Wake effects

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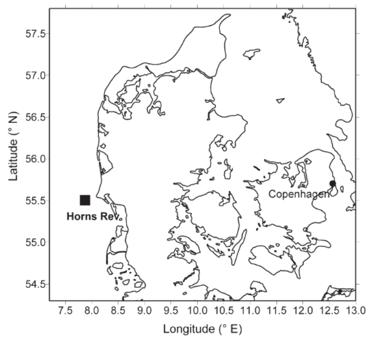
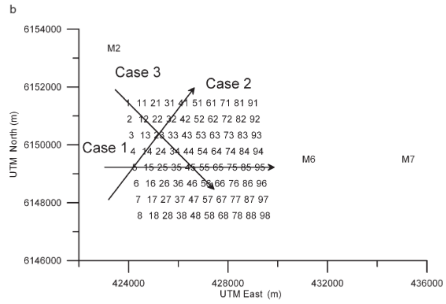
What is it – and why is it so important?

The presence of neighbouring turbines causes:

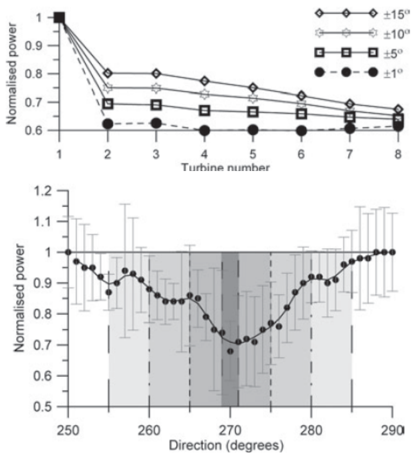
1. Reductions in windspeed.
2. Increased turbulence – turbine components fails (especially yaw system).

Observations from Horns rev 1





Horns rev

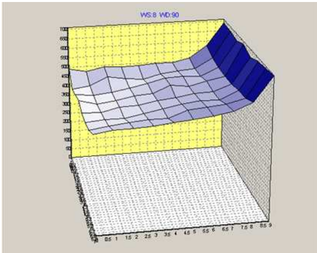


Models for power prediction exist but nearly all only depend on the upwind turbine thrust coefficient. Large uncertainty present.

Horns rev: Stability effects

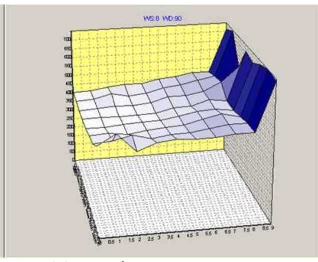
- Measurements from Danish (offshore) wind farms revealed a significant dependence of wake losses on atm. stability conditions.

Unstable



20% reduction in power

Neutral



40% reduction in power

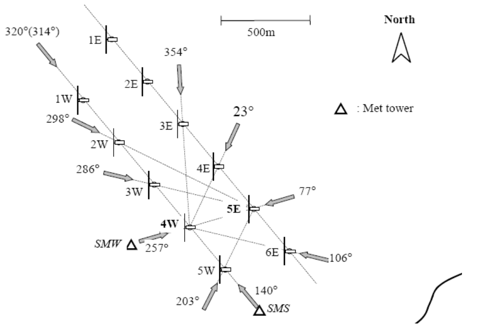
Example:

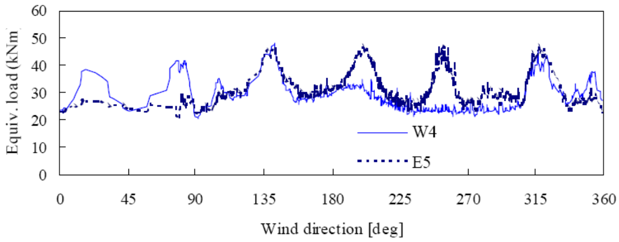
Unstable afternoon

Example:

Stable night

Load measurements on Vindeby 11 Bonus 450kW



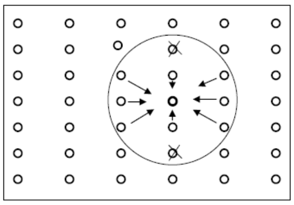


Assessment of turbulence intensity IEC61400-1, Frandsen 2003

For fatigue loads:

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

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

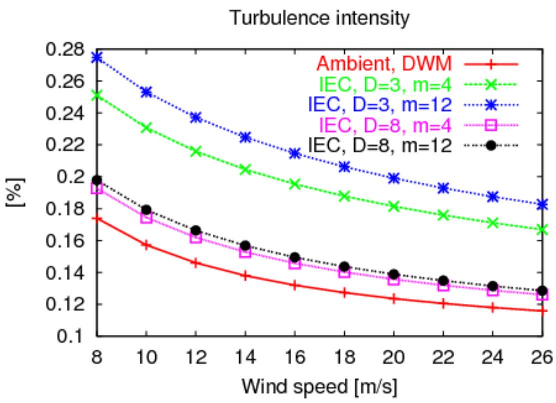


$$\sigma_1 \geq I_{\text{eff}} \cdot V_{\text{hub}} + 1{,}28\,\hat{\sigma}_{\sigma}$$

For extreme loads:

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

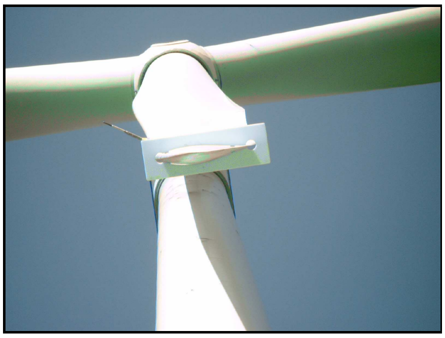
Used turbulence intensity for the IEC method



