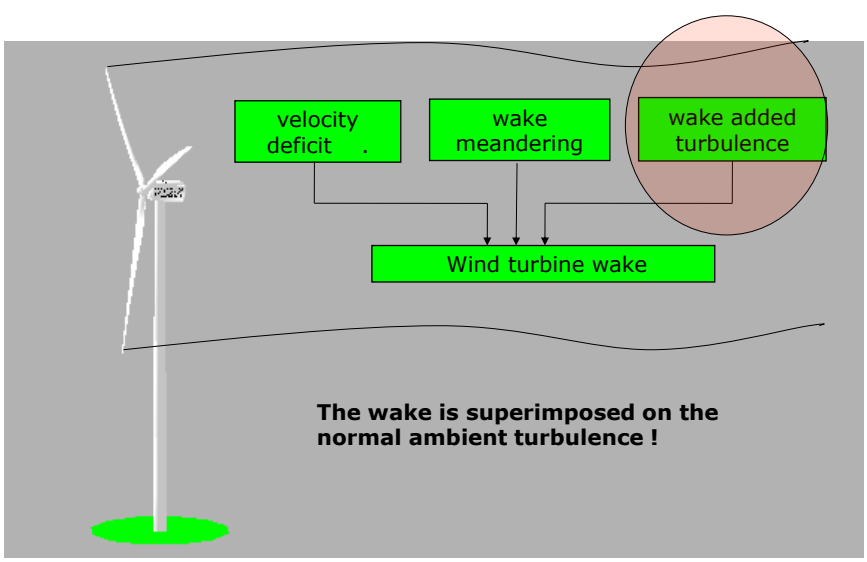


I_{amb}=5%

I_{amb}=10%

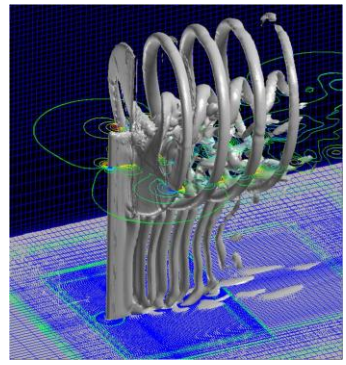
I_{amb}=15%

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



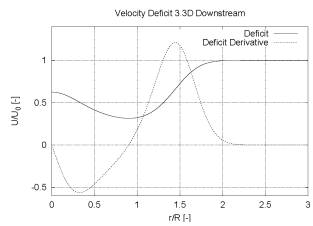
Added wake turbulence with micro structure

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

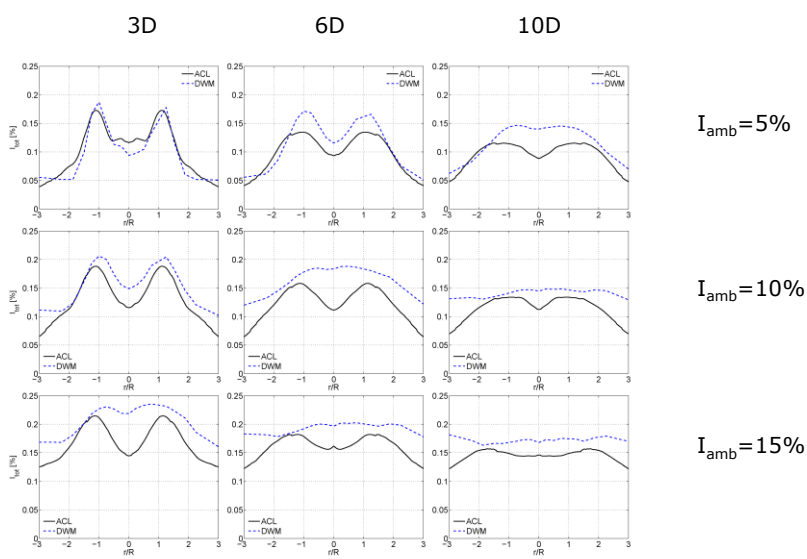


First approximation:
- Isotropic turbulence
- Reduced length scale compared to ambient turbulence. $L_M \approx R/10$
- Intensity proportional to depth of deficit and radial gradient of axial velocity. $k_{m1} \approx 0.6$, $k_{m2} \approx 0.35$

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



Comparison of AD and DWM effective turbulence intensity.

