A quasi-steady wind farm flow model in the context of distributed control of the wind farm

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Paper presented at the European Wind Energy Conference and Exhibition (EWEC),
April 20-23, 2010, Warsaw, Poland

ECN-M--10-052 May 2005

European Wind Energy Conference (EWEC 2010)

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Abstract

This work presents a preliminary version of a quasi-static wind farm flow model which will be part of distributed control of a wind farm. In addition outcome from this model is compared to data from the ECN Wind turbine Test site Wieringermeer EWTW.

Key words Model predictive control, Wind farms, Offshore wind energy

1 Introduction

In Europe wind farms are being developed at a large scale. These installations are expected to operate similar to conventional power plants and to provide quality power at the lowest possible cost. During operation this is achieved by addressing three control objectives at the farm level: maximum power production, minimum structural loads and optimal integration into the power system. The optimal trade-off between these sometimes conflicting control objectives depends on the market price of power.

The EU project FP7-ICT STREP 22548 / Aeolus is aimed at the development of distributed control of large offshore wind farms [1, 7]. In this context amongst others quasi-static wind farm flow models are developed. Such a model, which is to be part of the supervisory control algorithm, specifies in real time the wind speed at each turbine in a wind farm plus the tower bending moment, the blade bending moment, the rotor shaft torque and the aerodynamic power of each turbine as a function of "ambient" wind speed, wind direction and turbulence intensity. In this process the average as well as the standard deviation of each quantity is considered.

The paper addresses the preliminary version of the quasi-static wind farm flow model. Apart from sub-models based on classic momentum theory [8], inspired by the literature on wind turbine wakes [2, 3, 4, 5 section 2.4, 6, 9], this model includes specially developed sub-models for the creation and the decay of velocity deficit, the creation and decay of added turbulence, the impact of turbulence on average values, and the standard deviation of all quantities. First, section 2 presents the general research objective of the FP7 project Aeolus and the specific research objectives of the flow modeling work packages. Next, in section 3 the quasi-static wind farm flow model is introduced. Section 4 continues with preliminary maps of wind, loads and energy as calculated with the model and presents comparisons with measured data from the ECN Wind turbine Test site Wieringermeer EWTW. Finally, section 5 presents a summary and outlook.

2 Objectives

The general objective of the FP7 project Aeolus is to research and develop:

- Models that allow real-time predictions of the flow in a wind farm and incorporate data from a network of sensors, and
- Control paradigms that acknowledge the uncertainty in the modeling and dynamically manage the flow resource in order to optimize specific control objectives.

Specific objectives, contained in the two flow modeling work packages, include the development of:

- Quasi-static flow models which relate single turbine production and loading to a map of wind speeds, and
- Dynamic flow models which describe deviations from a static model due to rapidly changing flow effects.

The quasi-static flow model is derived from fluid dynamics principles and is based on a database of meteorological and wind turbine related measurements. The model is scaled to provide flow information for large-scale wind farms and to allow calculation of the expected electrical power output and the expected mechanical loads. It is developed in two stages: first a preliminary version and next the final version. The preliminary version, finished by April 2009 and reported in the confidential project deliverable D1.3, is the topic of this paper.

To be more specific the quasi-static flow model is a model of the control object "wind farm"; where "model" is a mathematical map/function in the form of equations (or initially look-up tables) which relate farm state (power and fatigue measures) to measured quantities (e.g. rotor speed, blade pitch angle, wind speed), references (e.g. power set point) and disturbance (what's not modelled); see figure 1. The model is static in the sense that it is valid over averaging periods of 10 minutes, say, in contrast to the dynamic flow model which is dynamic in the sense that it describes deviations from the average.

3 Quasi-static wind farm flow model

3.1 Outline

The wind farm flow model allows one to calculate the maps of wind, loads and energy, or to be more specific the wind speed at each turbine in a wind farm plus the tower bending moment, the blade bending moment, the rotor shaft torque and the aerodynamic power of each turbine as a function of "ambient" wind speed, wind direction and turbulence intensity. Apart from the average also the standard deviation of a quantity is calculated. The sub-models in the wind farm flow model have been selected on basis of their ability to predict wind, loads and energy in a computationally fast and cheap way by using a minimum of information on the ambient wind. The corresponding flow chart is shown in figure 2.

In this section the structure of the flow model is presented. First the single wind turbine is addressed. In section 3.2 it is explained how by using momentum theory the aerodynamic state of a wind turbine is expressed in terms of an axial induction factor. Relations for the average and the standard deviation of the axial induction factor are presented which both bring the effect of turbulence into account. Subsequently section 3.3 addresses the aerodynamic power, the tower bending moment, the blade bending moment and the rotor shaft torque. Next, in section 3.4 relations for the velocity deficit and the extra turbulence due to a single wind turbine are introduced. We then proceed in section 3.5 with a cluster of wind turbines, and explain how the streamwise and the spanwise distance downstream each wind turbine is determined for a given wind direction.

3.2 Wind turbine state

The state of a wind turbine is expressed in terms of the axial induction factor or the thrust coefficient. Under the assumption that over a relatively short time period (of several seconds to several minutes) the wind speed at hub height has a Normal distribution with average μ_U and standard deviation σ_U, it is shown that the axial induction factor as well as the thrust coefficient have an approximate Normal distribution with average μ_a resp μ_{CT} and standard deviation σ_a resp σ_{CT}. Figure 3 presents the wind turbine state model.

3.3 Wind turbine production and loading

As to production and loading of the wind turbine the model considers electrical power, tower bending moment, blade bending moment and rotor shaft torque. The production and loading model is illustrated in figure 3 too. Following momentum theory the power coefficient C_P is a function of the axial induction factor. In the model tower bending moment is the sum of the moments due to the thrust on the rotor, the aerodynamic force on the tower, and the eccentricity of the nacelle. The blade bending moment originates from the axial force on the rotor blade and the tangential force due to gravity. The rotor shaft torque is the ratio of the aerodynamic power and the rotor speed.

3.4 Velocity deficit and extra turbulence due to a wind turbine

3.4.1 Velocity deficit

The model for the velocity deficit downstream of a wind turbine is based on quite a large amount of experimental evidence [2, 6, 9] and theoretical work [3, 4, 5 section 2.4] which support a power law decay in streamwise direction x and a gaussian decay in spanwise direction r. Figure 4 presents the flow chart of this model. The velocity μ at a position (r,x) in the wake of a single turbine is:

$$\mu(r,x) = \mu_0 - \Delta\mu(r,x), \tag{1}$$

where μ_0 is the upstream velocity and Δμ is the velocity deficit:

$$\frac{\Delta\mu(r,x)}{\Delta\mu_{ini}} = \left(\frac{x}{2D}\right)^n \exp\left\{-\alpha_1 \frac{r^2}{\beta^2(x)}\right\} \tag{2}$$

with

$\Delta\mu_{ini} = 2a\mu_0$,

$n = -1.04 \pm 0.07$,

$\alpha_1 = 0.693$,

and

$$\frac{2\beta(x)}{D} = \gamma\left(\frac{x}{D}\right)^\delta \tag{3}$$

where

$\gamma = 0.3$ and $\delta = 0.63$.

Here $\Delta\mu_{ini}$ is the initial value of the velocity deficit which is reached at a distance of two rotor diameters behind the wind turbine and according to momentum theory has the value $2a\mu_0$ where a is the axial induction factor. The parameter β gives the spanwise size of the region of velocity deficit.

3.4.2 Added turbulence

Turbulence downstream of a wind turbine is modeled on basis of experimental evidence [6] and theoretical work [5 section 2.4] which express it in terms of the velocity standard deviation σ, and which support a power law decay in streamwise direction and a gaussian decay in spanwise direction. Figure 4 shows the flow chart. At a position (r,x) in the wake of a single turbine the velocity variance is the sum of the upstream velocity variance σ_0^2 and the velocity variance σ^2_{add} added by the wind turbine:

$$\sigma^2(r,x) = \sigma_0^2 + \sigma^2_{add}(r,x). \tag{4}$$

The added variance σ^2_{add} is the sum of two components, each originating from the production of turbulence at the edge of the rotor disc:

$$\sigma^2_{add}(r,x) = \sigma^2_{add,1}(r,x) + \sigma^2_{add,2}(r,x) \tag{5}$$

with

$$\sigma_{add,1} = f_1(r,x)\ \sigma_{add,stw}(x) \tag{6a}$$

and

$$\sigma_{add,2} = f_2(r,x)\ \sigma_{add,stw}(x), \tag{6b}$$

where $f_1(r,x)$ and $f_2(r,x)$ take care of the decay of turbulence in spanwise direction r and $\sigma_{add,stw}(x)$ takes care of the decay in streamwise direction.

