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

A.J. Brand

J.W. Wagenaar

Presented at:
Torque 2010, 28-30 June 2010, Crete, Greece

ECN-M--10-058 JULY 2010

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

A J Brand
ECN Wind Energy
P.O. Box 1, NL 1755 ZG Petten,
Netherlands
brand@ecn.nl

J W Wagenaar
ECN Wind Energy
P.O. Box 1, NL 1755 ZG Petten,
Netherlands
j.wagenaar@ecn.nl

Abstract

This work presents validation of an intermediate version of a quasi-steady wind farm flow model which will be part of distributed control of a wind farm. In addition power and three load quantifiers as calculated by the model are demonstrated. It is concluded that differences between measurement and prediction are 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, and main differences originate from un-modelled spatial variations in wind speed and too gradually modelled decay of wind speed.

Keywords: 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 wind farm level: maximum power production, minimum structural loads and optimal integration into the power system.

The EU project FP7-ICT STREP 22548 / Aeolus is aimed at the development of distributed control of large offshore wind farms [1, 2]. In this context a quasi-steady wind farm flow model is developed, which is to be part of the supervisory control algorithm [3].

This paper addresses validation of an intermediate version of the quasi-steady wind farm flow model, and presents load quantifiers calculated by the model. First, the research objectives of the FP7 project Aeolus are described (section 2) and the quasi-steady wind farm flow model is introduced (section 3). Next, a comparison is presented between model output for and measured data from the ECN Wind turbine Test site Wieringermeer EWTW (section 4). In addition power and three short-term load quantifiers as calculated for the considered cases are presented (section 5). Finally, a summary of the work and an outlook to future work are given (section 6).

2. Objectives and approach

The general objectives of the FP7 project Aeolus are to develop models that allow real-time predictions of flow in a wind farm and incorporate data from a network of sensors, and to develop control paradigms that acknowledge the uncertainty in the modelling and dynamically manage the flow resource in order to optimize specific control objectives.

Specific objectives of the project, contained in the two flow modelling work packages, include the development of a quasi-steady and a dynamic flow model. The quasi-steady flow model relates single turbine production and loading to a map of wind speeds [4, 5, 6], in contrast to the dynamic flow model which describes deviations from the steady model due to rapidly changing flow effects [7].

The quasi-steady flow model is derived from fluid dynamics principles and is based on a database of meteorological and wind turbine related measurements. It is developed in two stages: first a preliminary version (finished April 2009 and reported separately [4, 5, 6]) and next the final version (finished February 2010, also reported separately [8, 9] and partly covered in this paper).

In fact the quasi-steady flow model is a model of the control object "wind farm"; where "model" means a mathematical map/function in the form of equations (or initially look-up tables) which relates farm output (power and load quantifiers) to measured quantities (e.g. rotor speed, blade pitch angle, wind speed), references (e.g. power set point) and disturbances (unmodelled system inputs). Figure 1 shows the basic structure. The model is steady in the sense that it is valid over averaging periods of 10 minutes, in contrast to the dynamic flow model which is dynamic in the sense that it describes deviations from the mean. The model is quasi steady because it gives mean as well as standard deviation of a quantity, and by doing so provides information on variations which are translated into load quantifiers.

3. Quasi steady wind farm flow model

3.1 Flow model

The quasi-steady wind farm flow model allows the wind farm controller to calculate in real time maps of wind, loads and energy, or to be more specific, wind speed at each turbine in a wind farm plus tower bending moment, blade bending moment, rotor shaft torque and aerodynamic power of each turbine as a function of "ambient" wind speed, wind direction and turbulence intensity. The corresponding flow chart is shown in figure 2.

The structure and the details of the flow model, which are described in preceding publications [5, 6], are summarized in this section.

Apart from sub-models based on classic momentum theory [10], inspired by the literature on wind turbine wakes [11, 12, 13, 14 part 1 sub A section 2.4, 15, 16], this model includes specially developed sub-models for creation and decay of velocity deficit, creation and decay of added turbulence, impact of turbulence on average values, and standard deviation of all quantities.

The model treats individual wind turbines separately. By using momentum theory the aerodynamic state of a wind turbine is expressed in terms of an axial induction factor. Relations for the mean and the standard deviation of the axial induction factor both bring the effect of turbulence into account. Subsequently aerodynamic power, tower bending moment, blade bending moment and rotor shaft torque are calculated. In addition velocity deficit and extra turbulence due to the single wind turbine are calculated.

The model treats a cluster of wind turbines by linking individual wind turbines via their wakes. For the given wind direction, for all wind turbines in the cluster the streamwise and the spanwise distance downstream each wind turbine is determined. Subsequently, this infomation is employed in order to calculate all local values of velocity deficit and added turbulence by using decay laws.

