Wake effects

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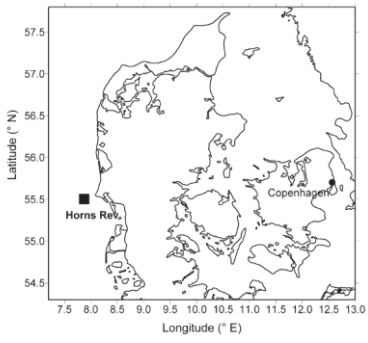
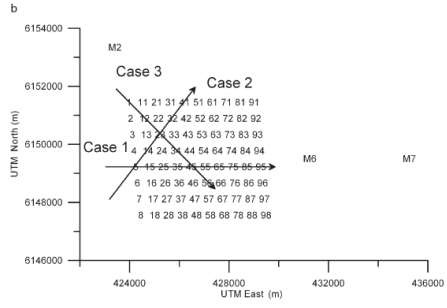
What is it – and why is it so important?

The presence of neighbouring turbines causes:

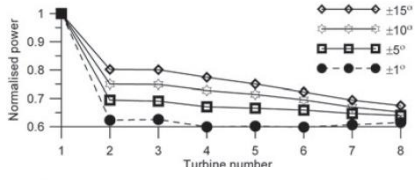
1. Reductions in windspeed.
2. Increased turbulence – turbine components fails (especially yaw system).

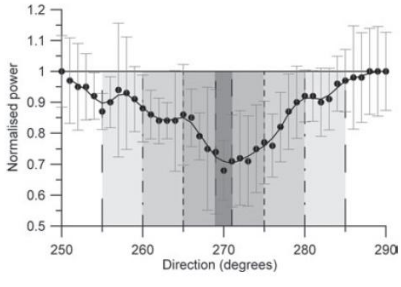
Observations from Horns rev 1





Horns rev



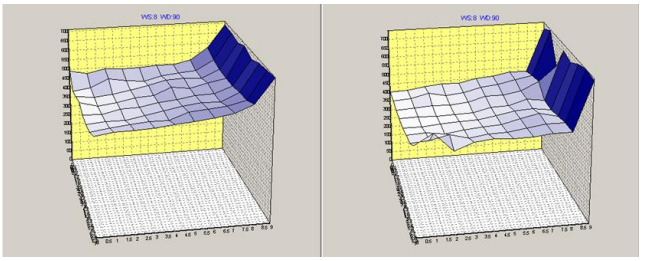


Models for power prediction exist but nearly all only depend on the upwind turbine thrust coefficient. Large uncertainty present.

Horns rev: Stability effects

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

Unstable



Neutral

20% reduction in power 40% reduction in power

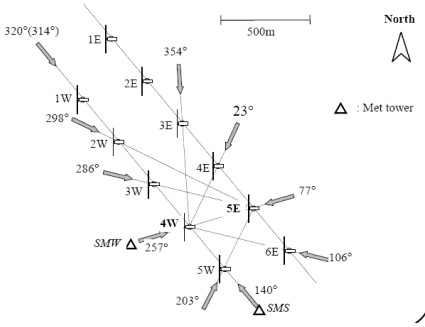
Example:

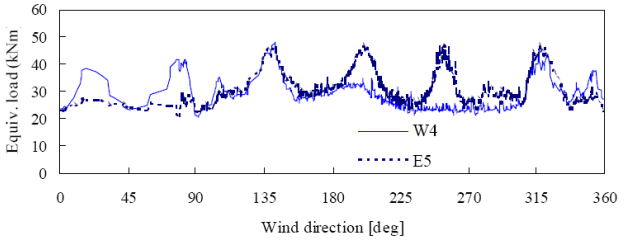
Unstable afternoon

Example:

Stable night

Load measurements on Vindeby 11 Bonus 450kW



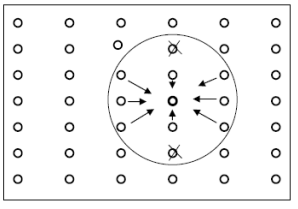


Assessment of turbulence intensity IEC61400-1, Frandsen 2003

For fatigue loads:

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

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

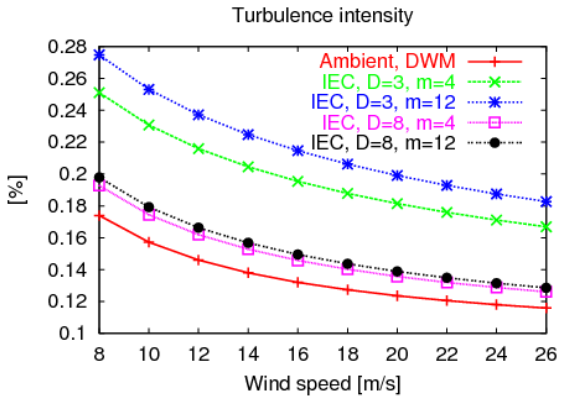


$$\sigma_1 \geq I_{\text{eff}} \cdot V_{\text{hub}} + 1{,}28\,\hat{\sigma}_{\sigma}$$

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

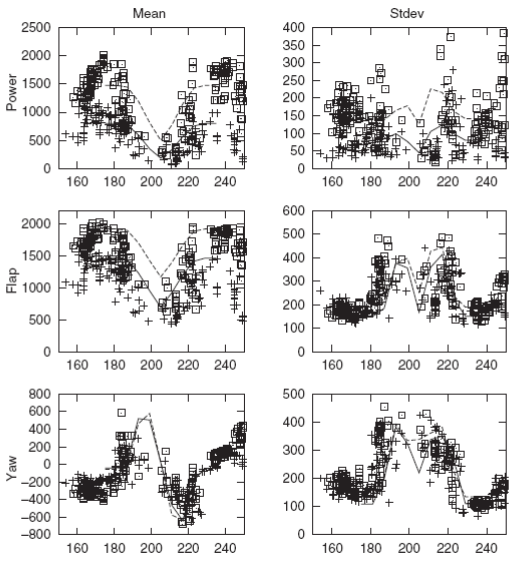


Figure 5. Measured and simulated loads at 8 m s^{-1} (full lines and crosses) and 10 m s^{-1} (broken lines and squares)