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

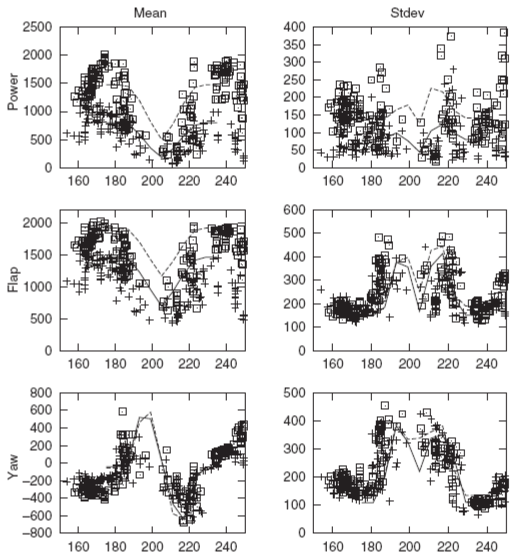


Figure 5. Measured and simulated loads at 8 m s⁻¹ (full lines and crosses) and 10 m s⁻¹ (broken lines and squares)

Focus on the yaw moment

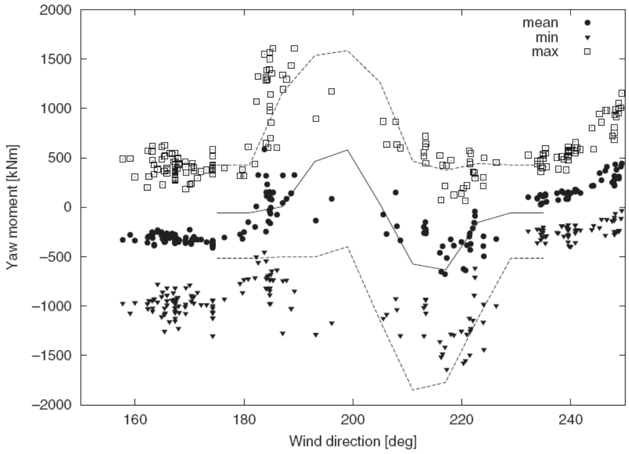
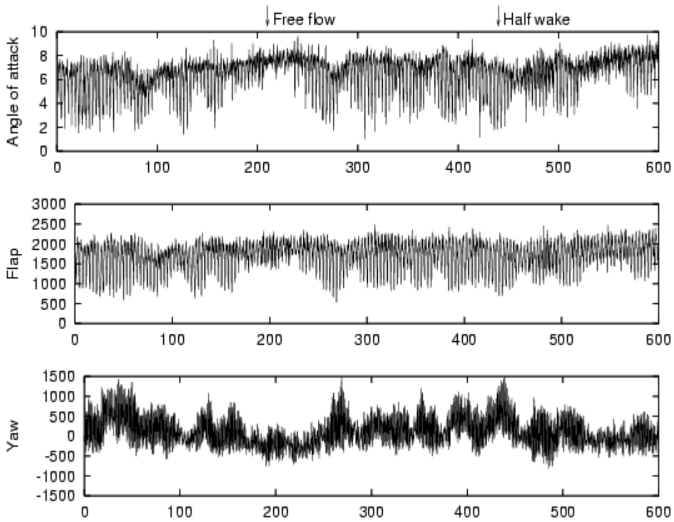


Figure 11. Extremes of yaw moment in a 3·3D wake situation at 9–11 m s⁻¹

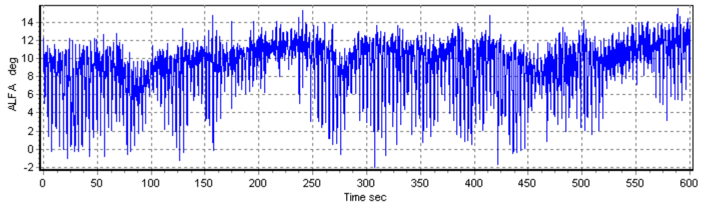
Observations on NM80



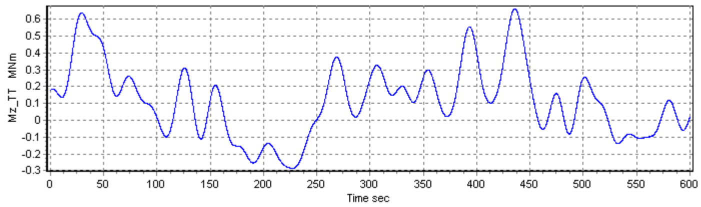
Observations on NM80

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

LOCAL INFLOW ANGLE



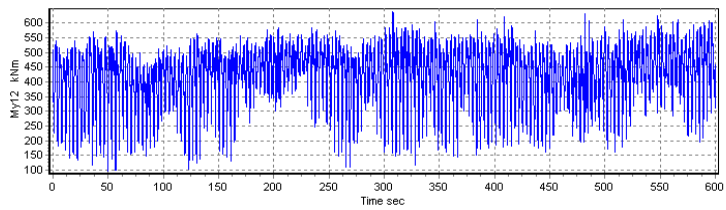
FILTERED YAW MOMENT



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

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

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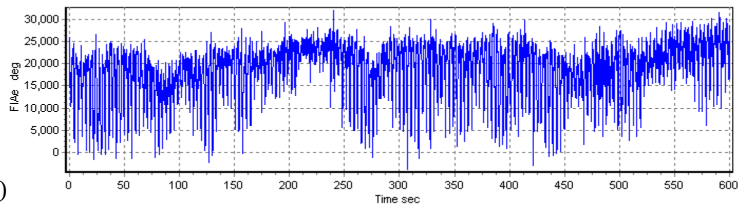