We model σ_{add} with a power function:

$$\sigma^2_{add}(x) = \sigma^2_{add,ini}\left(\frac{x}{2D}\right)^m \tag{7}$$

with

$$\sigma^2_{add,ini} \propto a\mu_0^2 \tag{8}$$

and

$$m = \frac{1-2a}{a(1-a)}\frac{n}{1+k}, \tag{9}$$

where $\sigma^2_{add,ini}$ is the initial value of the added turbulence [5 section 2.4.1], and k is the energy redistribution factor. We model $f_1(r,x)$ and $f_2(r,x)$ with an exponential function:

$$f_1(r,x) = \exp\left\{-\alpha_2\left(\frac{r - R_1(x)}{R}\right)^2\right\} \tag{10a}$$

and

$$f_2(r,x) = \exp\left\{-\alpha_2\left(\frac{r + R_1(x)}{R}\right)^2\right\}, \tag{10b}$$

where the $R_1(x)$ function causes the two peaks originating from the rotor disc edge to merge at a downstream position of eight rotor diameters:

$$\frac{R_1(x)}{R}=1 \text{ if } 0\le\frac{x}{D}<2, \quad (11a)$$

$$\frac{R_1(x)}{R}=\frac{1}{6}\left[8-\frac{x}{D}\right] \text{ if } 2\le\frac{x}{D}\le 8, \quad (11b)$$

or

$$\frac{R_1(x)}{R}=0 \text{ if } \frac{x}{D}>8. \quad (11c)$$

The parameter α_2 essentially sets the spanwise size of the region with added turbulence; with the value

$$\alpha_2 = \ln 100/4 \approx 1.15$$

the added turbulence at one edge of the disc due to the other edge is minimal, and vice versa.

3.5 Cluster of wind turbines

The ranking of wind turbines in a cluster is determined by considering the wind direction and the distances in streamwise and in spanwise direction to another wind turbine. The flow chart is illustrated in figure 5. To this end the wind front is introduced in the form of a line perpendicular to the wind direction. It is assumed that the wind front travels through the cluster such that first the wind turbine with the smallest distance to the front is reached, next the one with the second-smallest and so on until the wind turbine with the largest distance.

The velocity wake is handled by adding local velocity deficits to the velocity field, where a so calculated velocity is the input to the next wind turbine. The turbulence wake is handled in a similar way by adding local velocity variances to the velocity variance field.

4 Maps of wind, loads and energy

4.1 Wind turbine model and measured data

The wind turbine model consists of the thrust curve, which relates the thrust coefficient c_T to the tip-speed ratio λ. Figure 6 shows the thrust curve of the wind turbines in the EWTW as obtained form public information [10 pages 109 and 131]. Note this thrust curve is an effective thrust curve as it includes the effect of the variation of the rotor speed between 10.9 rpm and 19.1 rpm. Also shown in figure 6 are the power curve from the same source and the power curve which originates from the parameterized thrust curve. Apart from the obviously erroneous points beyond a wind speed of 21 m/s the difference between the published and the modelled power curve is less than 4%. The reason for the erroneous points is the limited accuracy of the public thrust coefficient at low tip-speed ratios.

4.2 Inflow perpendicular to or aligned with row of turbines

In this section inflow perpendicular to the row of turbines together with four wind speed cases is considered. This wind direction case is relevant because it shows to what extent the state of each turbine is predicted if all turbines have the same inflow. The wind speed cases are relevant because they correspond to near cut-in, halfway nominal power, near nominal power and constant power. The wind speed cases have been set on basis of the 10-minute averaged standard deviation of the wind speed as measured at the meteo mast in the EWTW and correspond to an upstream turbulence intensity of the order of 10%.

In figure 7 calculated and measured averages are compared. First it should be noted that even over the small separation distances there is some spatial variation in the average inflow wind speed. For example, there are differences of the order of 1 m/s between the average wind speed at the meteo mast and the individual wind turbines. As another example all wind speeds at the high wind speed case should be equal to the meteo mast reading 17-18 m/s, but in fact vary between 16 m/s and 18 m/s. These variations, which have not been taken into account in the modeling, cause variations in the calculated power between the wind turbines.

In addition inflow aligned with the row of turbines together with the four wind speed cases is considered. This wind direction case is relevant because it shows to what extent the state of each turbine is predicted if all but one turbine is in the wake of another turbine.

Figure 8 shows wind speed and power as a function of distance along the row of turbines, plus, in the case of wind speed, the upstream wind speed as measured at the meteo mast. First it is checked whether the upstream wind turbine (T1) has the same inflow as the meteo mast (T0). This is the case for the average wind speed. Next, it is found that, apart from the high wind speed case, the predicted average wind speed in the wake is within a meter per second of the measured wind speed. On the other hand the predicted decay of wind speed deficit is too gradual, and the measured wind speed minimum at the second or third turbine is not calculated. This picture also emerges from the power.

5 Summary and outlook

A preliminary version of a quasi-static wind farm flow model has been presented. In addition outcome of the model in the form of preliminary maps of wind, loads and energy have been compared to data from the ECN Wind turbine Test site Wieringermeer EWTW. These maps include tables with the average and the standard deviation of five quantities (wind speed at the turbine, tower bending moment, blade bending moment, aerodynamic power, and rotor shaft torque) as a function of three input quantities (ambient wind speed, wind speed standard deviation, and wind direction).

In the subsequent phase of the FP7 project Aeolus the final version of the quasi-static wind farm flow model will be developed. To this end the approach will be improved by taking experimental data from the ECN Scale Wind Farm into account. In particular the following points will be considered:

- A varying rather than a constant rotor speed.
- The value of the constants in the velocity deficit decay law.
- The correlation between the exponent n in the velocity deficit decay law and the turbulence.
- The ranking of turbines in a cluster as a function of wind direction, including a varying rather than a constant wind direction.
- The correlation between the power m in the added turbulence decay law and the power n in the velocity deficit decay law.

In addition blade pitch angle and fatigue measures will be included in the turbine model, and some dynamics will be included in the wake model.

Acknowledgemenst

This work was performed in the framework of the EU project FP7-ICT STREP 22548 / Aeolus "Distributed control of large-scale offshore wind farms".

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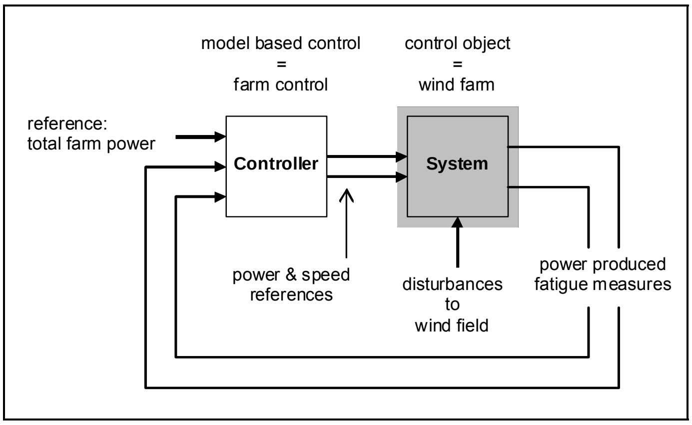