Focus on the yaw moment

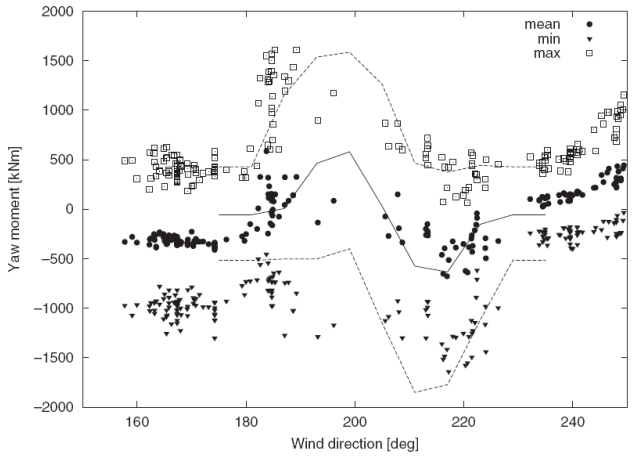
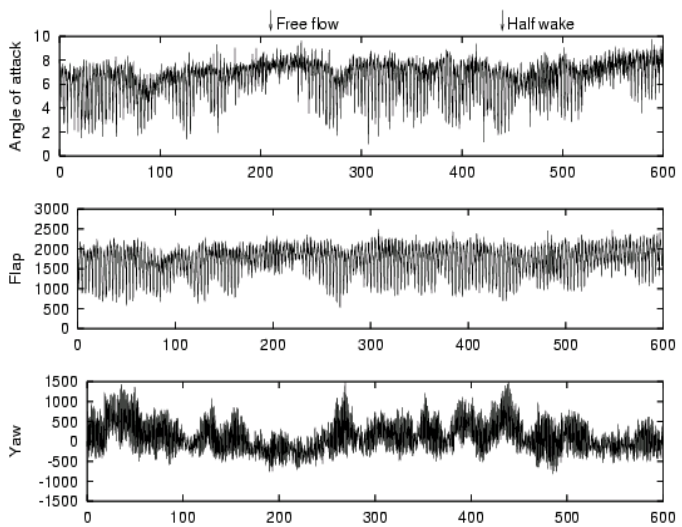


Figure 11. Extremes of yaw moment in a 3×3D wake situation at 9–11 m s^{-1}

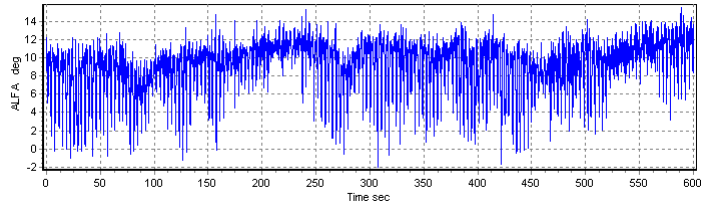
Observations on NM80



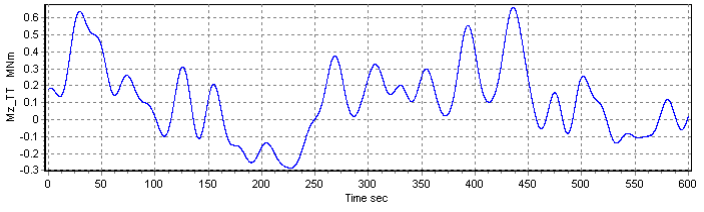
Observations on NM80

- Increased yaw moments in partial wake situations as caused by a meandering wake deficit

LOCAL INFLOW ANGLE



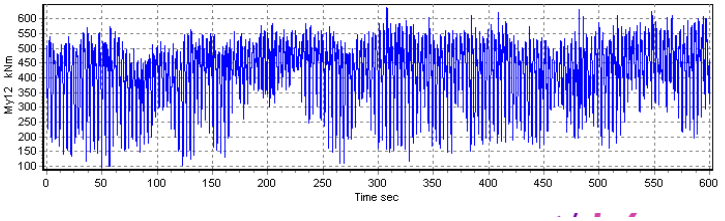
FILTERED YAW MOMENT



Observations on NM80

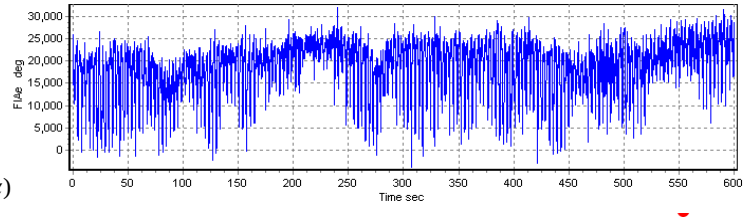
- Intermittent character of a fatigue generating flapwise load pattern as caused by a meandering wake deficit

FLAPWISE MOMENT



Derived load signal from measured "alfa" and local relative velocity.

Uncalibrated

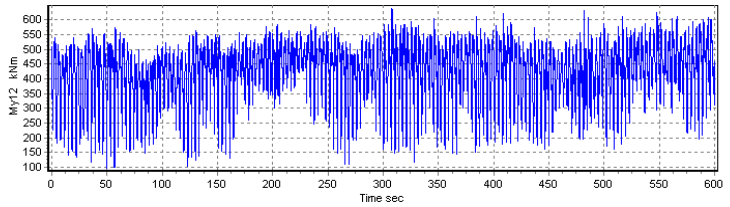


$$F_{aero} \approx W^2 (2\pi\alpha)$$

Observations on NM80

- Intermittent character of a fatigue generating flapwise load pattern as caused by a meandering wake deficit

FLAPWISE MOMENT



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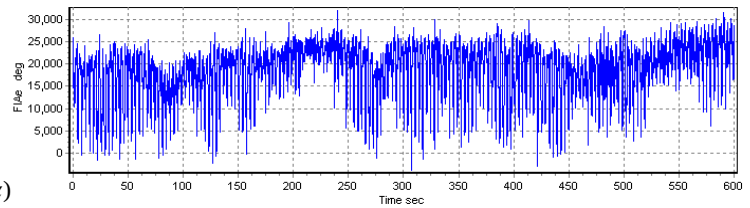
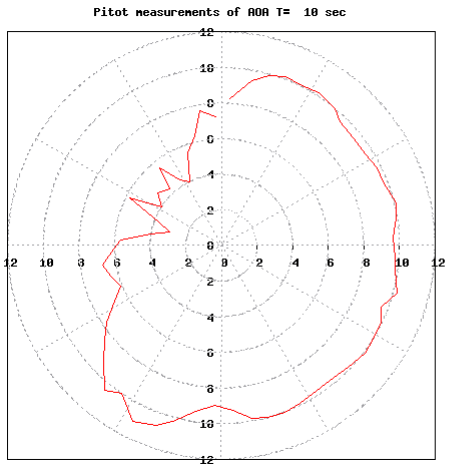