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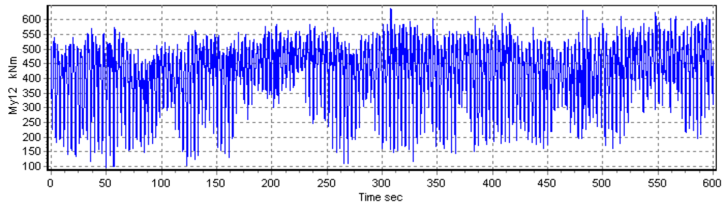
FLAPWISE MOMENT



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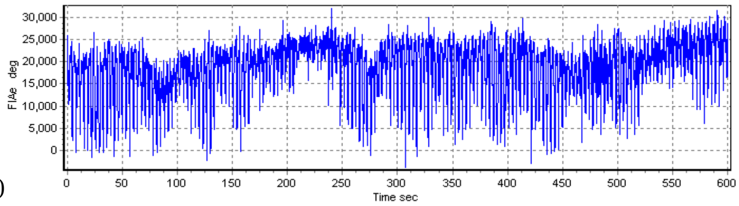
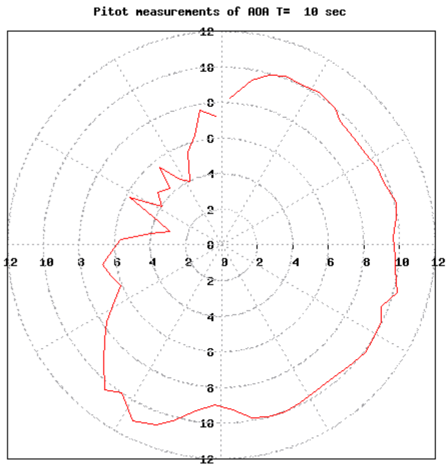


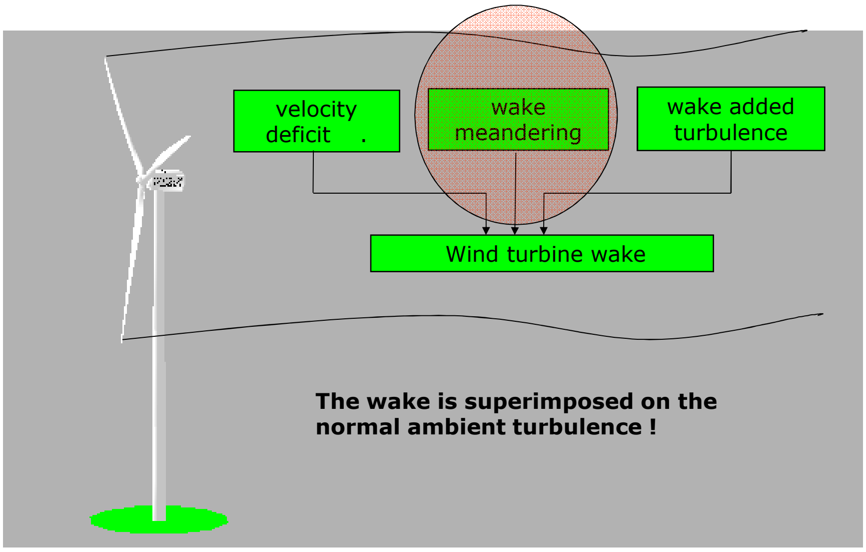
$F_{aero} \approx W^2 (2\pi\alpha)$

Observations on NM80

- Wake deficit dynamics illustrated by measured AOA



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

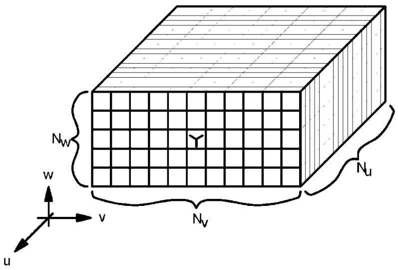


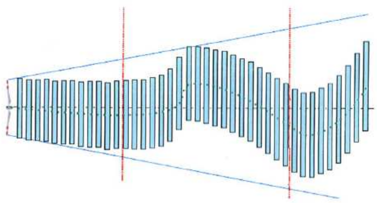
The Meandering

- 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)

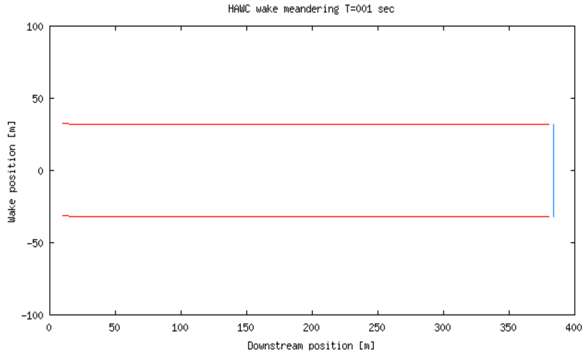
$$\frac{dy(t,t_0)}{dt} = v_c(y,z,t,t_0)$$

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





Simulation of wake deficit meandering

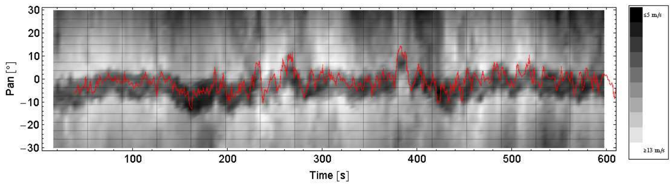


The Tellus experiment

Results -1D line scan (1)

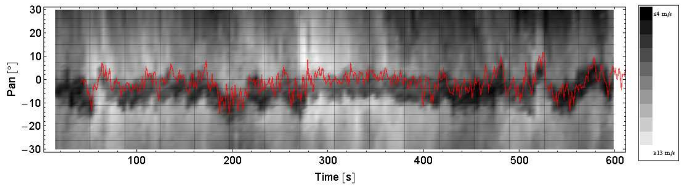
Date 2005–11–15 Time 18:00 Number of Scans 82274