Figure 1: Basic structure of the quasi-static wind farm flow model

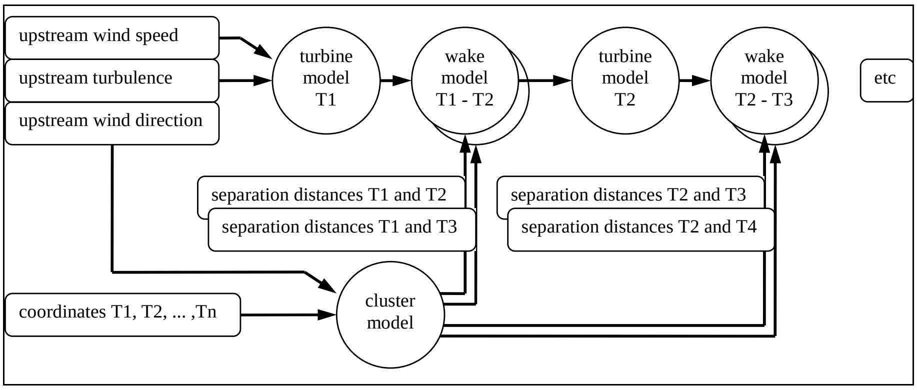

Figure 2: Flow chart wind farm model

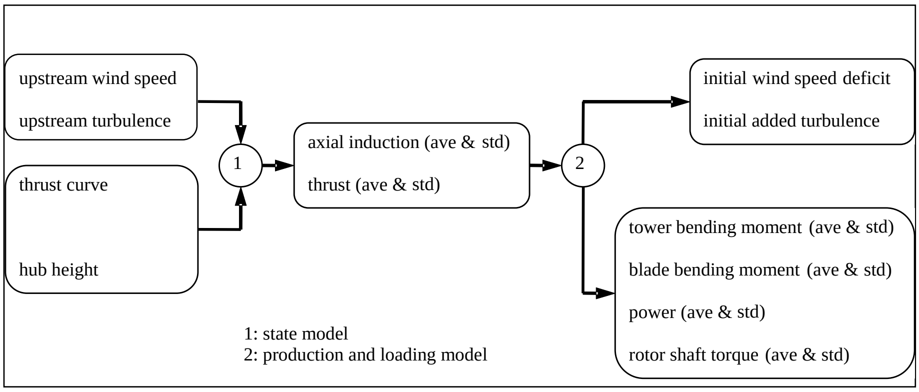

Figure 3: Flow chart turbine model

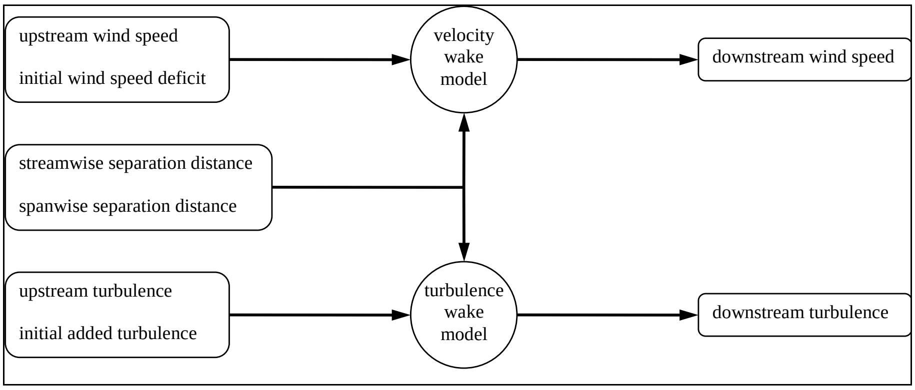

Figure 4: Flow chart wind turbine wake model

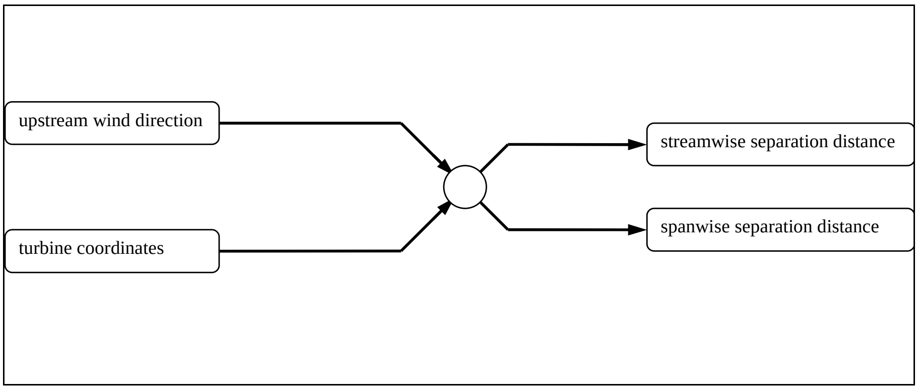

Figure 5: Flow chart cluster model

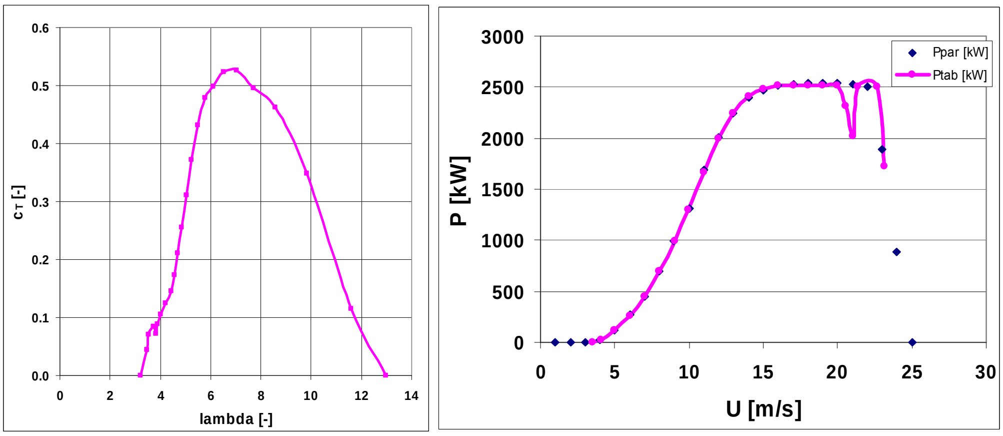

Figure 6: Model of the wind turbines in the form of the published thrust curve (left) and the resulting power curve P_{par} compared to the published power curve P_{tab} (right); Source: BWE 2007. The erroneous points are excluded from the analysis

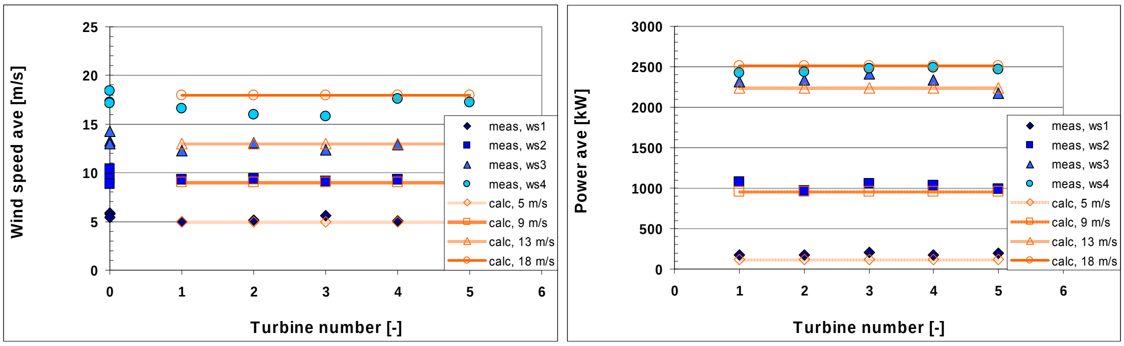

Figure 7: Average wind speed (left) and average power (left) for the EWTW as predicted by the flow model and as measured in the case of inflow perpendicular to the turbine row. Turbine #0 indicates the meteo mast. Wind speeds at turbine #1 - #5 were measured at the hub

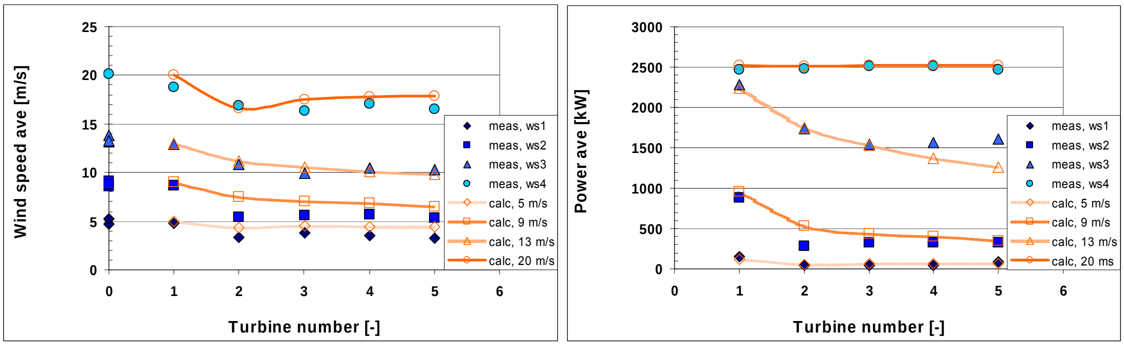

Figure 8: Average wind speed (left) and average power (left) for the EWTW as predicted by the flow model and as measured in the case of inflow along the turbine row. Turbine #0 indicates the meteo mast. Wind speeds at turbine #1 - #5 were measured at the hub

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Abstract

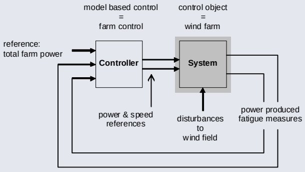
- A preliminary version is presented of a quasi-steady wind farm flow model which will be part of the distributed control of a wind farm
- The outcome of this model is compared to data from the ECN Wind Turbine Test Site EWTW

Motivation

- In the future: Large-scale wind power plants
- The wind farms have to meet control objectives
- Challenge: Distributed wind farm control
- Wind farm control requires wind farm flow models

Objectives

To develop a wind farm flow model that
- Relates production and loading to wind
- Models the control object "wind farm"
- Is valid over periods of 10 minutes
- Is part of the control algorithm

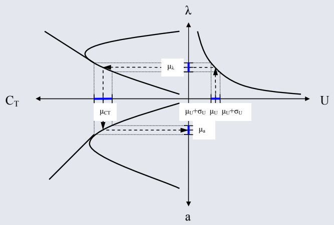

model based control = farm control
control object = wind farm
reference: total farm power
Controller
System
power & speed references
disturbances to wind field
power produced fatigue measures

Method

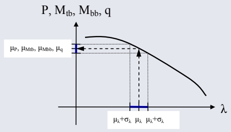
Assumptions
- Momentum theory for wind turbine states and wakes
- Ten-minute wind speed is normally distributed
- Derived quantities are normally distributed

Concepts

Wind turbine state

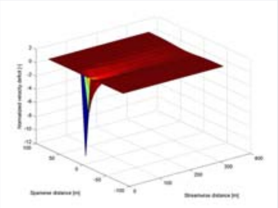


Wind turbine production and loading

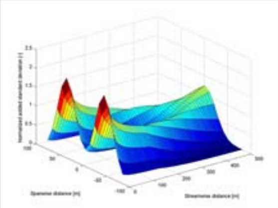


Wind turbine wake

Velocity deficit

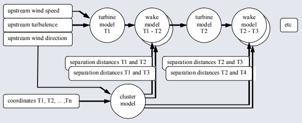


Added turbulence

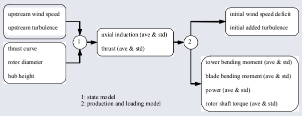


Flow charts

Wind farm flow model

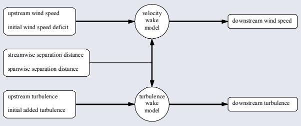

upstream wind speed
upstream turbulence
upstream wind direction
turbine model T1
wake model T1 - T2
turbine model T2
wake model T2 - T3
etc
separation distances T1 and T2
separation distances T1 and T3
separation distances T2 and T3
separation distances T2 and T4
coordinates T1, T2, ... ,Tn
cluster model