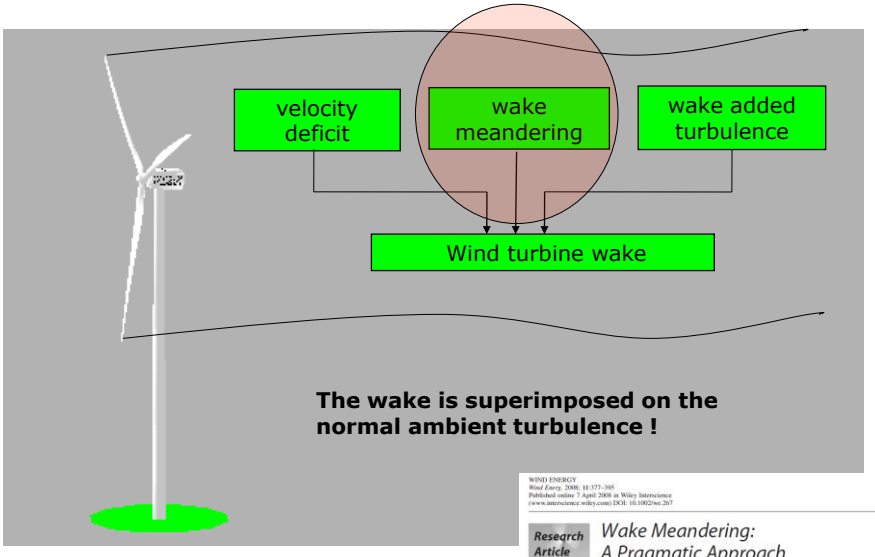
$$F_{aero} \approx W^2 (2\pi\alpha)$$

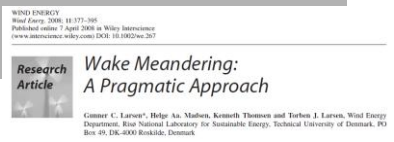
Observations on NM80

- Wake deficit dynamics illustrated by measured AOA



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




WIND ENERGY
Wind Energy, 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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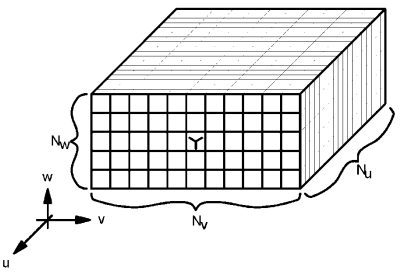
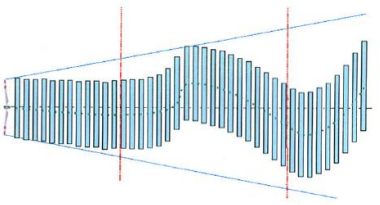
The Meandering

- 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)

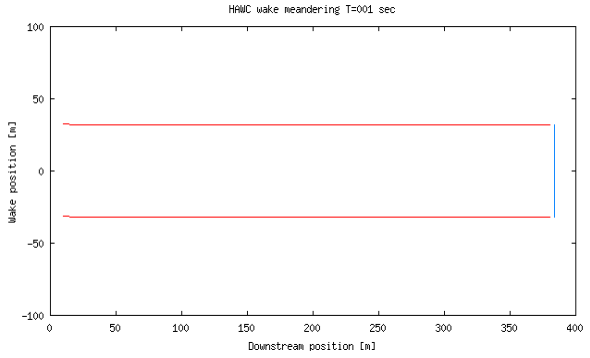
$$\frac{dy(t,t_0)}{dt} = v_c(y,z,t,t_0)$$

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



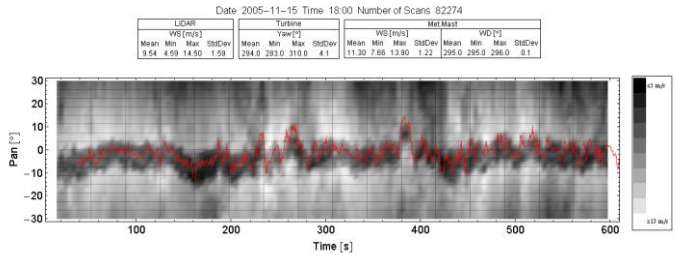


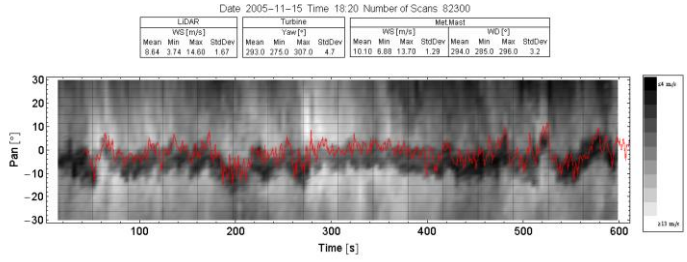
Simulation of wake deficit meandering



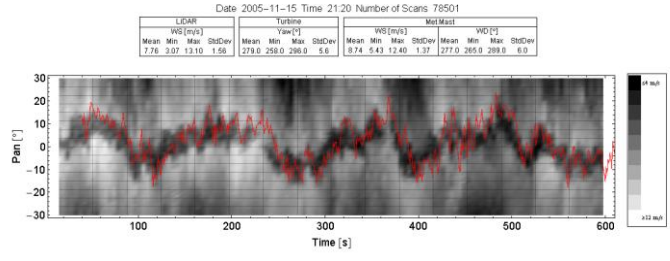
The Tellus experiment

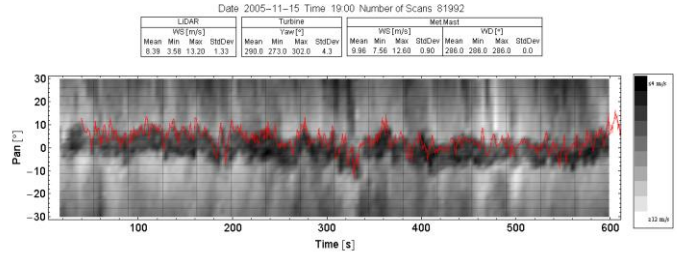
Results -1D line scan (1)