LiDAR WS [m/s]				Turbine Yaw [°]				Met.Mast WS [m/s]				Met.Mast WD [°]			
Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev
9.54	4.59	14.50	1.59	294.0	283.0	310.0	4.1	11.30	7.66	13.90	1.22	295.0	295.0	296.0	0.1



Date 2005–11–15 Time 18:20 Number of Scans 82300

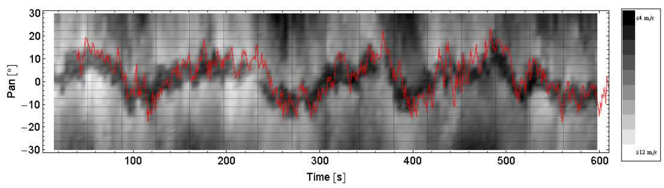
LiDAR WS [m/s]				Turbine Yaw [°]				Met.Mast WS [m/s]				Met.Mast WD [°]			
Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev
8.64	3.74	14.60	1.67	293.0	275.0	307.0	4.7	10.10	6.88	13.70	1.29	294.0	285.0	296.0	3.2



Results -1D line scan (2)

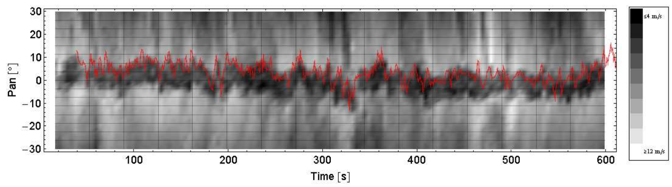
Date 2005–11–15 Time 21:20 Number of Scans 78501

LiDAR WS [m/s]				Turbine Yaw [°]				Met.Mast WS [m/s]				Met.Mast 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

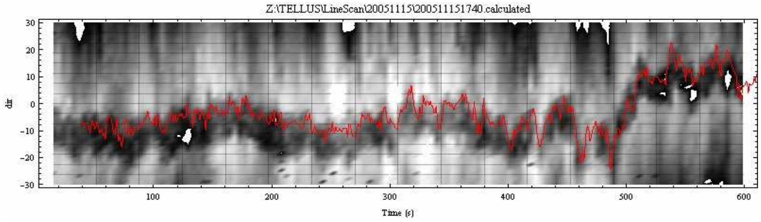


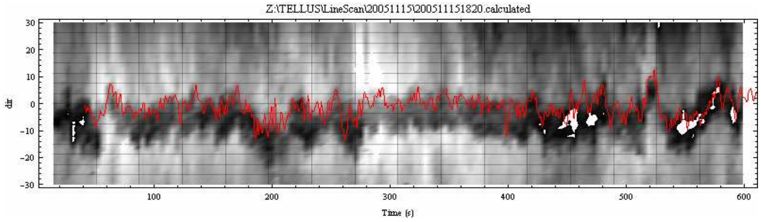
Date 2005–11–15 Time 19:00 Number of Scans 81992

LiDAR WS [m/s]				Turbine Yaw [°]				Met.Mast WS [m/s]				Met.Mast 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

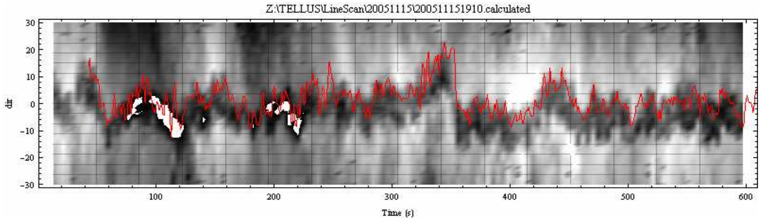


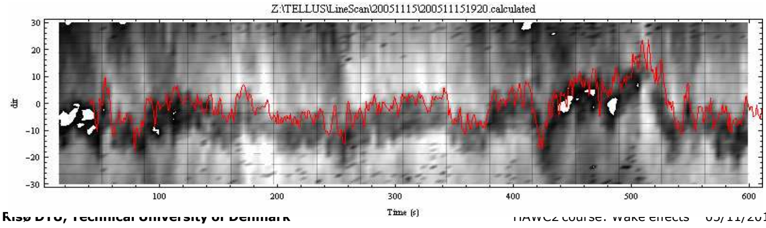
Results -1D line scan (3)



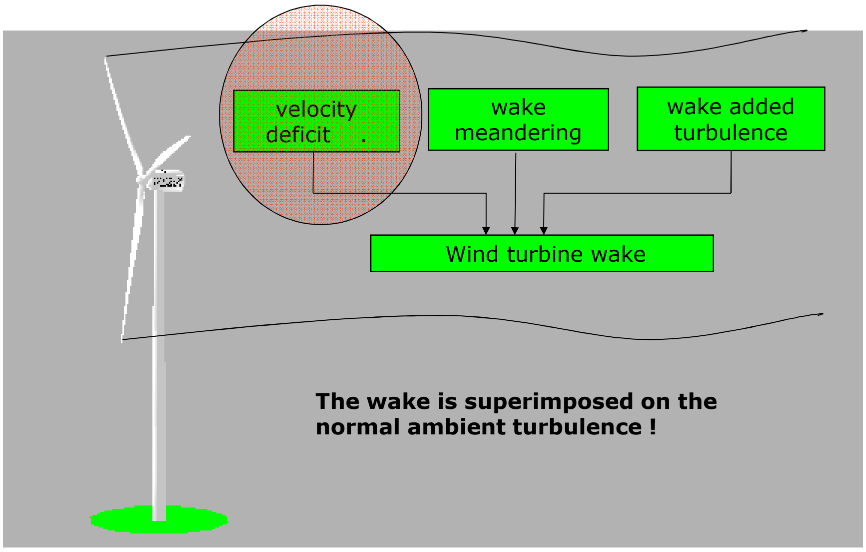


Results -1D line scan (4)