Wind turbine model

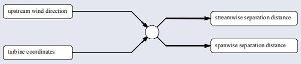

upstream wind speed
upstream turbulence
thrust curve
rotor diameter
hub height
1
axial induction (ave & std)
thrust (ave & std)
2
initial wind speed deficit
initial added turbulence
tower bending moment (ave & std)
blade bending moment (ave & std)
power (ave & std)
rotor shaft torque (ave & std)

1: state model
2: production and loading model

Wind turbine wake model


upstream wind speed
initial wind speed deficit
velocity wake model
downstream wind speed
streamwise separation distance
spanwise separation distance
upstream turbulence
initial added turbulence
turbulence wake model
downstream turbulence

Cluster model

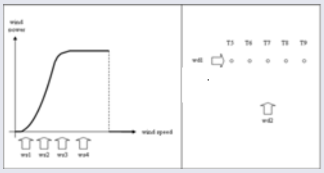

upstream wind direction
turbine coordinates
streamwise separation distance
spanwise separation distance

Results

Model output:
- External conditions: Wind speed, Wind direction, Turbulence intensity
- State of turbines: Hub wind speed, Blade pitch angle, Rotor speed
- Output of turbines: Power, Loads

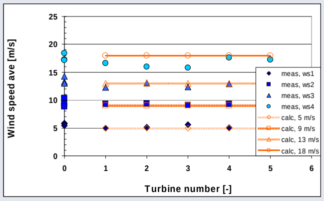
Measurements:
Research wind turbines at EWTW
- Nominal power: 2.5 MW
- Hub height: 80 m
- Rotor diameter: 80 m
- Turbine separation: 3.8D

Flow cases

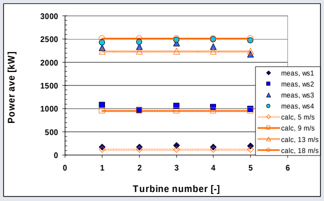


Flow perpendicular to turbine row (wd2)

Wind speed

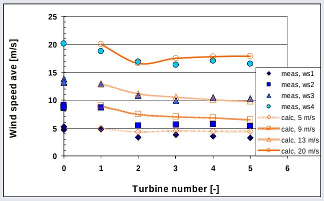


Aerodynamic power

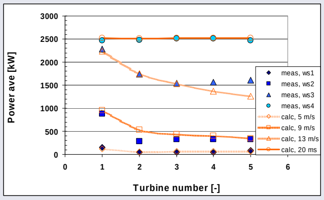


Flow parallel to turbine row (wd1)

Wind speed



Aerodynamic power



Conclusions

- Difference between measurement and prediction is smaller than 2 m/s (wind speed) and 200 kW (power).
- Measured minimum in wind speed and aerodynamic power at second or third turbine is not predicted.
- Main differences originate from un-modelled spatial variations in wind speed, and too gradually modelled decay of wind speed.

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Acknowledgements

EU project FP7-ICT STREP 22548 / AEOLUS

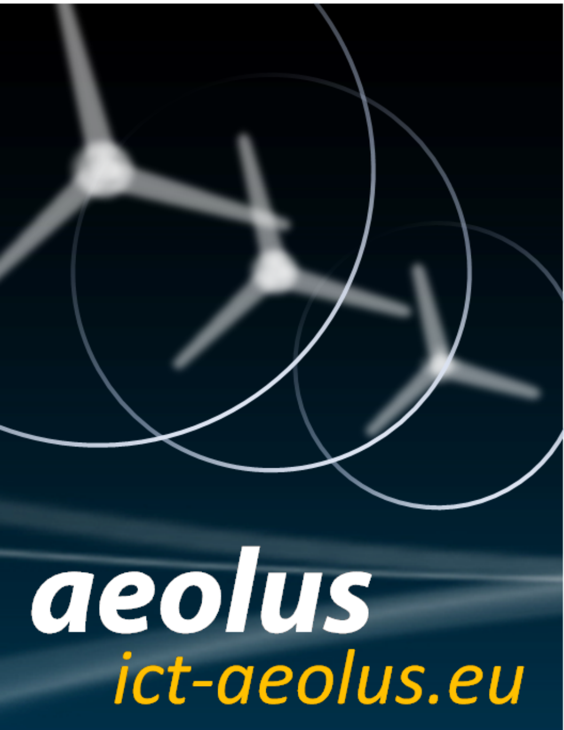
Distributed control of large-scale offshore wind farms

European Wind Energy Conference & Exhibition 2010, Tuesday 20 - Friday 23 April 2010, Warsaw, Poland

ECN

Energy research Centre of the Netherlands

A quasi-steady wind farm flow model



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SEVENTH FRAMEWORK PROGRAMME

FP7-ICT STREP 224548 / Aeolus

Outline

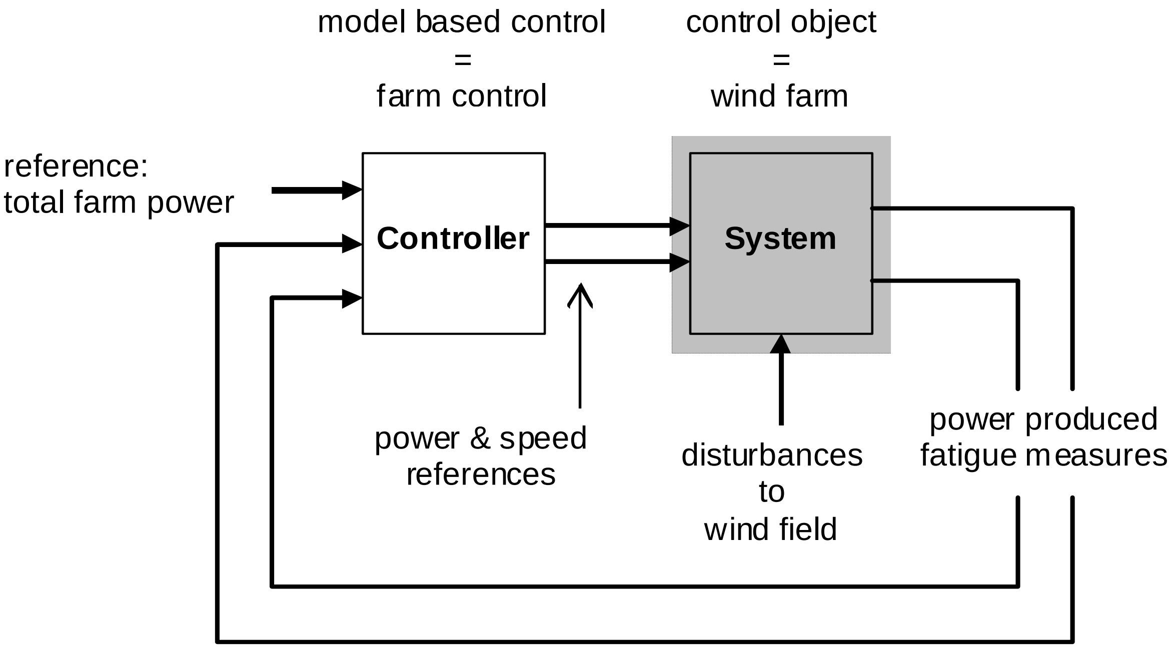
- ❑ Objectives
- ❑ Method
- ❑ Results
- ❑ Summary & Outlook

Objectives

To develop a wind farm flow model that

- ❑ Relates production and loading to wind
- ❑ Models the control object “wind farm”
- ❑ Is valid over averaging periods of 10 minutes
- ❑ Is part of the control algorithm