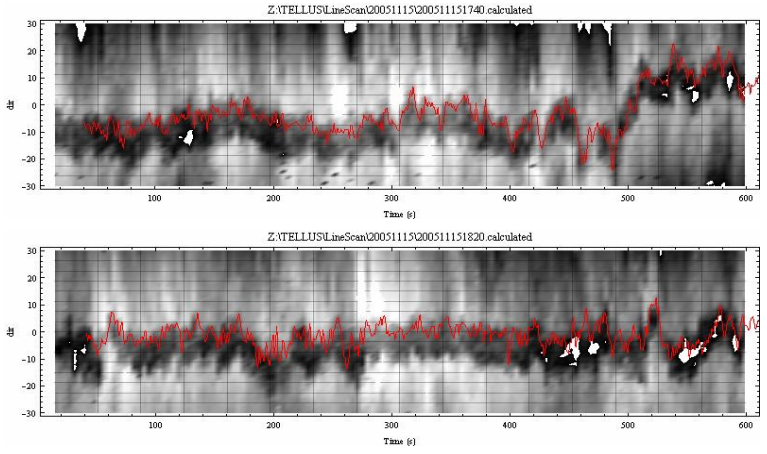


Results -1D line scan (2)

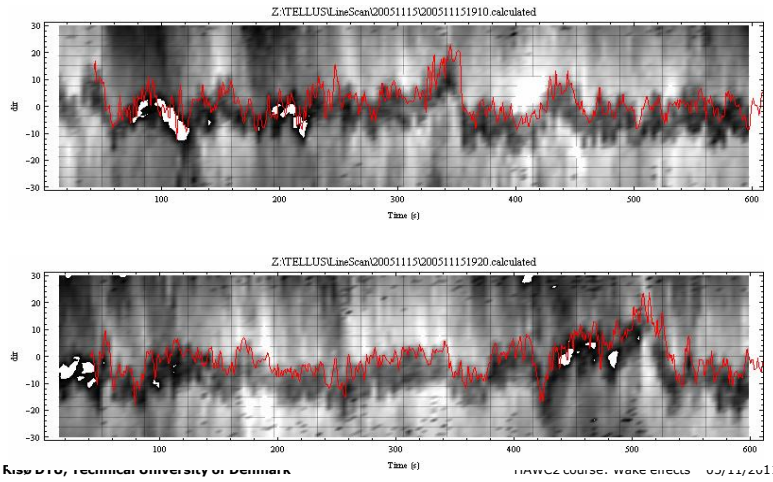




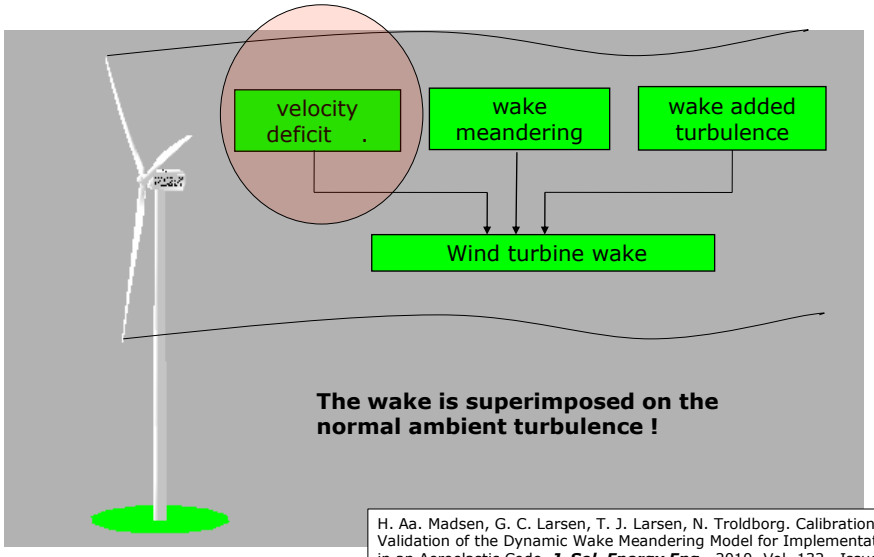
Results -1D line scan (3)



Results -1D line scan (4)



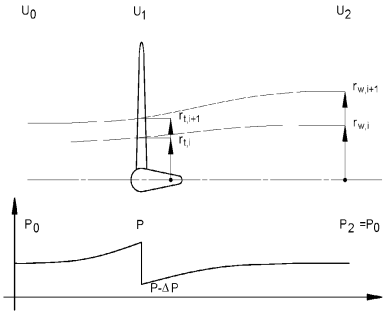
Derivation of the velocity deficit in local meandering coordinates



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.



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

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

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

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.

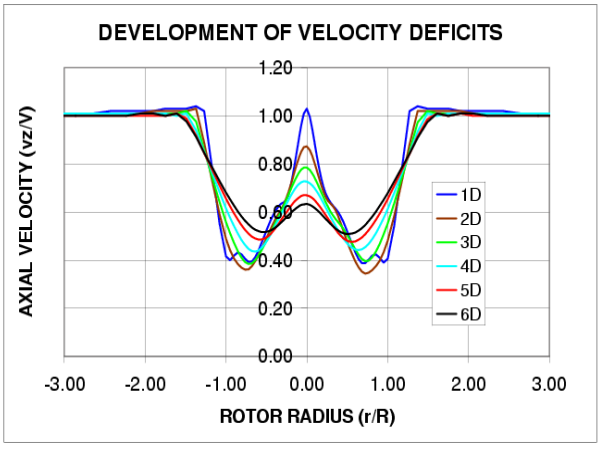
$$U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial r}=\left(\frac{\upsilon_T}{r}\right)\frac{\partial}{\partial r}\left(r\frac{\partial U}{\partial r}\right)$$

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

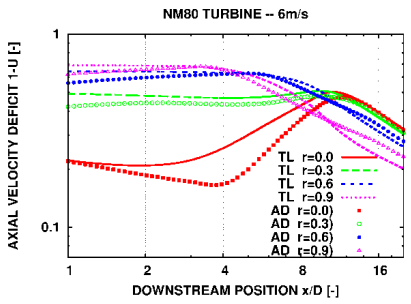
The eddy viscosity handles turbulent mixing by small vortices due to the deficit itself and mixing from ambient turbulence.