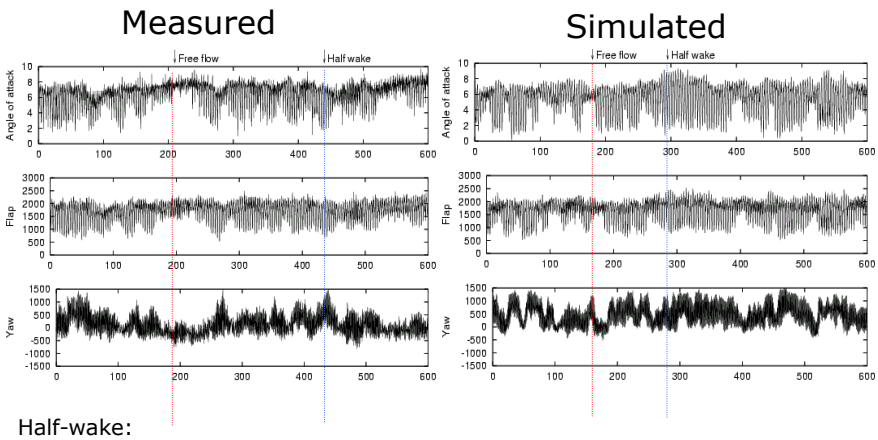


I_{amb}=5%

I_{amb}=10%

I_{amb}=15%

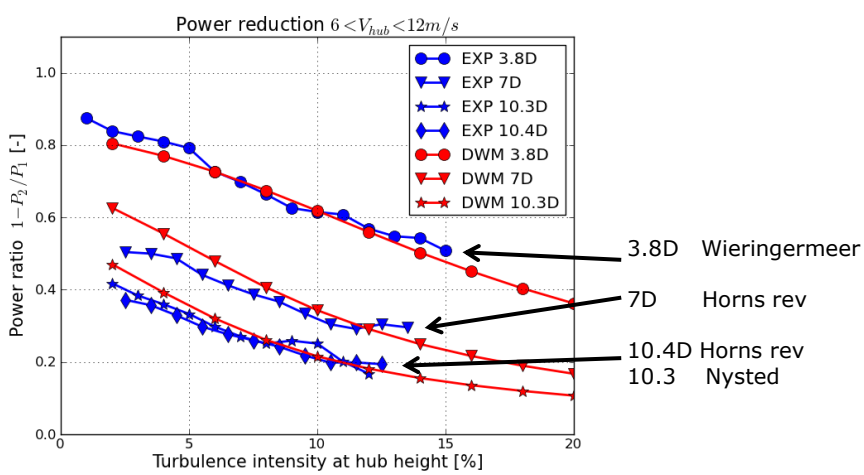
RESULTS NM80 3.3D spacing



Half-wake:

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

Validation for single wake situation

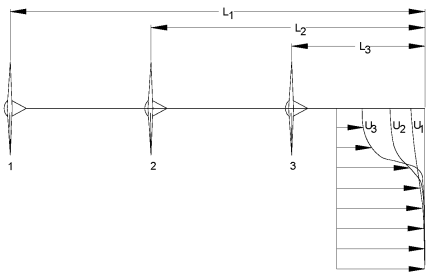


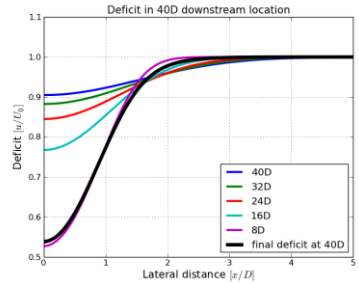
Increased turbulence causes higher production. The reason is increased turbulence mixing and an increased meandering.

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.

Wakes from multiple turbines

Ambient turbulence is low (2%), meandering is ignored



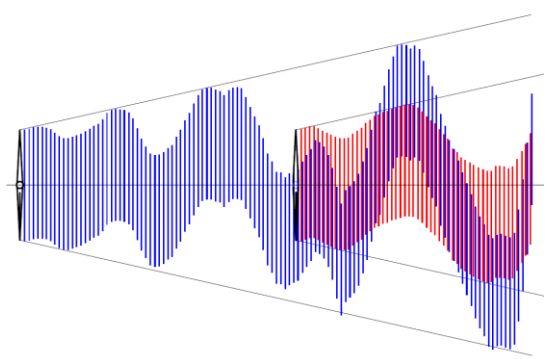


Deficits from individual turbines are compared with a more accurate solution including the wake of the upstream turbines.