3.2 Load quantifiers

The quasi-steady wind farm flow model translates wind speed mean values and standard deviations into mean values and standard deviations of mechanical loads. Subsequently the model translates this information into load quantifiers. In this section the approach is presented.

First, as described in preceding publications [4, 8], it is assumed that load mean μ_L as well as load standard deviation σ_L depend on wind speed mean μ_U and wind speed standard deviation σ_U:

$$\mu_L = \mu_L(\mu_U, \sigma_U) \text{ and } \sigma_L = \sigma_L(\mu_U, \sigma_U).$$

This crucial assumption is motivated by experimental and modelling based identification of the parameters that influence equivalent loads [14, part 1, sub B, section 5.4]. The conclusions in the referred work are that:

- The primary fatigue load parameter is the standard deviation of the longitudal wind speed component[1], and
- The equivalent load is a function of the wind speed standard deviation σ_U and, because at higher wind speeds a constant value of the turbulence intensity may be assumed, the mean wind speed μ_U.

[1] The second important parameter is yaw misalignment, and the third important parameter is turbulence structure

Secondly, it is assumed that loads are normally distributed. This assumption is fair in a short-term assessment of wind turbine components because:

- In a short time period (10 minutes) the number of observations or revolutions is high (600 resp. ~200), and
- Under normal operation during a 10-minute period wind turbine loads have experimentally been found to vary with well-defined mean and standard deviation.

The load quantifier selected is the equivalent load L_{eq} [e.g. 17, page 80] of a series of loads L_j (j = 1, 2, 3, …, N):

$$L_{eq}^{m} \equiv \frac{1}{N}\sum_{i} n_i L_i^{m} = \frac{1}{N}\sum_{j} L_j^{m}$$

= m-th raw moment of the observed loads.

Here L indicates the load, m is the slope of the SN-curve of the material and N is the number of load observations in the time period. Furthermore n_i is the number of loads with value L_i, whereas j indicates an individual load in the series L_j.

If the load is a moment (e.g. tower bending moment, or blade bending moment), n_i is the number of load observations of level L_i in the time period and $N = \Sigma_i \ n_i$ is the number of load observations in that period [e.g. 17, page 80].

If, on the other hand, the load is a shaft load (e.g. rotor shaft torque), m is 3, n_i is the number of revolutions at shaft load L_i and $N = \Sigma_i \ n_i$ is the number of revolutions [e.g. 17, pages 136-137].

Under the assumption that observed loads are normally distributed with mean μ_L and standard deviation σ_L, the m-th raw moment, and for that reason the equivalent load, is expressed in terms of μ_L and σ_L:

$$\frac{1}{N}\sum_{j} L_j^{m} = f(\mu_L, \sigma_L).$$

For example, the 4-th order (m = 4) equivalent load is [18]:

$$L_{eq} = \left(\mu_L^4 + 6\mu_L^2\sigma_L^2 + 3\sigma_L^4\right)^{\frac{1}{4}}.$$

Methods to find the raw moment for other integer and even non-integer values of m can be found in the literature [18].

Section 5 demonstrates the equivalent load concept on basis of measured data. Future work is aimed at relating equivalent load to fatigue load.

4. Model output versus measured data comparison

4.1 Overview

In this section output from an intermediate version of the quasi-steady flow model is compared to measured data from the ECN Wind turbine Test site Wieringermeer EWTW. (The EWTW consists of a row of five 2.5 MW wind turbines plus a meteo mast.) Various wind speed and direction cases are presented and discussed, see figure 3 for a definition sketch, and modelling issues are identified in the light of the modelling objective.

4.2 Inflow perpendicular to turbine row

In this section inflow perpendicular to the row of turbines (wd2) 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 (ws1), halfway nominal power (ws2), near nominal power (ws3) and constant power (ws4). The wind speed cases have been set on basis of the 10-minute averaged wind speed as measured at the meteo mast and correspond to an upstream turbulence intensity of 9-11%. Figure 4 shows a comparison between calculated and measured mean values, and figure 5 shows a comparison between calculated and measured standard deviations.

First it should be noted that even over the small separation distances between the wind turbines in the EWTW there is some spatial variation in the mean inflow wind speed. For example, there are differences of the order of 1 m/s between the mean wind speed at the meteo mast and the individual wind turbines, and even larger differences between the wind speed standard deviations. As another example all wind speeds at the high wind speed case (ws4) should be equal to the meteo mast reading 17-18 m/s. However in fact these vary between 16 m/s and 18 m/s. These variations, which have not been taken into account in the modelling, cause variations in the calculated power between the wind turbines, and to a smaller extent in the tower bending moment and the blade bending moment.