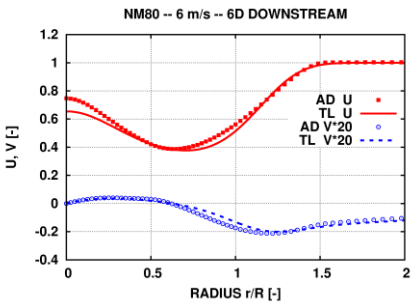
$$\upsilon_T = F_2 k_2 b\left(U_0 - U_{def,\min}\right) + F_1 \upsilon_{TA} \quad ,$$

Shear profiles for different downwind positions



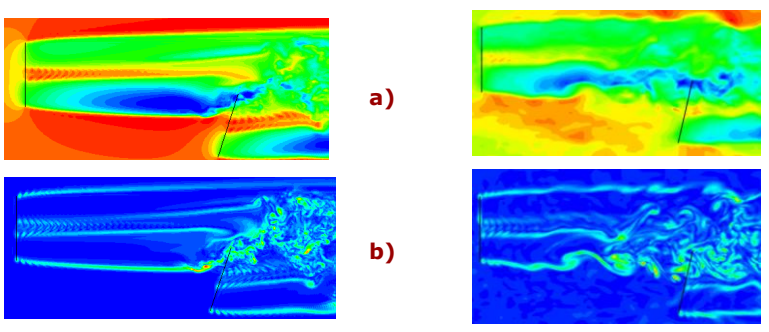
Comparison for NM80 at 6m/s





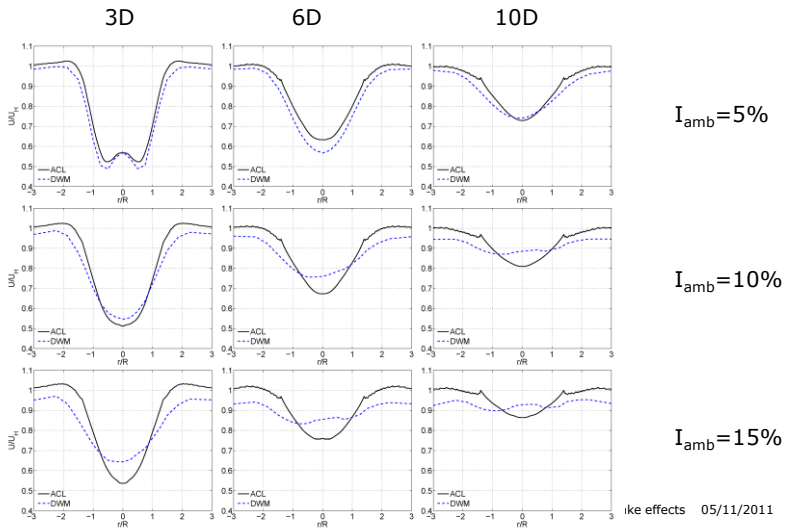
Simulations with the ACL model

no ambient turbulence **3% ambient turbulence**

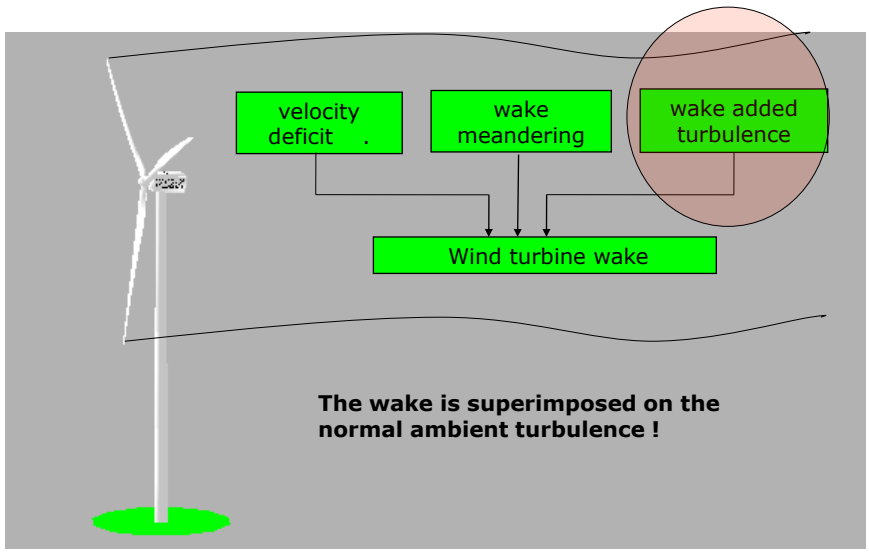


Visualization of flow field in a horizontal plane located in hub height. The rotors are indicated as black lines; a) Stream-wise velocity; b) vorticity

Comparison of AD and DWM effective deficits including meandering.