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

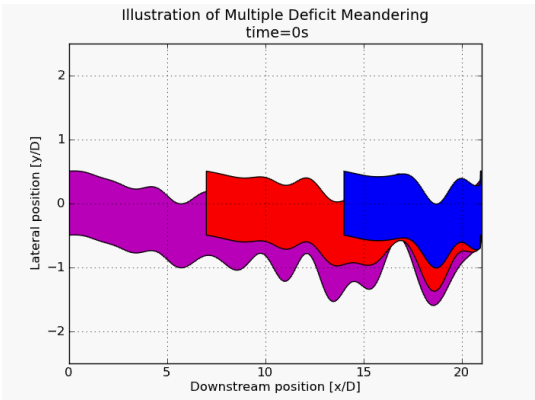
A good and practical approximation: $u_{def,final}(r) = \mathrm{MIN}(u_{def,i..N}(r))$

Meander path from multiple turbines - straight forward extension of DWM



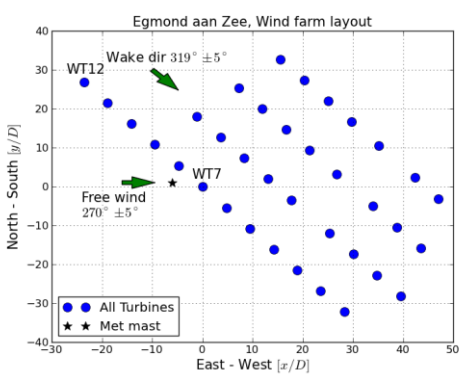
The wakes from two turbines (or more) only rarely coincide. Even in full wake direction, the path's will be different.
It would be convinient if the total wake velocity (when they collide) could be modeled based on individual wake deficits.

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.

Comparison of loads for the Egmond aan Zee windfarm

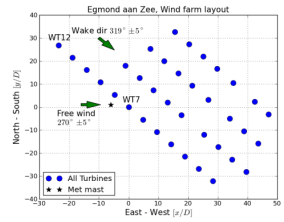


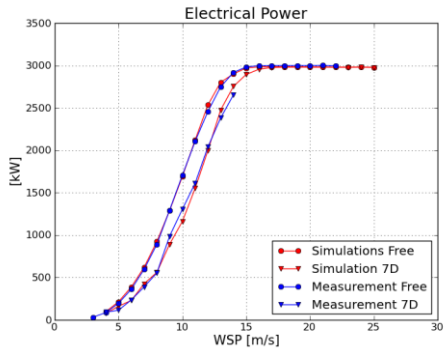
36 turbines installed in 4 rows. SCADA data for entire farm are monitored and detailed load measurements of WT7. MET mast data available. Please see the paper for information about calibration.

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°

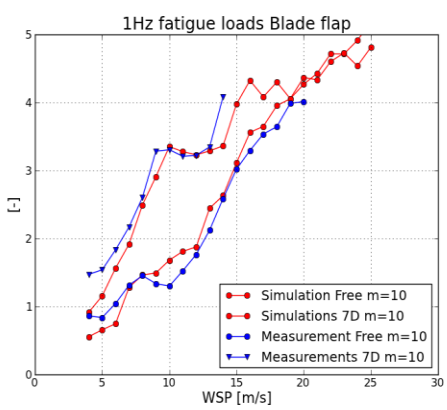
The turbine operates in wake of 5 upstream turbines!