Quasi-steady flow model basic structure



model based control
=
farm control

control object
=
wind farm

reference:
total farm power

Controller

System

power & speed
references

disturbances
to
wind field

power produced
fatigue measures

Assumptions

- ☐ Momentum theory for wind turbine states and wakes

- ☐ Ten minute wind speed normally distributed

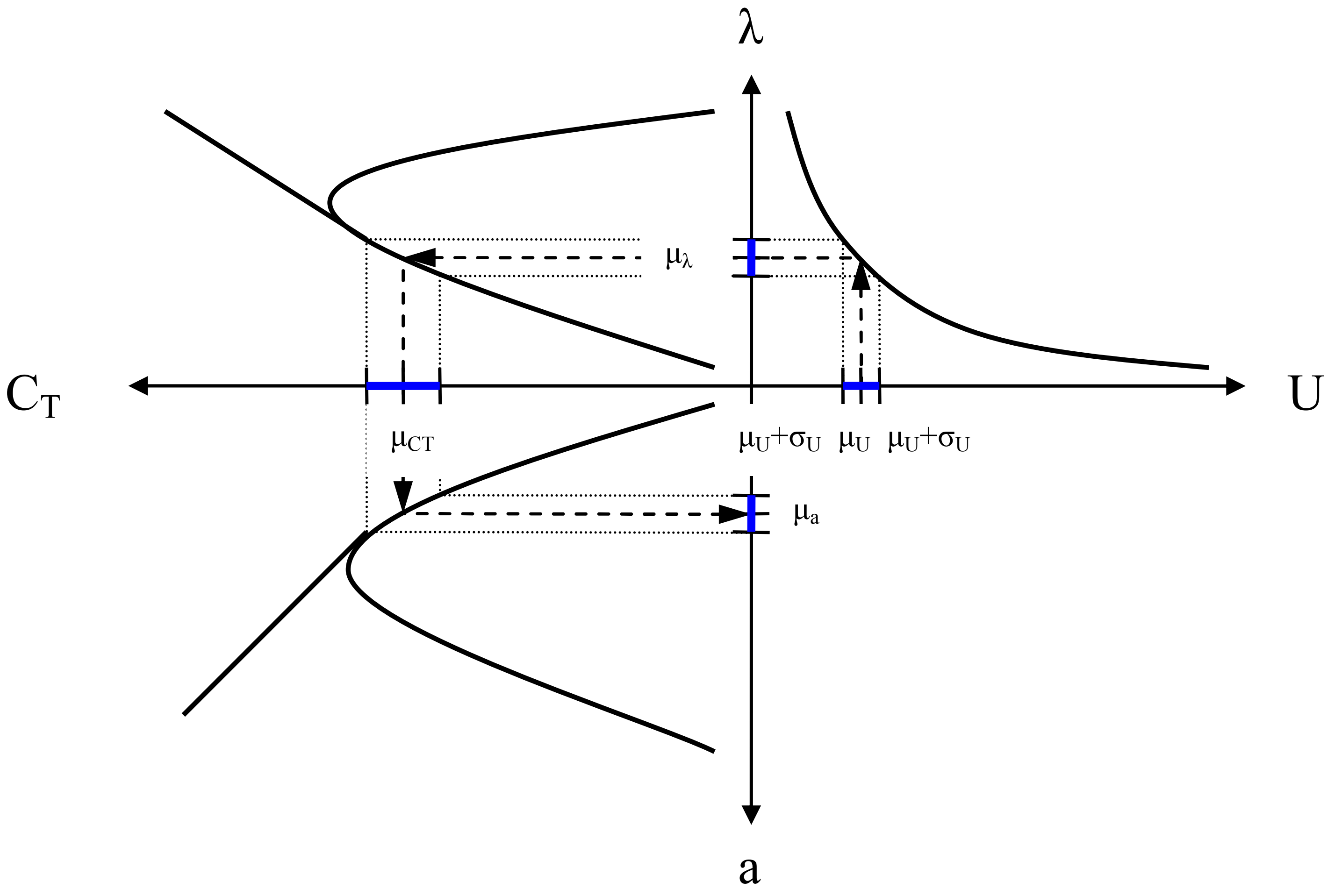
$$U : N(\mu_U, \sigma_U)$$

- ☐ Derived quantities normally distributed, e.g.

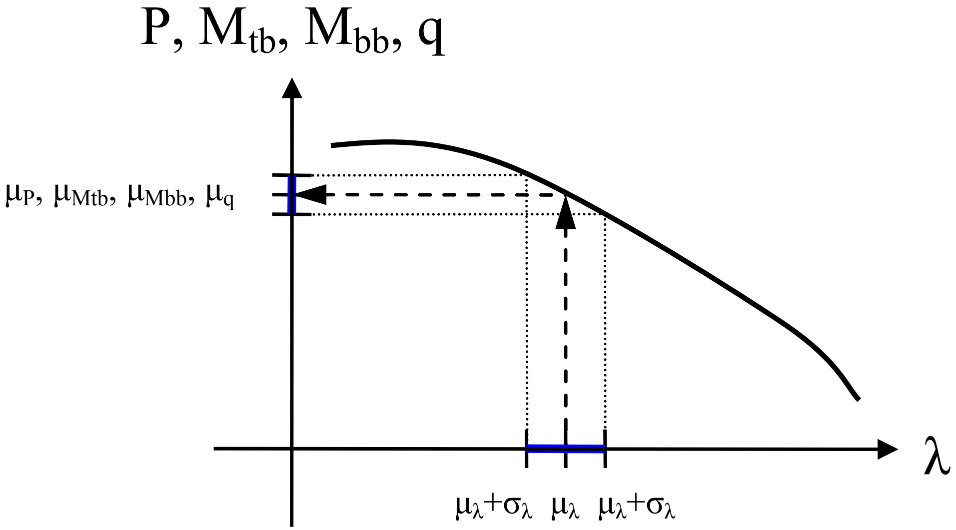
$$x = f(U)$$

$$x : N(\mu_x, \sigma_x) \qquad \mu_x = g_1(\mu_U, \sigma_U) \qquad \sigma_x = g_2(\mu_U, \sigma_U)$$