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

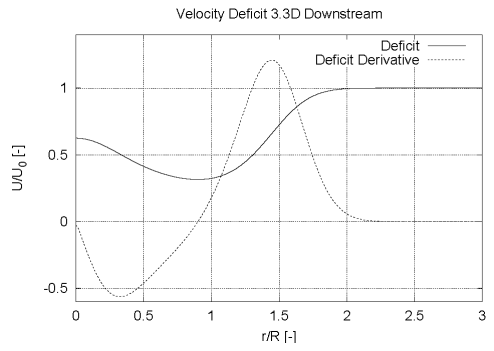


Added wake turbulence with micro structure

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

First approximation:

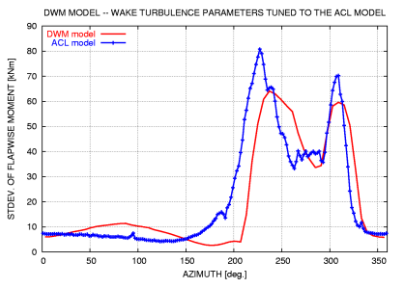
- Isotropic turbulence
- Reduced length scale compared to ambient turbulence. $L_M \approx R/10$
- Intensity proportional to depth of deficit and radial gradient of axial velocity. $k_{m1} \approx 0.6$, $k_{m2} \approx 0.35$

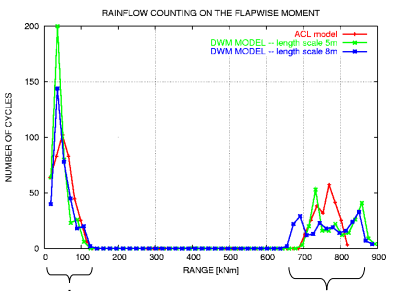


wake added turbulence intensity factor ⟶

$$k_{mt}(r) = \left|1 - U_{def}(r)\right| k_{m1} + \left|\frac{\partial U_{def}(r)}{\partial r}\right| k_{m2}$$

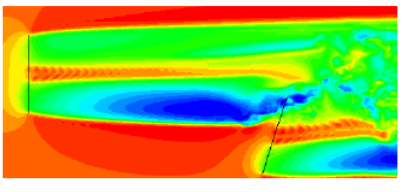
Comparison of DWM and actuator line model no ambient turbulence





Influence of wake added turbulence

Influence of velocity deficit



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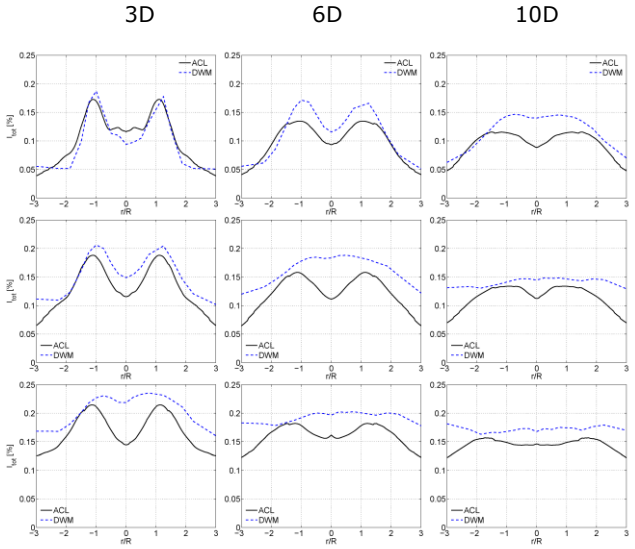
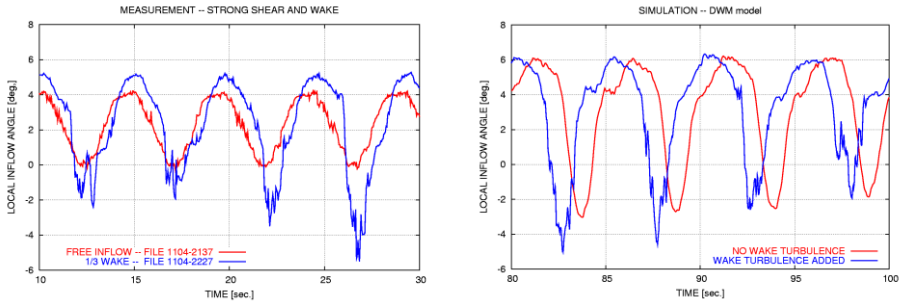
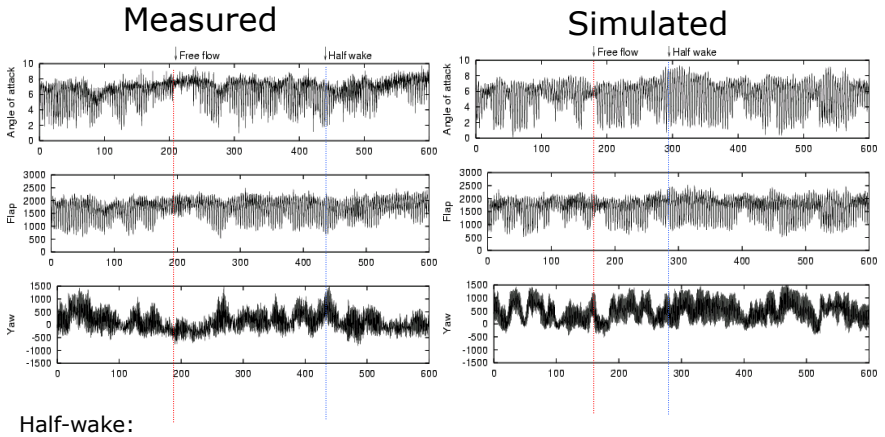