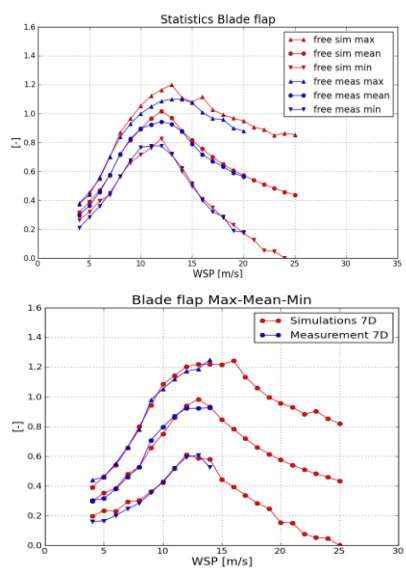




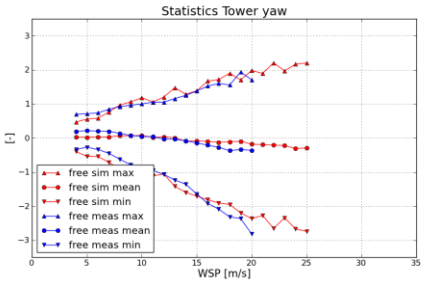
Load comparison at Egmond aan Zee

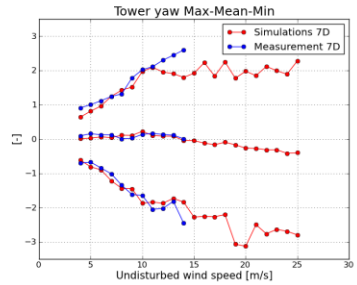
- Fatigue and mean loads

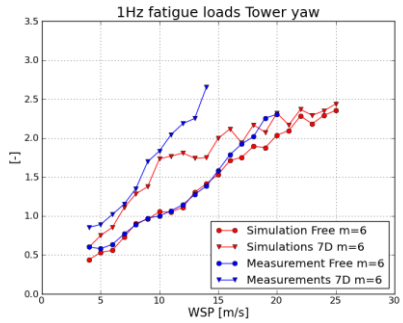




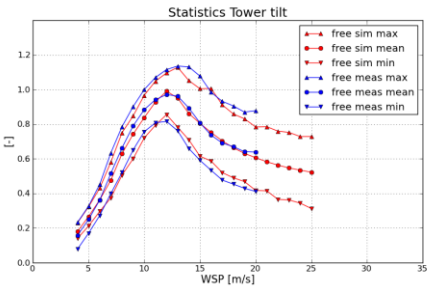
Yaw moment comparison

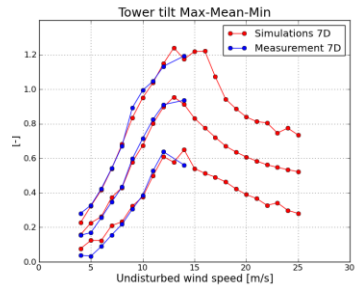


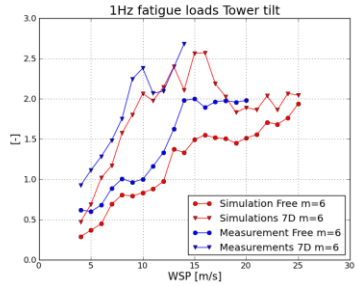




Tower moment comparison

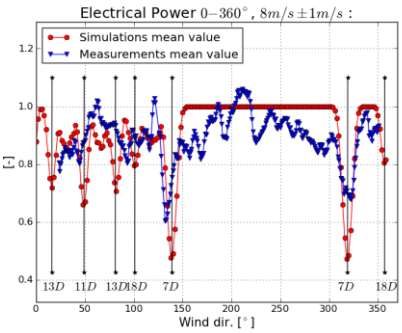




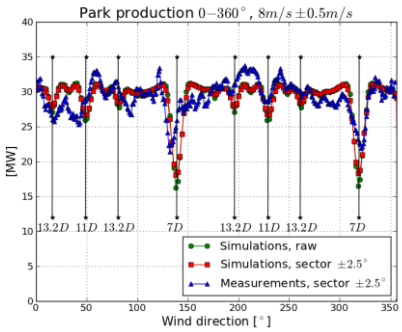


Power production for 0-360°, 8m/s

Single turbine

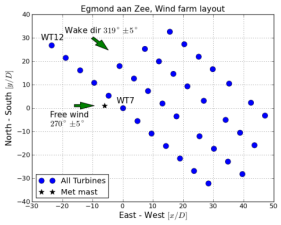


Entire wind farm



Power drops are seen in measurements and simulations for 7,11 and13D spacing.

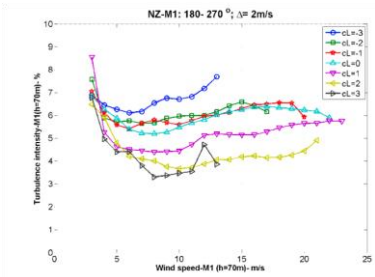
Differences may be caused by sector averaging in measurements (direction and wsp) and lack of wind direction trends in the simulations.