In addition, between the wind turbines there is a clear variation in the standard deviation of the inflow wind speed. This variation is caused by the IJsselmeer, where turbulence intensity is lower than over land. Nevertheless calculated standard deviations are of the correct order of magnitude.

4.3 Inflow aligned with turbine row

In this section inflow aligned with the row of turbines (wd1) 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. Again the wind speed cases have been set on basis of the 10-minute mean of the wind speed as measured at the meteo mast, and correspond to an upstream turbulence intensity of 9-11%. Figures 6 and 7 show the various quantities as a function of distance along the row of turbines, plus, in the case of wind speed, 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 mean wind speed (figure 6), but not for the wind speed standard deviation as there are differences up to 1 m/s (figure 7). The latter hampers the assessment of the impact of turbulence.

Figure 6 compares calculated and measured 10-minute mean values. Here it is found that, apart from the high wind speed case, the predicted mean wind speed in the wake is within a meter per second of the measured wind speed. On the other hand predicted decay of wind speed deficit is too gradual, and measured wind speed minimum at second or third turbine is not calculated. This picture also emerges form power, tower bending moment, and blade bending moment.

Figure 7 compares calculated and measured 10-minute standard deviations. As to calculated and measured wind speed standard deviation it must be noted that these can not be compared because the latter is measured at the hub, in the centre of the rotor disc, where turbulence is higher due to the hub. Anyway, there is a good agreement between calculated and measured decay of turbulence. In addition, there is a reasonable although not very good agreement for power standard deviation of turbines T1, T4 and T5. However the agreement for power of the other turbines and for all bending moments is poor.

5. Demonstration of power and load quantifiers

In this section power and three short-term load quantifiers, as calculated by the intermediate version of the quasi-steady flow model, are presented for the cases introduced in section 4. The motivation is that these quantities, together with for example rotor speed and blade pitch angle, are the primary quantities that are considered by the supervisory control algorithm.

The short-term load quantifiers are equivalent tower bending moment (m=4), equivalent blade bending moment (m=12), and equivalent rotor-shaft torque (m=3).

Figure 8 shows calculated power and calculated load quantifiers as a function of wind speed in the case of inflow perpendicular to the row of five wind turbines in the EWTW. Clearly, since all turbines have the same inflow (mean wind speed and turbulence intensity of 9-11%), the options to control the wind farm via the turbine wakes under these conditions are few.

Figure 9, on the other hand, shows that power and load quantifiers differ between the individual wind turbines when inflow is along the row of wind turbines. This illustrates the options to control the power of and the loads in the wind farm via the wakes of the turbines. Note however that in this case the coupling via the wakes is strong because of the short distance of 3.8 rotor diameters between the turbines in the EWTW.

6. Summary and outlook

The intermediate version of a quasi-steady wind farm flow model has been compared to data from the ECN Wind turbine Test site Wieringermeer EWTW, and various modelling issues have been identified. In addition power and three load quantifiers have been demonstrated. It is concluded that differences between measurement and prediction are 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, and main differences originate from un-modelled spatial variations in wind speed and too gradually modelled decay of wind speed.

The modelling issues that have been identified include:

- The value of the constants in the velocity deficit decay law.
- The value of the constants in the added turbulence decay law.
- The inhomogeneity of the inflowing wind speed.

These modelling issues will be addressed by applying the model to the ECN Scale Wind Farm. (The ESWF consists of ten 10 kW wind turbines and fourteen meteo masts.) In addition the equivalent loads will be related to fatigue load. Subsequently, the final version of the quasi-steady wind farm flow model will be developed.