Influence of added wake turbulence



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
  tint_meander 0.1572 ;
  op_data      1.8 0 ;1.87 0.0 rad/sec, pitch [grader] opstrøms;
  begin mann_meanderturb ;
    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 ;
    std_scaling   1.0 0.8 0.5 ;
  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 ;
    std_scaling   1.0 1.0 1.0 ;
  end mann_microturb;
end wakes;
```

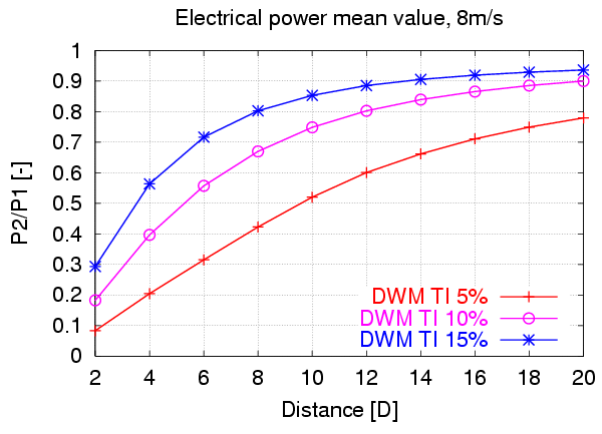
An example is also presented in the last part of the manual (version 4.1)

Influence on power production and loads by turbine spacing and turbulence intensity using the DWM model

Torben J. Larsen, Helge A. Madsen, Gunner Larsen, Niels Troldborg, N. Johansen

Euromech 20.-22. October 2009, Madrid

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



WIND ENERGY
Wind Energ. 2011; **00**:1–??
DOI: 10.1002/we

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 Larsen, Kurt S. Hansen

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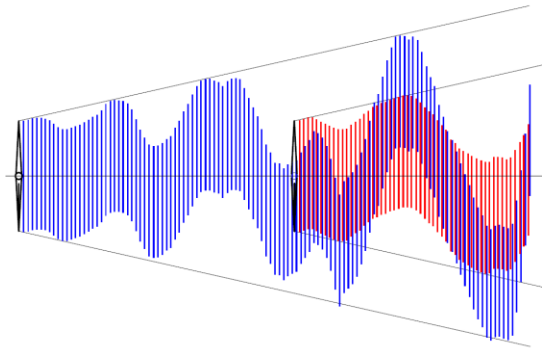
Meander path from multiple turbines - straight forward extension of DWM

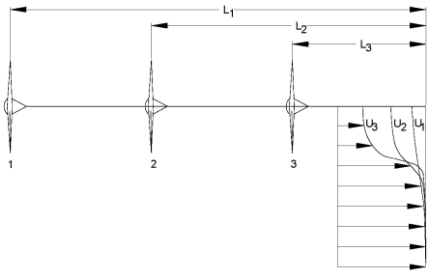


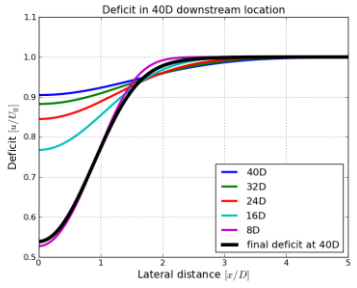
The wakes from two turbines (or more) only rarely coincide. Even in full wake direction, the path's will be different.

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

Wakes from multiple turbines

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



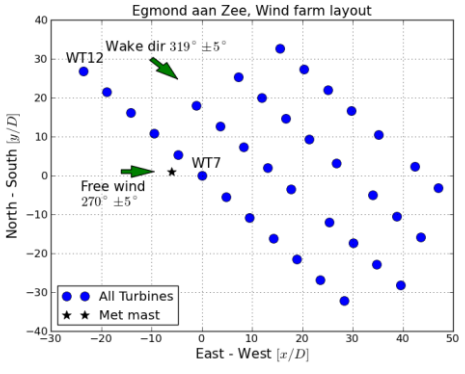