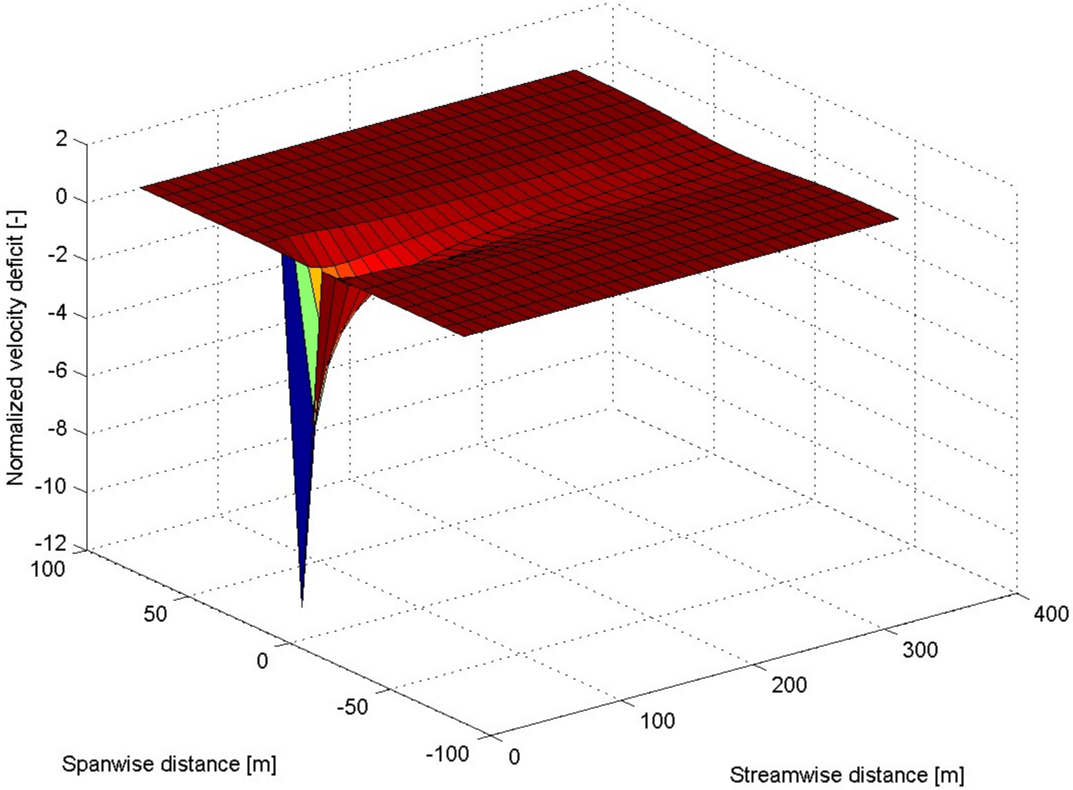
Wind turbine state



Wind turbine production and loading



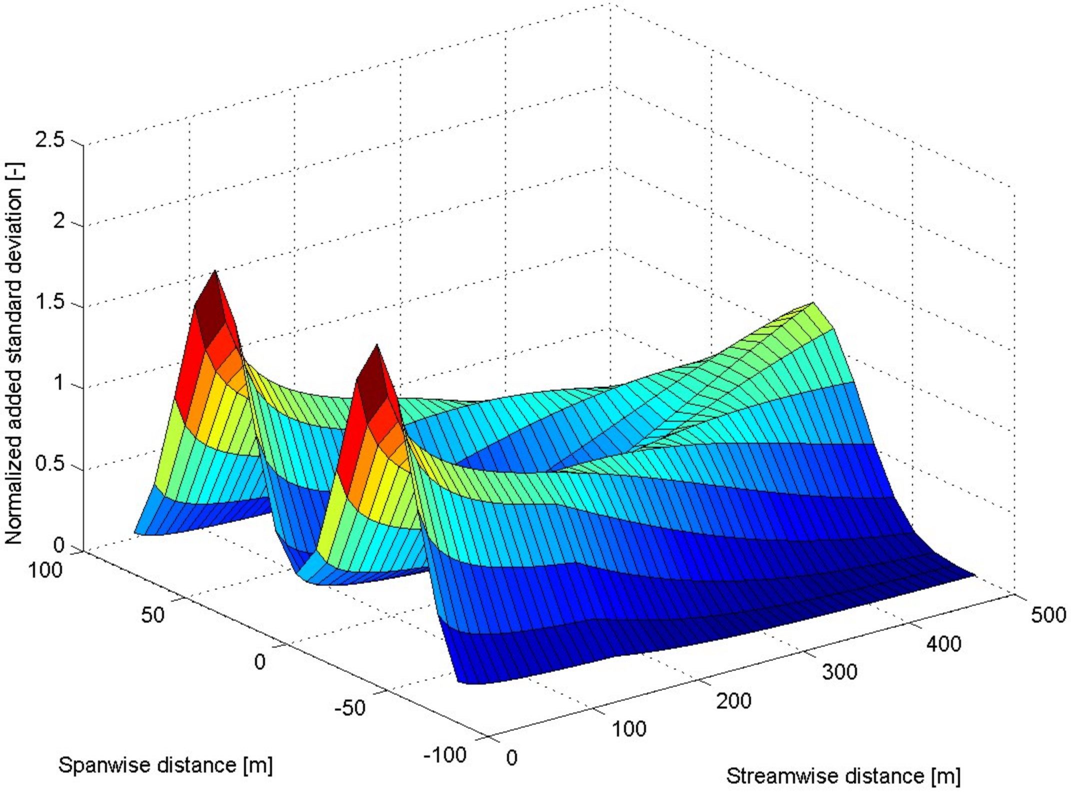
Velocity deficit



D = 80 m

a = 1/3

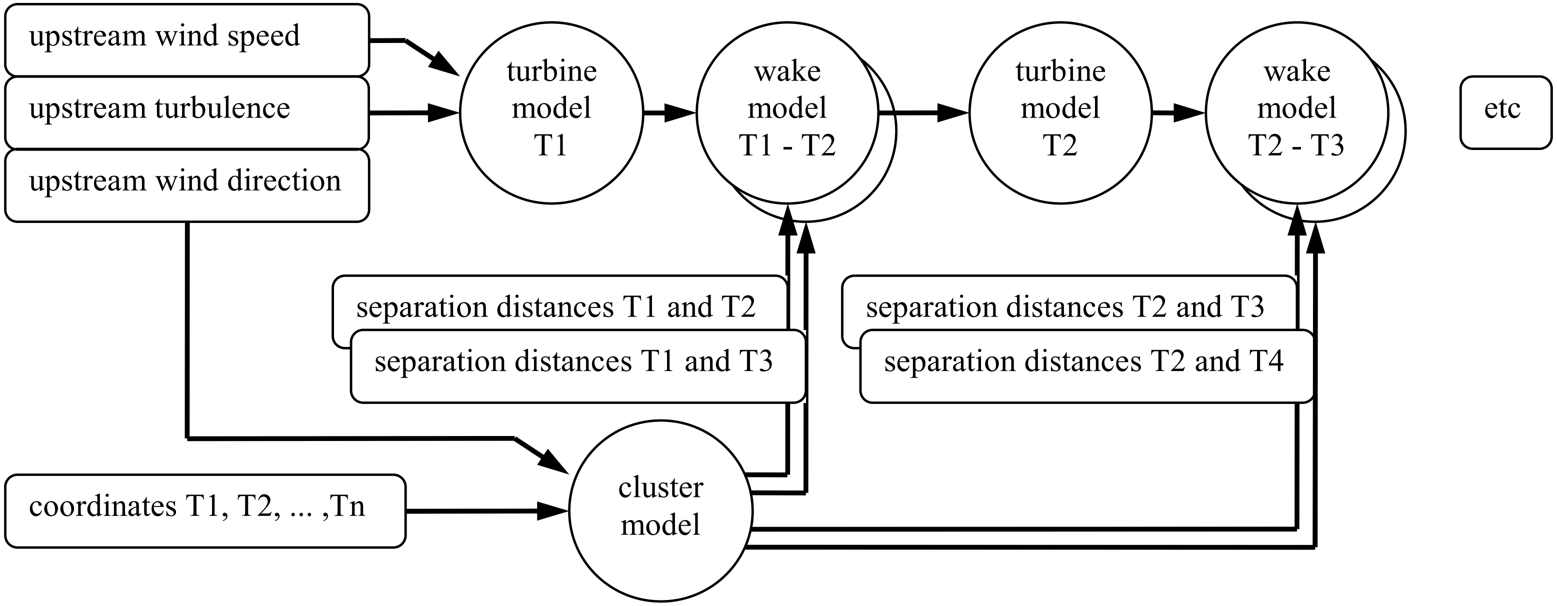
Added turbulence



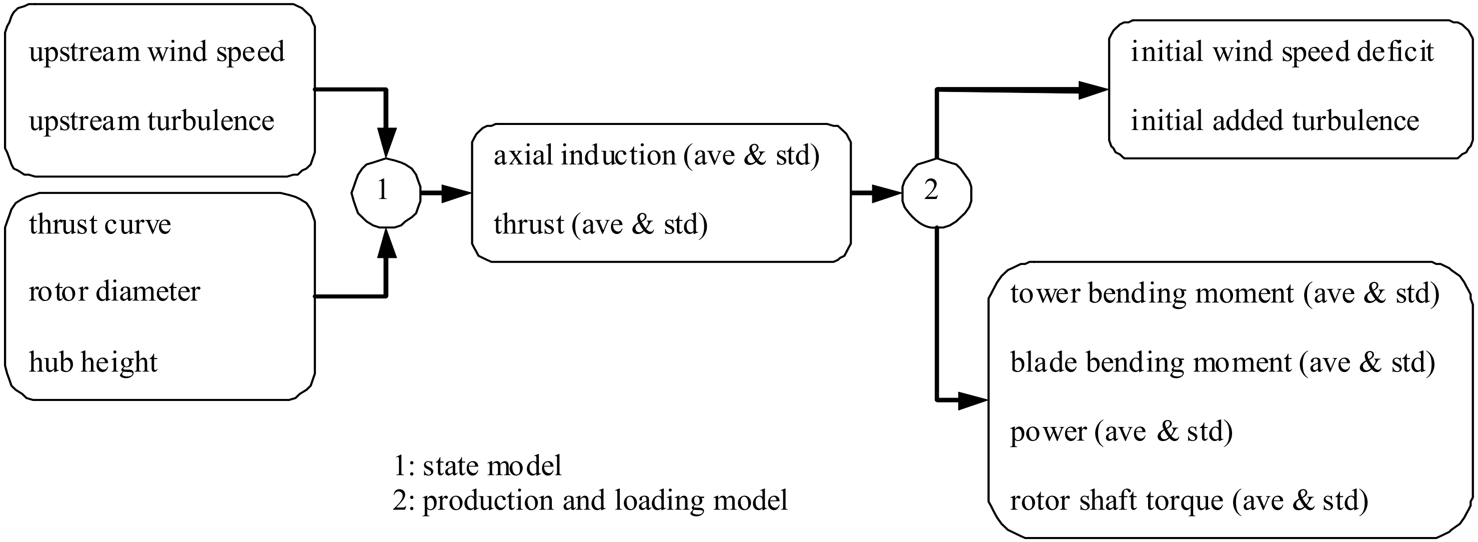
D = 80 m

a = 1/3

Wind farm flow model



Wind turbine model



upstream wind speed

upstream turbulence

thrust curve

rotor diameter

hub height

axial induction (ave & std)

thrust (ave & std)

initial wind speed deficit

initial added turbulence

tower bending moment (ave & std)

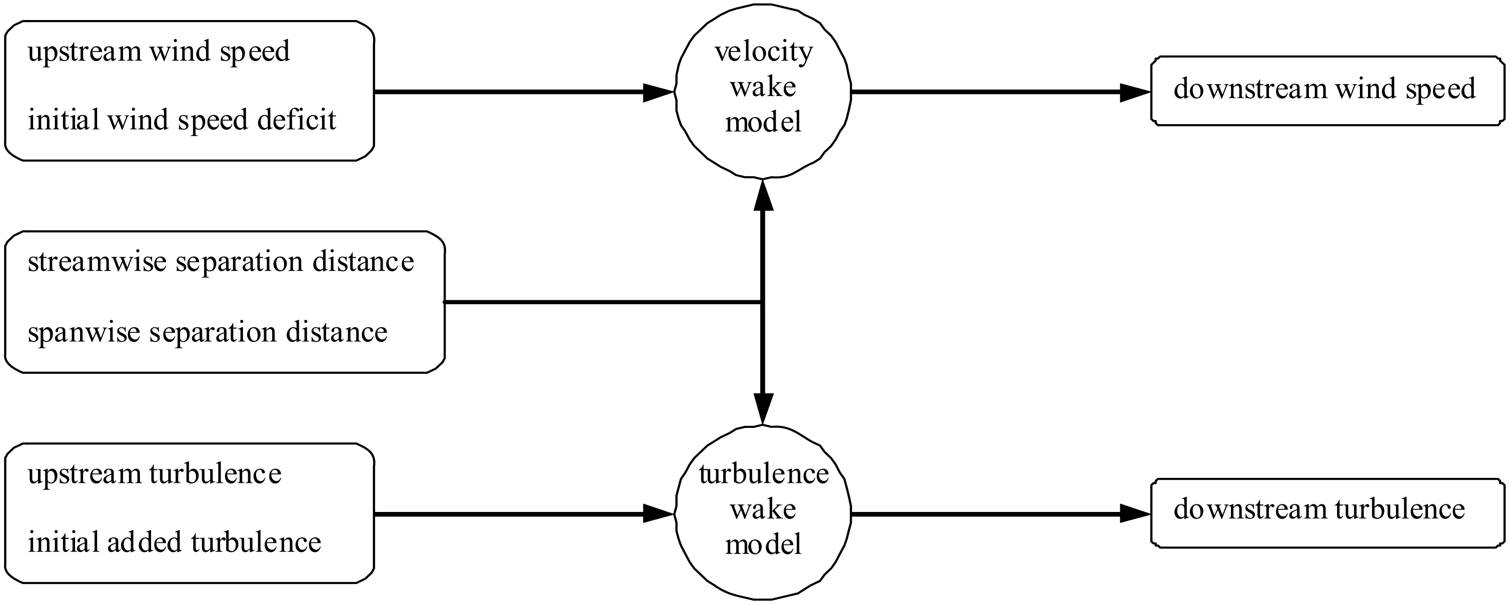
blade bending moment (ave & std)

power (ave & std)