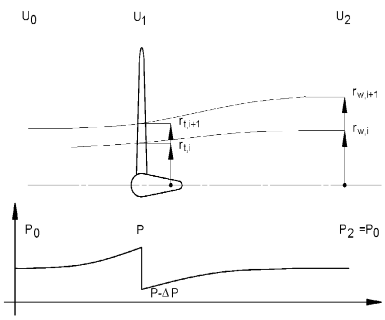


The basic idea of the Dynamic Wake Meander model (DWM)



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.



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

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

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

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.

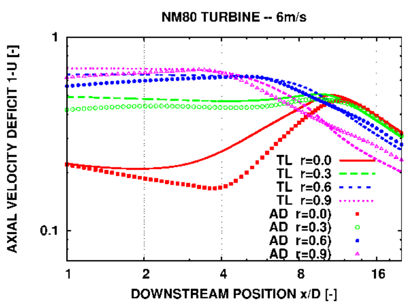
$$U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial r}=\left(\frac{\upsilon_T}{r}\right)\frac{\partial}{\partial r}\left(r\frac{\partial U}{\partial r}\right)$$

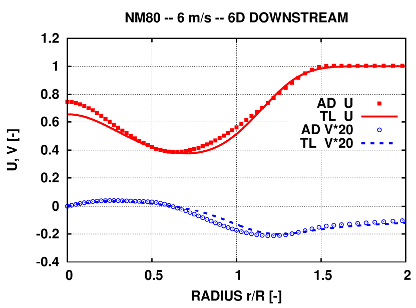
$$\frac{1}{r}\frac{\partial}{\partial r}(rV)+\frac{\partial U}{\partial x}=0$$

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

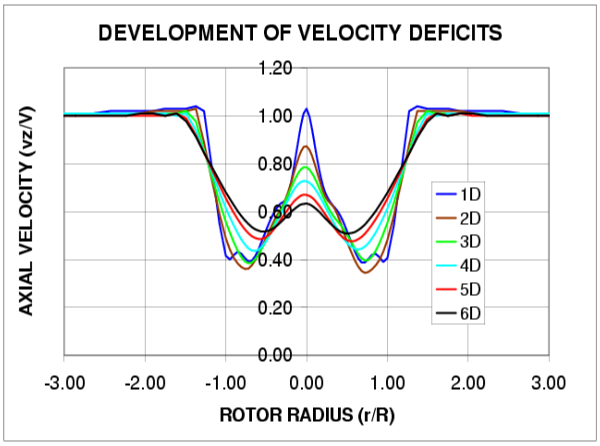
$$\upsilon_T = F_2 k_2 b\left(U_0 - U_{def,\min}\right) + F_1 \upsilon_{TA} \quad ,$$

Comparison for NM80 at 6m/s



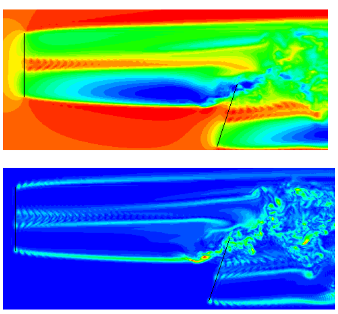


Shear profiles for different downwind positions



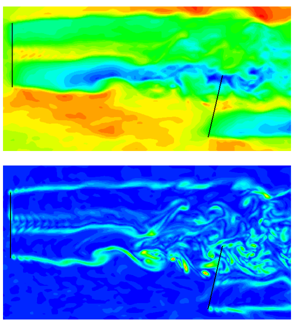
Simulations with the ACL model

no ambient turbulence **3% ambient turbulence**



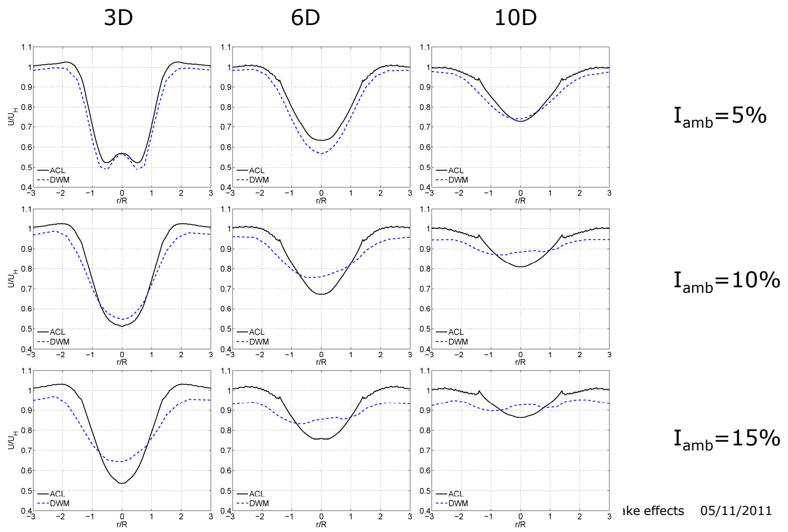
a)

b)