Deficits from individual turbines are compared with a more accurate solution including the wake of the upstream turbines.

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

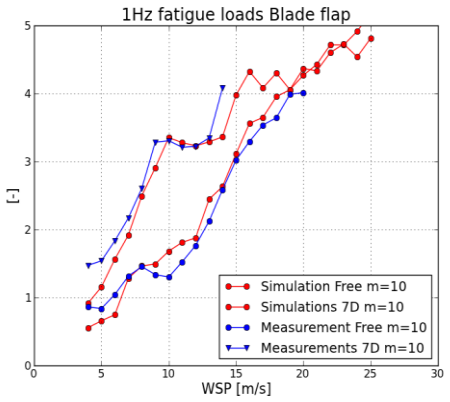
A good and practical approximation: $u_{def,final}(r) = \mathrm{MIN}(u_{def,i..N}(r))$

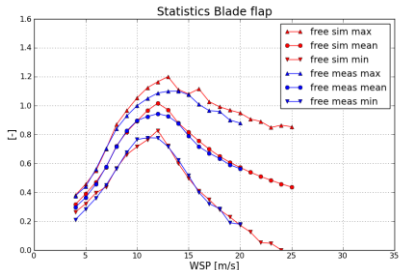
Comparison of loads for the Egmond aan Zee windfarm

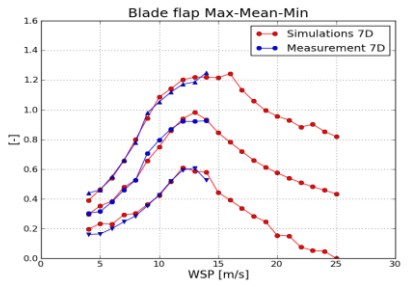


Comparison of loads

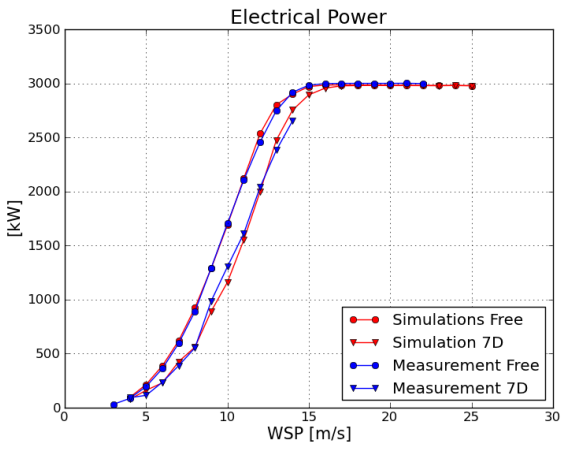
- Fatigue and mean loads



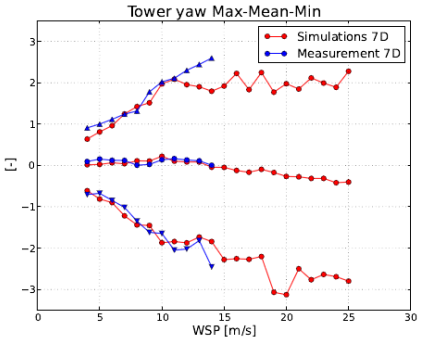


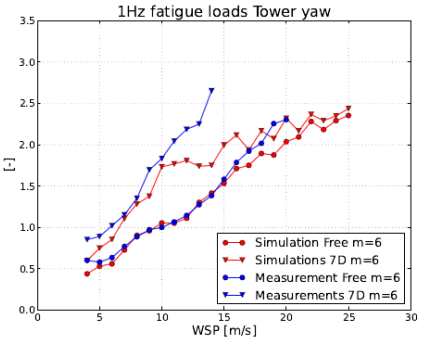


Comparison of power production

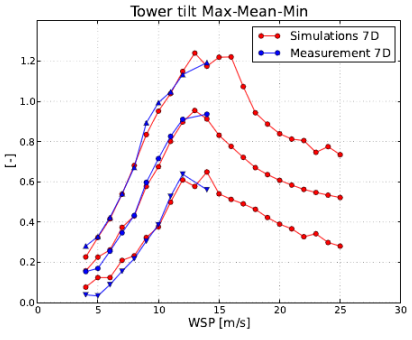


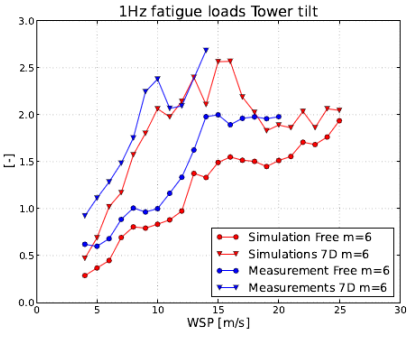
Yaw moment



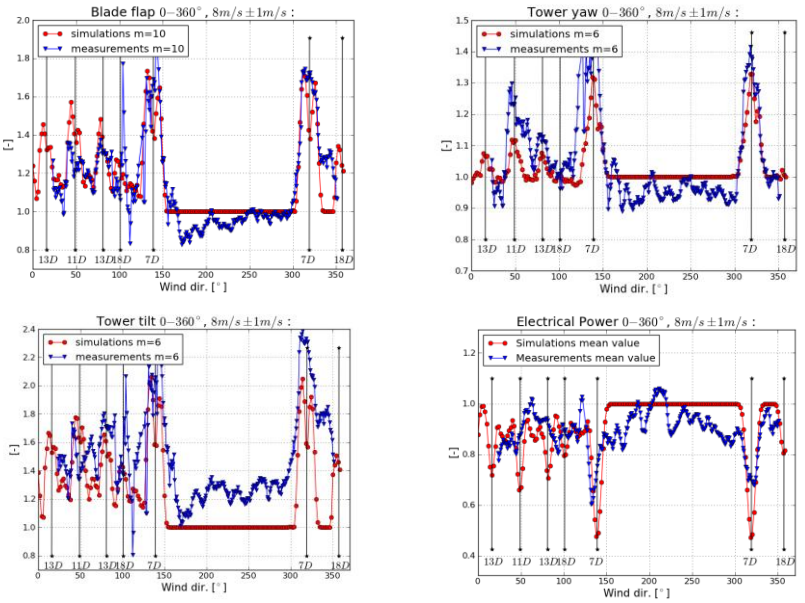


Tower bending

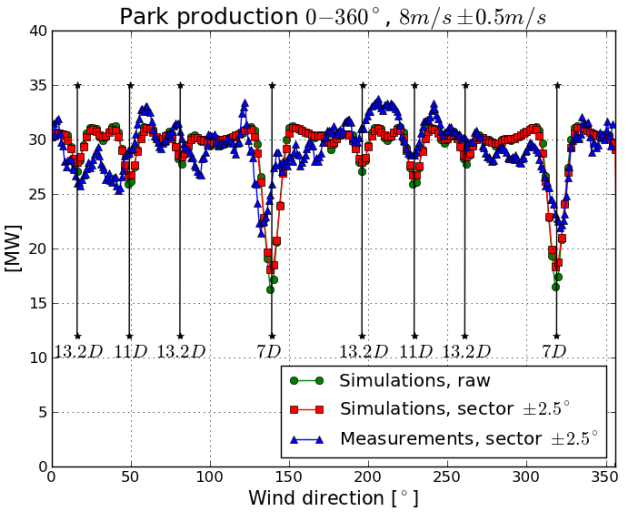




Loads for 0-360°, 8m/s



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



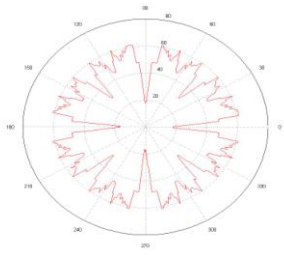
Production sensitivity to wind direction and ambient turbulence level, simulated with the DWM model.

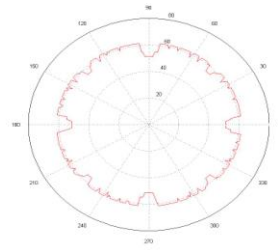
A Wind farm configured in a cartesian 5x5 grid with a spacing of 8D.

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.

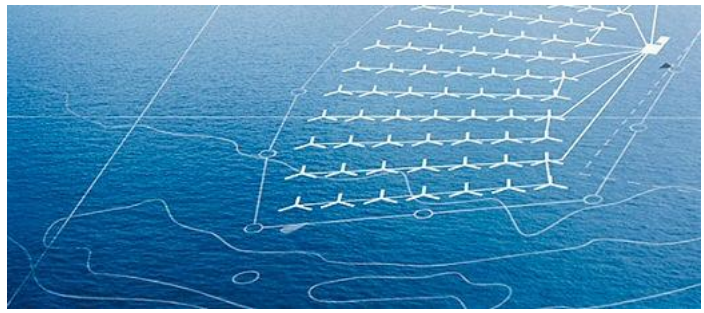
The decrease is from 60MW to 20MW for the worst situation.

DO NOT PLACE TURBINES IN STRAIGHT ROWS!

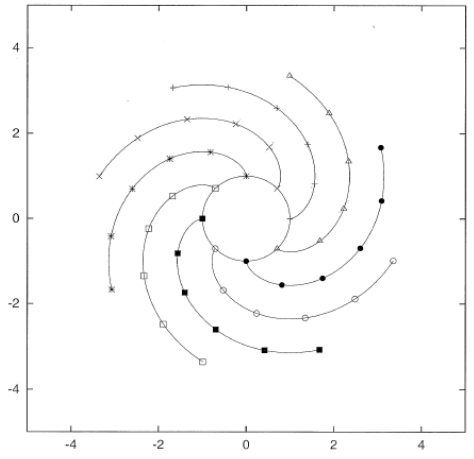




The new layout of Horns rev2



A different possible outcome -based on evolvente expressions



Torben J. Larsen 10. Dec. 2008