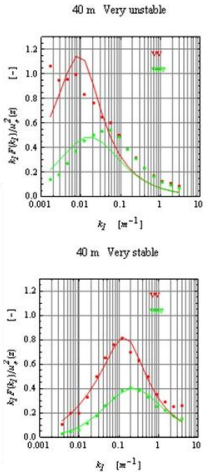


Influence of atmospheric stability

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

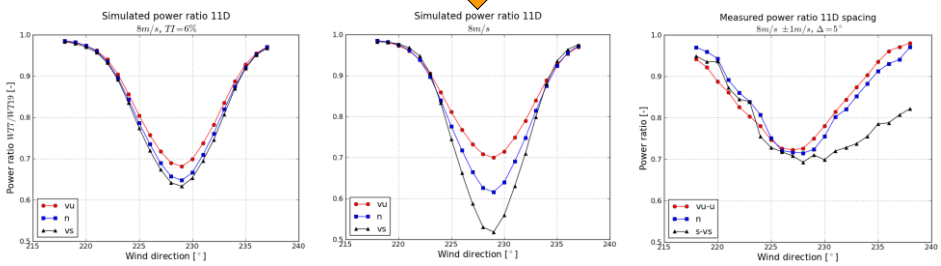
Unstable condition causes higher turbulence in combination with an increase in the low frequent contribution



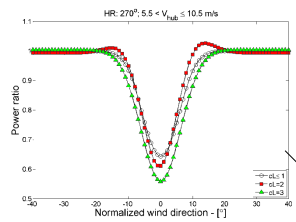


Results of stability study, Egmond aan Zee

Turbulence intensity matching measured levels



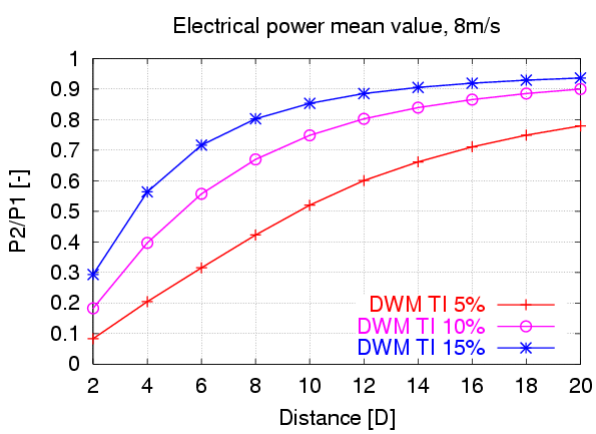
Turbulence intensity constant at 6%



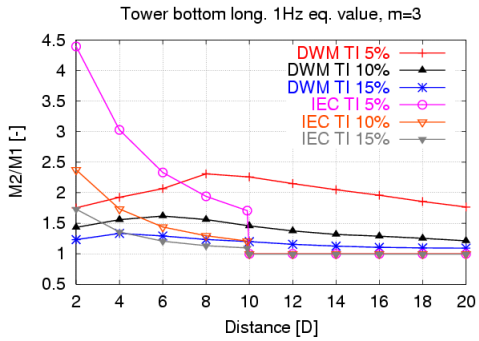
Measurements extracted - Too little data for final conclusions

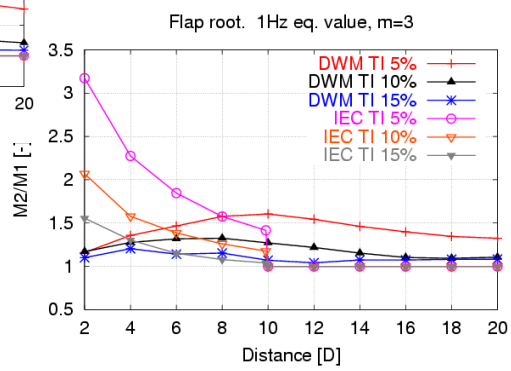
K. Hansen et. Al, *The impact of turbulence intensity and atmospheric stability on power deficits due to wind turbine wakes at Horns Rev wind farm. Wind Energy 2011*

Effect on power by turbine spacing and ambient turbulence (neutral cond.).



Effect on fatigue loads by turbine spacing and ambient turbulence. 8m/s



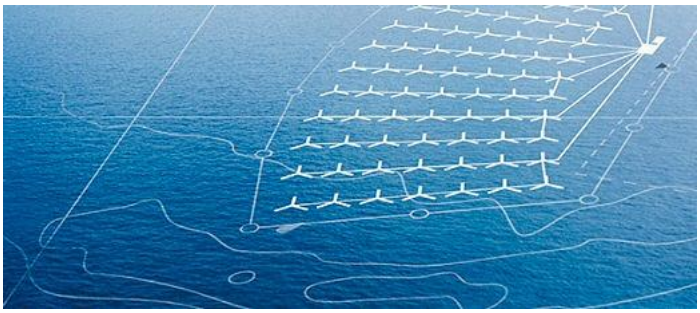


Input parameters

An example is also presented in the last part of the manual (version 4.1 and more recent versions)