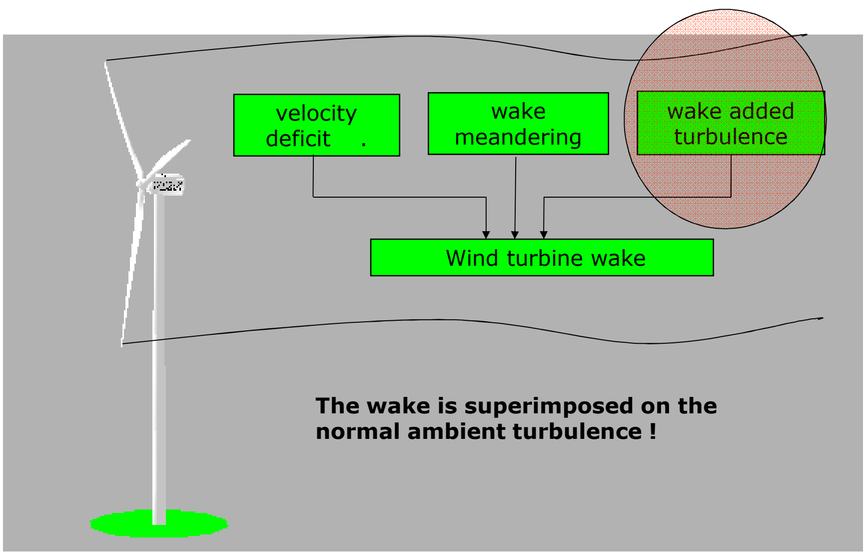


Visualization of flow field in a horizontal plane located in hub height. The rotors are indicated as black lines; a) Stream-wise velocity; b) vorticity

Comparison of AD and DWM effective deficits including meandering.



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

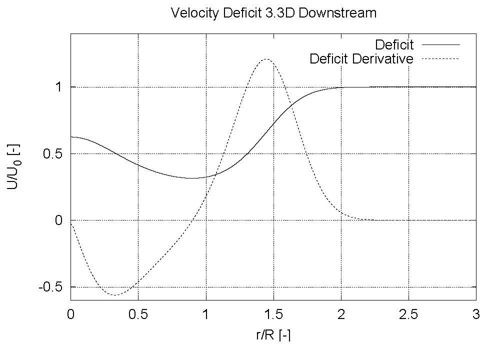


Added wake turbulence with micro structure

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

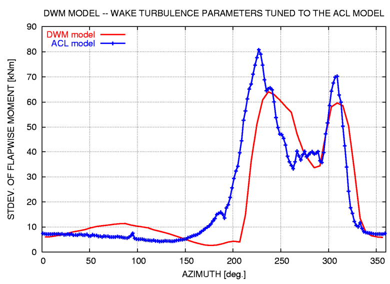
First approximation:

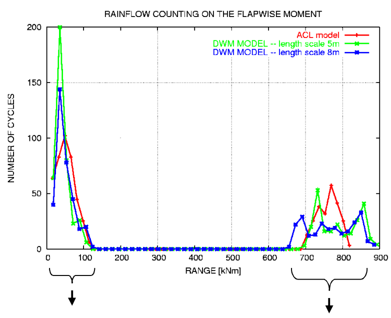
- Isotropic turbulence
- Reduced length scale compared to ambient turbulence. $L_M \approx R/10$
- Intensity proportional to depth of deficit and radial gradient of axial velocity. $k_{m1} \approx 0.6$, $k_{m2} \approx 0.35$



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

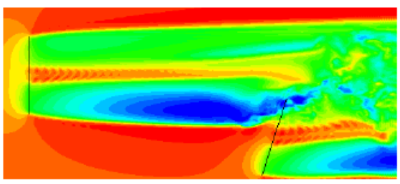
Comparison of DWM and actuator line model no ambient turbulence



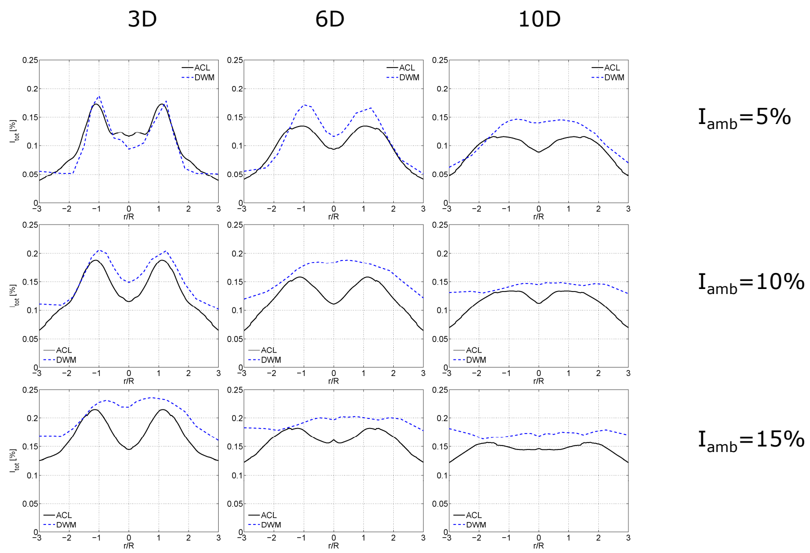


Influence of wake added turbulence

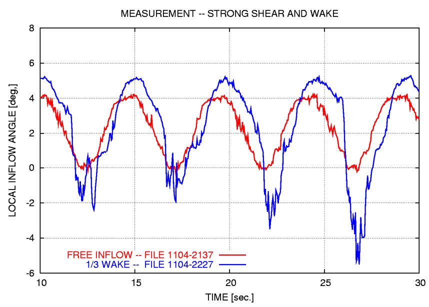
Influence of velocity deficit

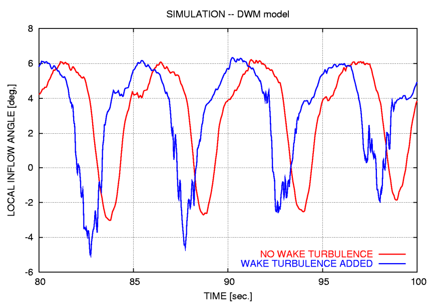


Comparison of AD and DWM effective turbulence intensity.