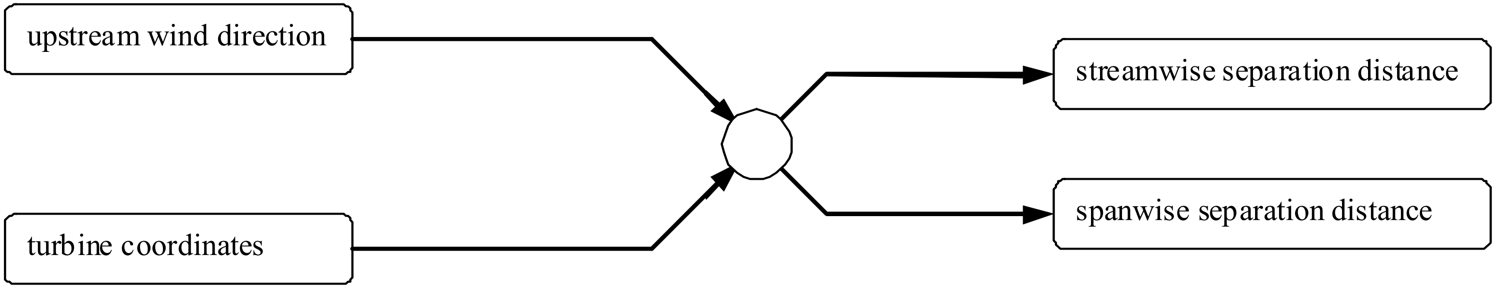
rotor shaft torque (ave & std)

1: state model
2: production and loading model

Wind turbine wake model



Cluster model



upstream wind direction

turbine coordinates

streamwise separation distance

spanwise separation distance

Model output

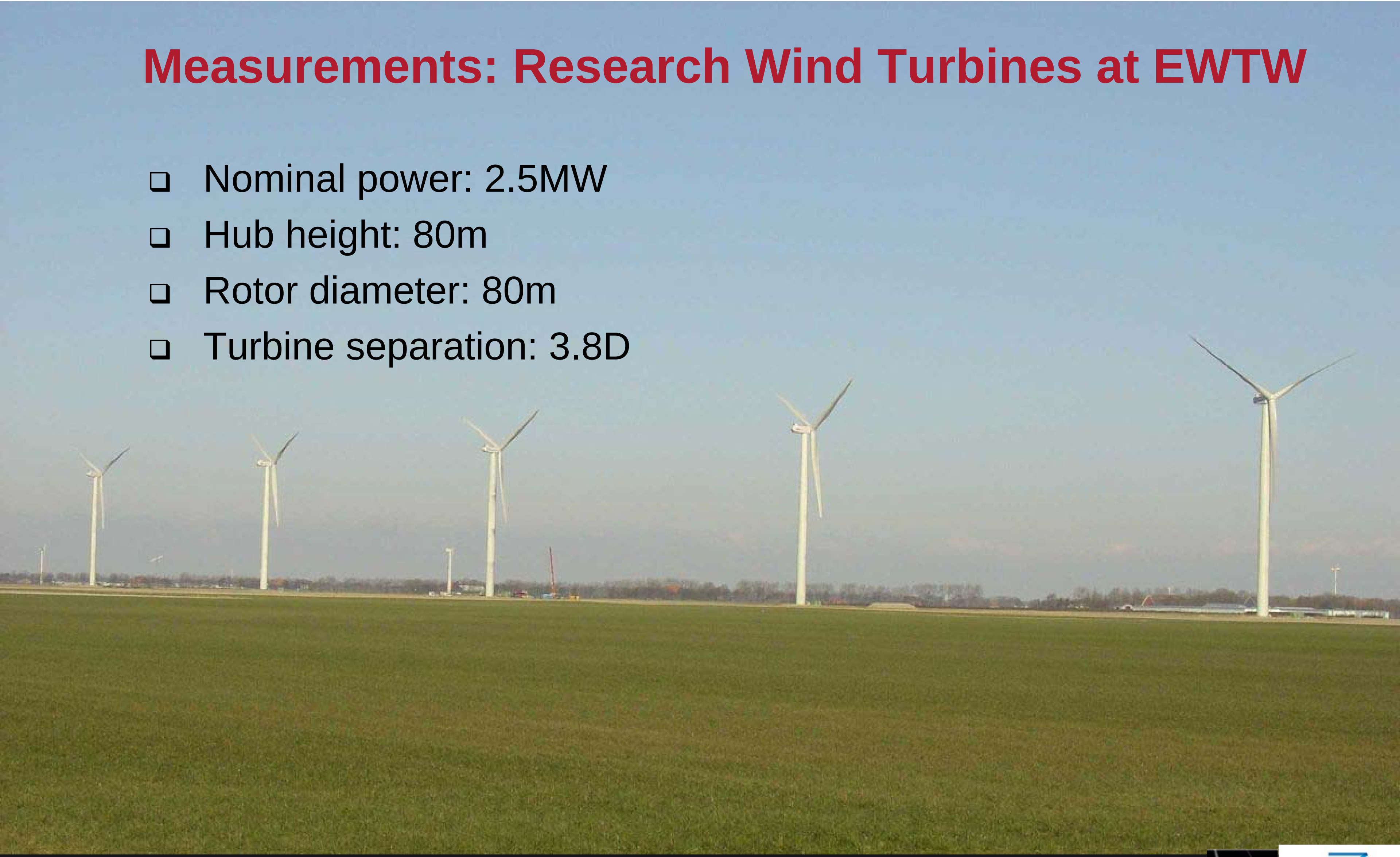
- ❑ External conditions:

  Wind speed, Wind direction, Turbulence intensity
- ❑ State of all turbines:

  Hub wind speed, Blade pitch angle, Rotor speed
- ❑ Output of all turbines:

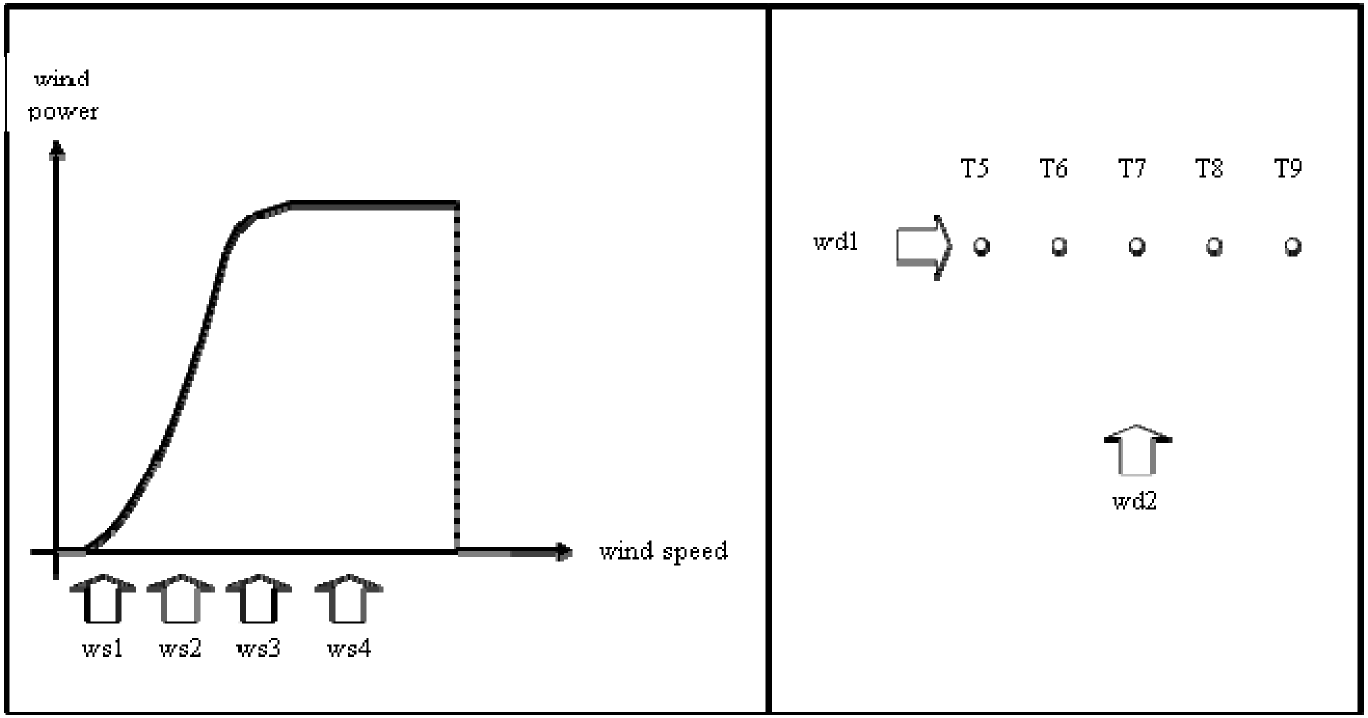
  Power, Loads

Measurements: Research Wind Turbines at EWTW

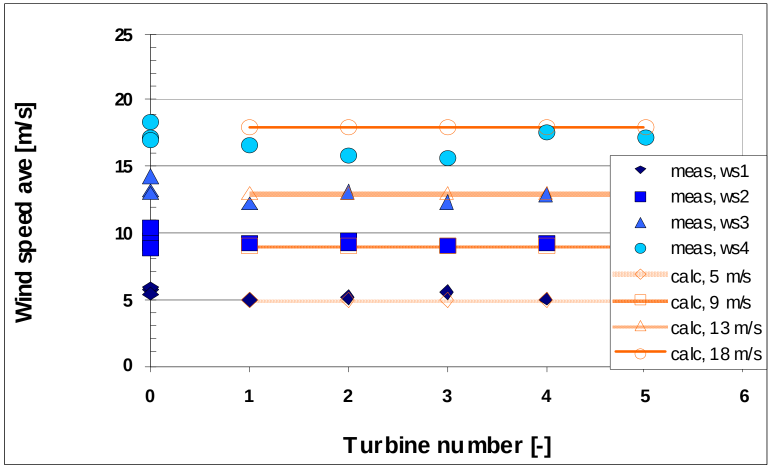


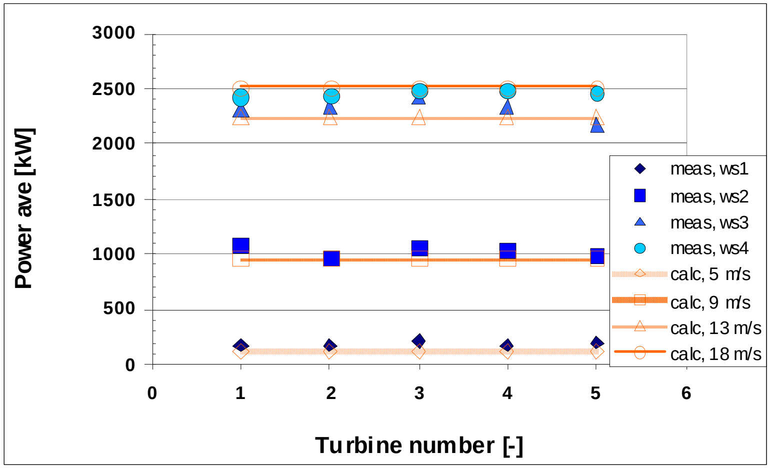
- Nominal power: 2.5MW
- Hub height: 80m
- Rotor diameter: 80m
- Turbine separation: 3.8D

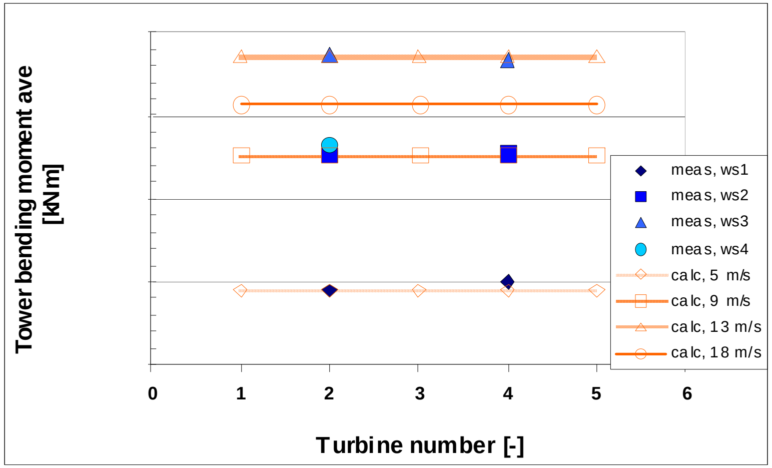
Wind speed and wind direction cases

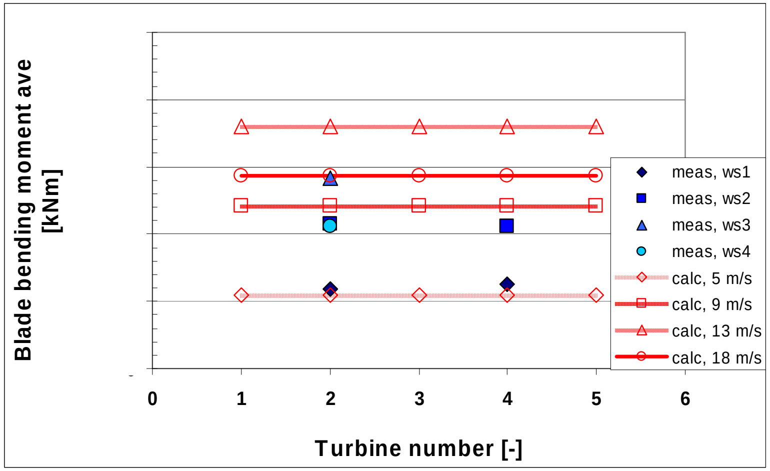


Perpendicular inflow (wd2)

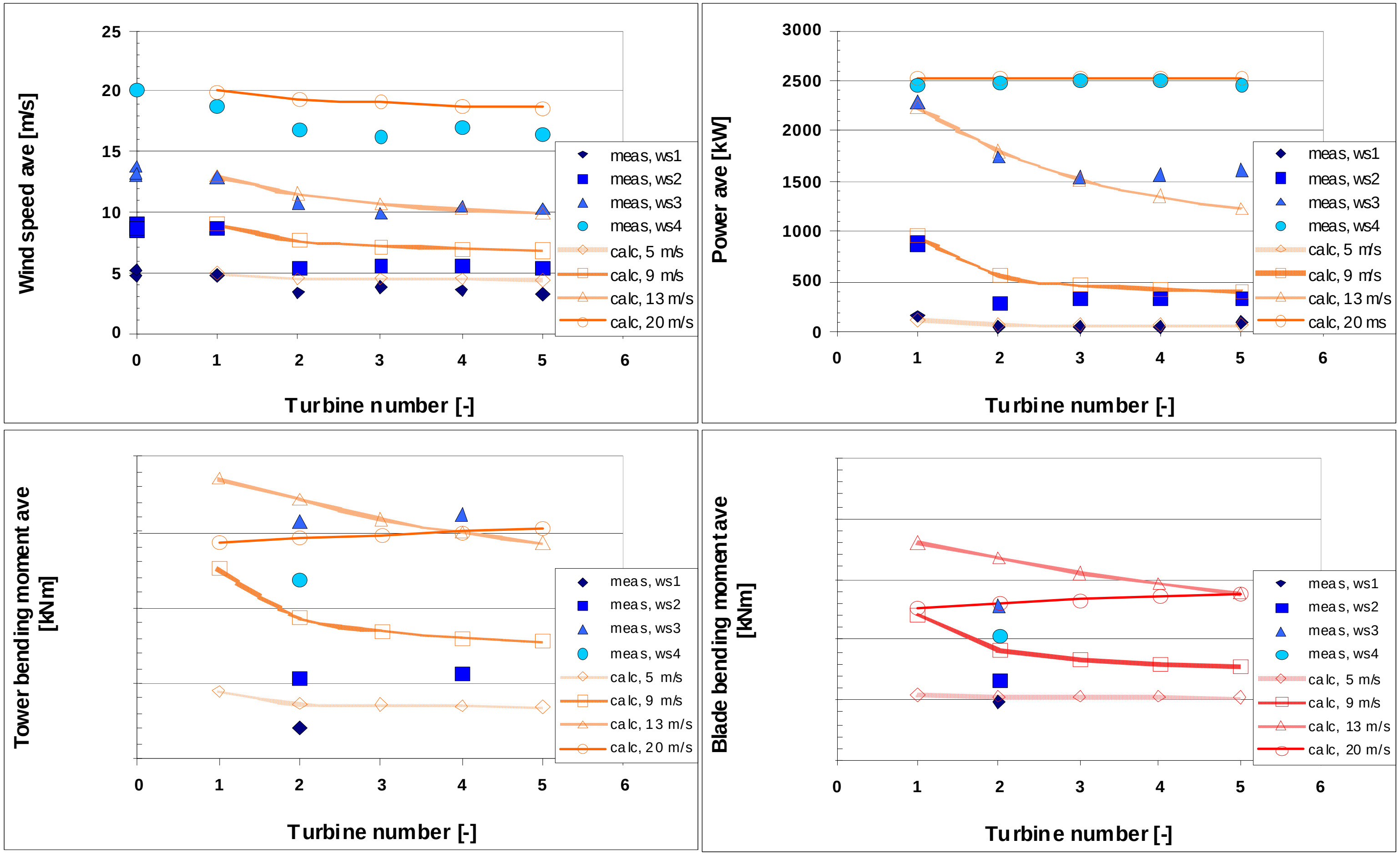








Parallel inflow (wd1)



Conclusion

- Difference between measurement and prediction is smaller than
    * 2 m/s (wind speed) and
    * 200 kW (power).
- Measured minimum in wind speed and aerodynamic power at second or third turbine is not predicted.
- Main differences originate from
    * Un-modelled spatial variations in wind speed, and
    * Too gradually modelled decay of wind speed.

Summary and outlook

- ❑ A quasi-steady wind farm flow model has been presented
- ❑ Outcome of the model have been compared to data from the ECN Wind Turbine Test Site Wieringermeer (EWTW)
- ❑ Outcome of the model will be compared to data from the ECN Scale Wind Farm (ESWF)
- ❑ Various modeling issues will be addressed

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