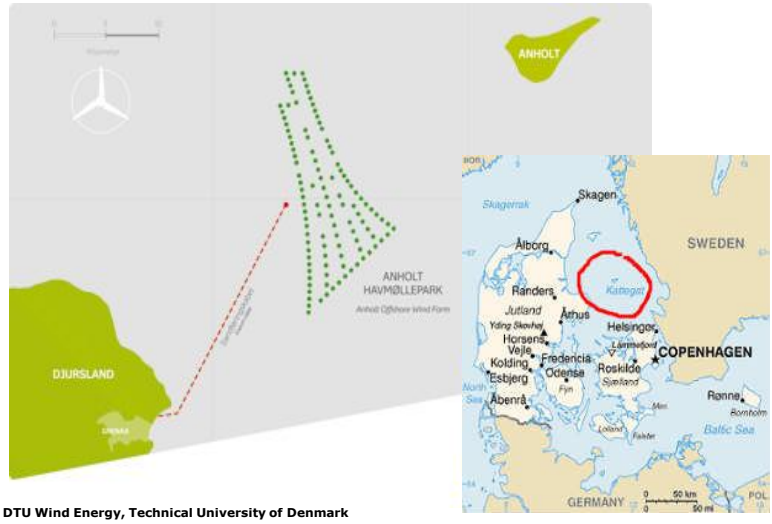
```
begin wakes;
   nsource 35;
   source_pos   2548        2900        -70         ;
   source_pos   2123        2417        -70         ;
   …
   source_pos   3813        -205        -70         ;
   source_pos   3163        -944        -70         ;
   source_pos   2679        -1495       -70         ;
   source_pos   2254        -1979       -70         ;
   source_pos   1829        -2463       -70         ;
   source_pos   1404        -2947       -70         ;
   op_data      1.42 2 ; rotor speed rad/sec, pitch [grader] (free conditions setting);
   begin mann_meanderturb ;
     create_turb_parameters 33.6 1 3.7 508 0.0 ;      L, alfaeps,gamma,seed, highfrq compensation
     filename_u    ./free_sector_monopile/wake-meander/wake_meand_turb_wsp8_s508_t1800u.bin ;
     filename_v    ./free_sector_monopile/wake-meander/wake_meand_turb_wsp8_s508_t1800v.bin ;
     filename_w    ./free_sector_monopile/wake-meander/wake_meand_turb_wsp8_s508_t1800w.bin ;
     box_dim_u   16384 1.7578125 ;
     box_dim_v     32 90 ;
     box_dim_w     32 90 ;
   end mann_meanderturb;
;
   begin mann_microturb ;
     create_turb_parameters 8.0 1.0 0.0 508 1.0 ;      L, alfaeps,gamma,seed, highfrq compensation
     filename_u    ./free_sector_monopile/wake-micro/wake_turb_wsp8_s508_t1800u.bin ;     wake-turbulence
     filename_v    ./free_sector_monopile/wake-micro/wake_turb_wsp8_s508_t1800v.bin ;
     filename_w    ./free_sector_monopile/wake-micro/wake_turb_wsp8_s508_t1800w.bin ;
     box_dim_u   128 1.0 ;
     box_dim_v     128 1.0 ;
     box_dim_w     128 1.0 ;
   end mann_microturb;
  end wakes;
```

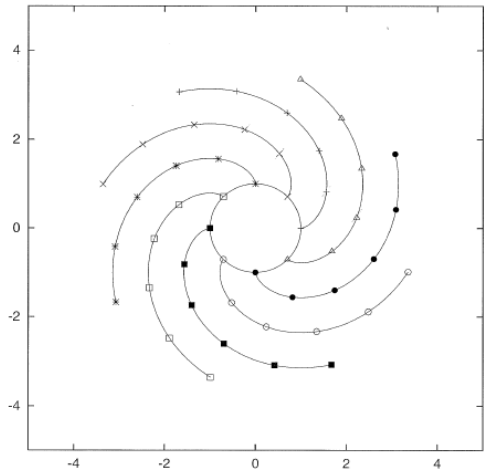
The layout of Horns rev2



DTU Wind Energy, Technical University of Denmark

The new layout of the Anholt wind farm



DTU Wind Energy, Technical University of Denmark

A different possible outcome -based on evolvente expressions