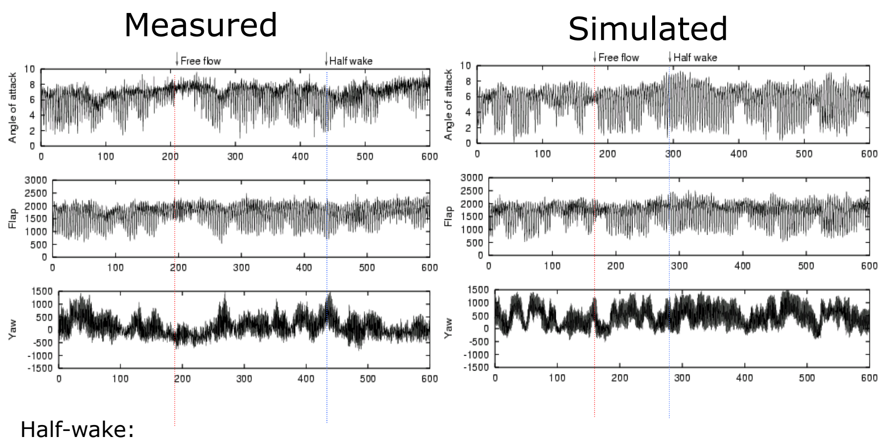


Influence of added wake turbulence





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;
```

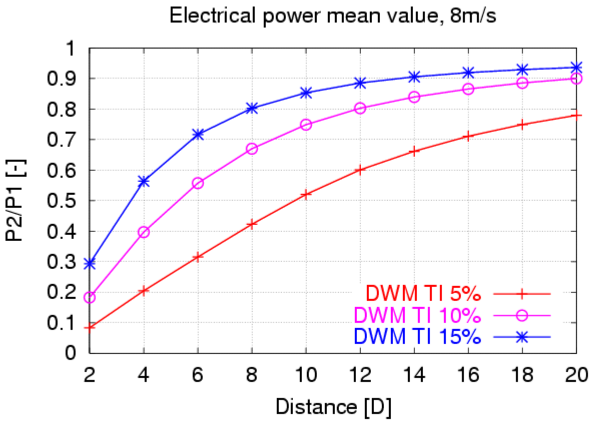
Influence on power production and loads by turbine spacing and turbulence intensity using the DWM model

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

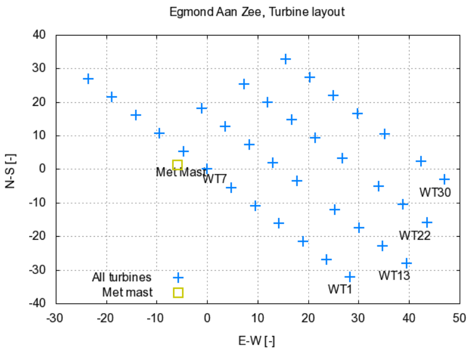
Euromech 20.-22. October 2009, Madrid

1) H. Aa. Madsen, G. C. Larsen, T. J. Larsen, N. Troldborg, R. Mikkelsen. Calibration and validation of the Dynamic Wake Meandering (DWM) model implemented in the aeroelastic code HAWC2. Submitted to JSEE.

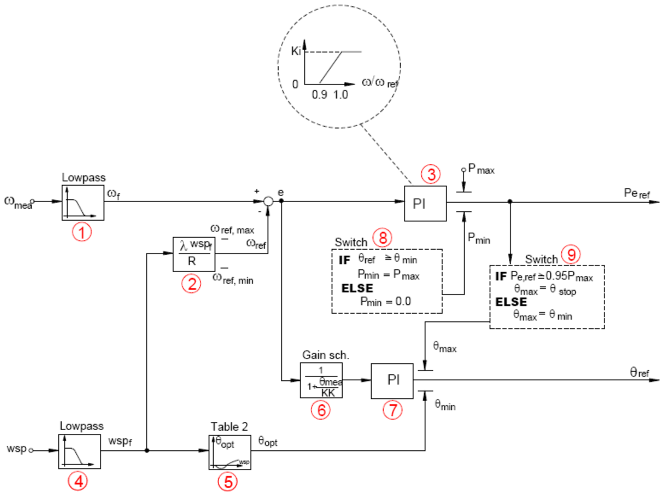
Effect on power by turbine spacing and ambient turbulence (neutral cond.).



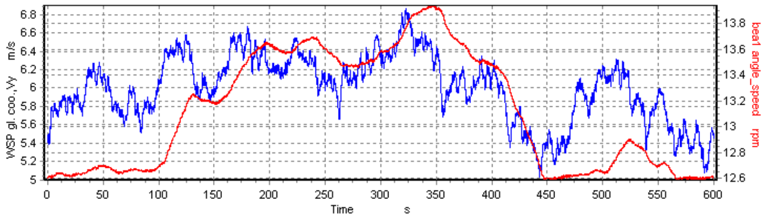
Comparison of loads for the Egmond aan Zee windfarm

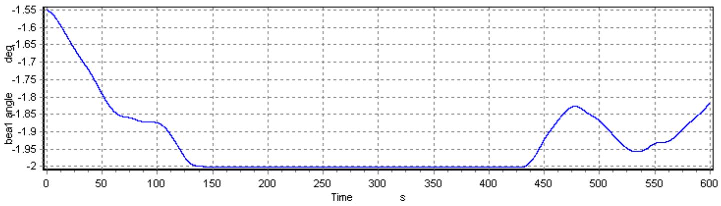


Pitch control generated

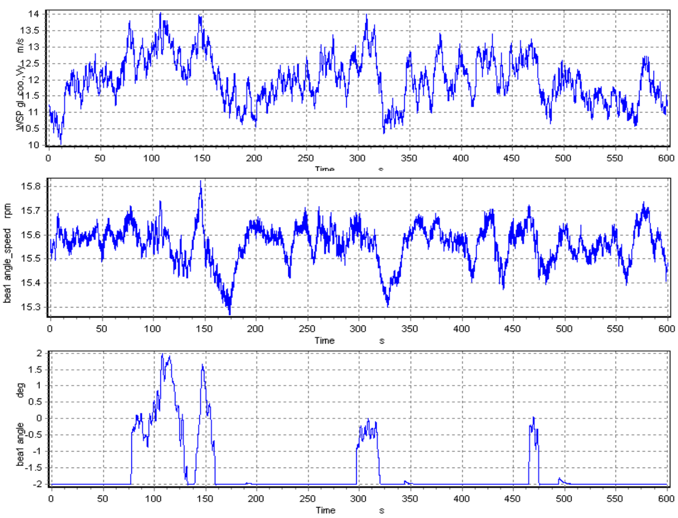


Controller performance 6m/s





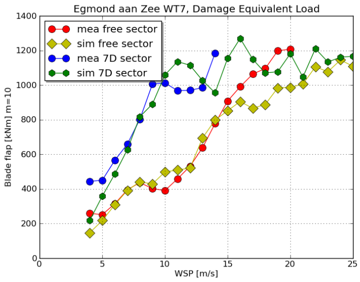
Control performance 12m/s

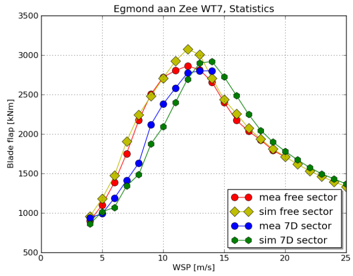


Comparison of measured and simulated loads.

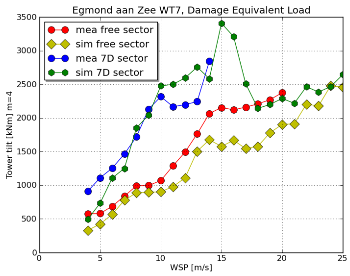
Damage eq. load DEL | Mean value

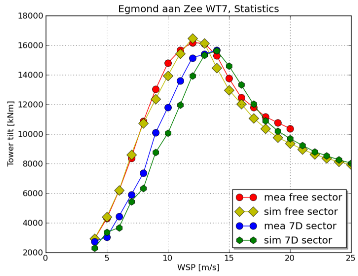
Blade Flap





Tower long. bending.

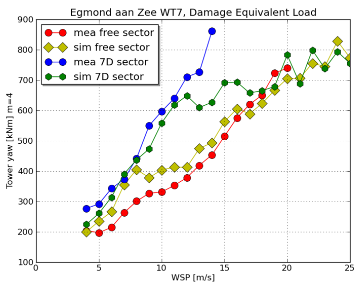




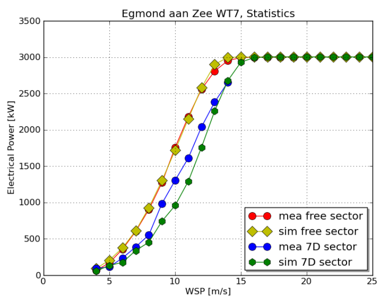
Comparison of measured and simulated loads.

Damage eq. load DEL | Mean value

Yaw moment



Electrical power.



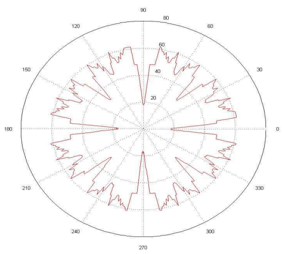
Production sensitivity to wind direction and ambient turbulence level, simulated with the DWM model.

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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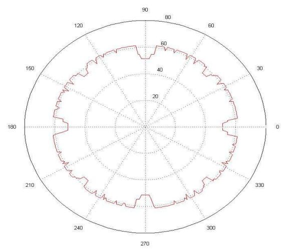
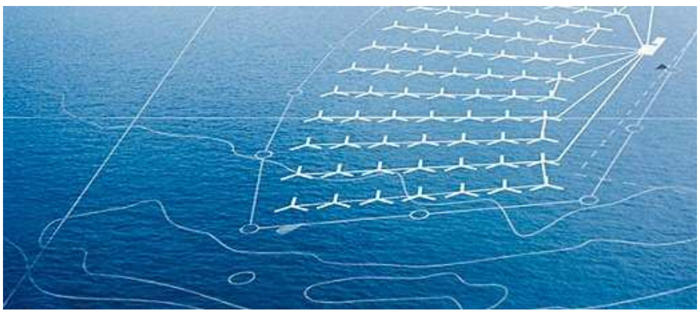
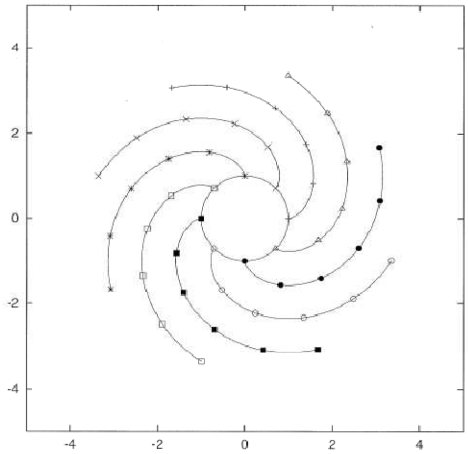


The new layout of Horns rev2



A different possible outcome -based on evolvente expressions



Torben J. Larsen 10. Dec. 2008