Acknowledgements

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

References

[1] Aeolus - Distributed control of large-scale offshore wind farms, http://ict-aeolus.eu, 2008-2010 (17 February 2010)
[2] Knudsen T, Bak Th and Soltani M, "Distributed control of large-scale offshore wind farms", European Wind Energy Conference 2009, Marseille, France, April 2009
[3] Spudić V, Baotić M, Jelavić M and Perić N, "Hierarchical wind farm control for power/load optimization", Torque 2010, Heraklion, Greece, June 2010
[4] Brand A J, FP7-ICT STREP 22548 / Aeolus Deliverable D1.3, "Preliminary maps of wind, loads and energy", confidential, April 2009
[5] Brand A J and Wagenaar J W, "A wind farm model in the context of distributed control", Euromech Colloquium 508 "Wind turbine wakes", Madrid, Spain, October 2009
[6] Brand A J and Wagenaar J W, "A quasi-steady wind farm flow model in the context of distributed control of the wind farm", European Wind Energy Conference 2010, Warsaw, Poland, April 2010
[7] Knudsen T, Soltani M and Bak Th, "Prediction models for wind speed at turbines in a farm with application to control", Euromech Colloquium 508 "Wind turbine wakes", Madrid, Spain, October 2009
[8] Brand A J and Wagenaar J W, FP7-ICT STREP 22548 / Aeolus Deliverable D1.4a, "Scale wind farm flow model improvements Part 1: Quasi-steady wind farm flow model - Model description", confidential, February 2010
[9] Brand A J and Wagenaar J W, FP7-ICT STREP 22548 / Aeolus Deliverable D1.4b, "Scale wind farm flow model improvements Part 2: Quasi-steady wind farm flow model - User's manual", confidential, February 2010
[10] Manwell J F, McGowan J G and Rogers A L, Wind energy explained, John Wiley and Sons, ISBN 0 471 49972 2, 2002
[11] Barthelmie R et al., "Efficient Development of Offshore Windfarms (ENDOW)", Report Risø-R-1407(EN), 2003
[12] Barthelmie R et al., "Modelling the impact of wakes on power output at Nysted and Horns Rev", European Wind Energy Conference 2009, Marseille, France, April 2009
[13] Cleve J, "Wake flow model for large wind farms", Euromech Colloquium 508 Wind Turbine Wakes, Madrid, Spain, October 2009
[14] Dekker J W M and Pierik J T G (ed.), European Wind Turbine Standards II ECN-C--99-073, 1999
[15] Elliott D L, "Status of wake and array loss research", Windpower91, Palm Springs, California, 1991
[16] Milborrow D J, "The performance of arrays of wind turbines", J. Industrial Aerodynamics, 5 (1980), pp. 403-430
[17] Guidelines for Design of Wind Turbines (1st ed.), Det Norske Veritas and Risø National Laboratory, ISBN 87-550-2870-5, 2001
[18] Weisstein E.W., Normal Distribution, From MathWorld - A Wolfram Web Resource, http://mathworld.wolfram.com/NormalDistribution.html (17 February 2010)

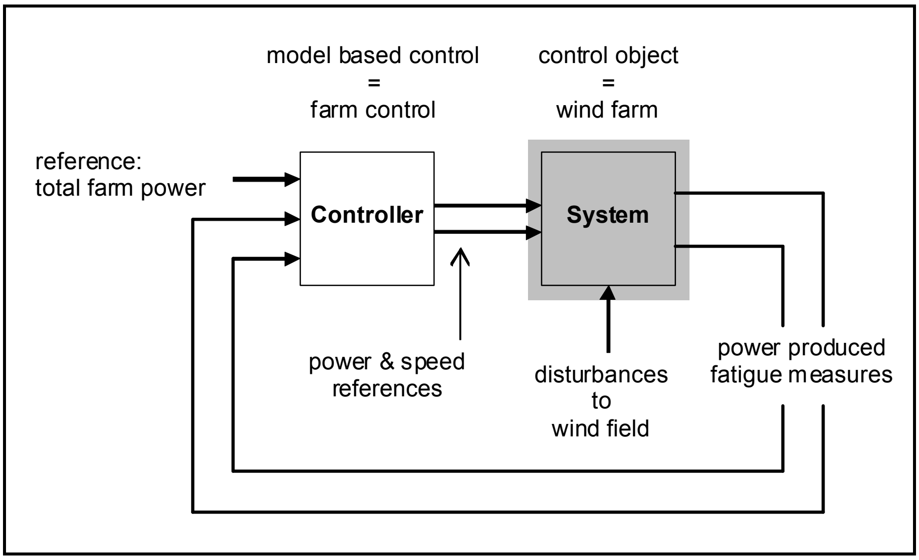


Figure 1 Basic structure of the quasi-steady wind farm flow model

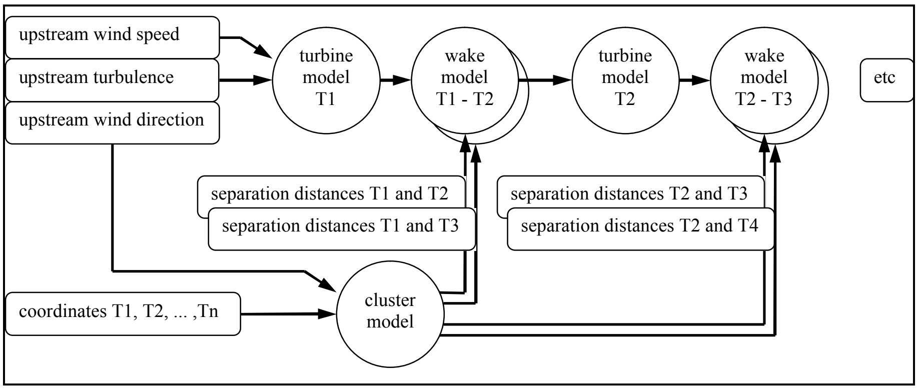


Figure 2 Flow chart of the quasi-steady wind farm flow model

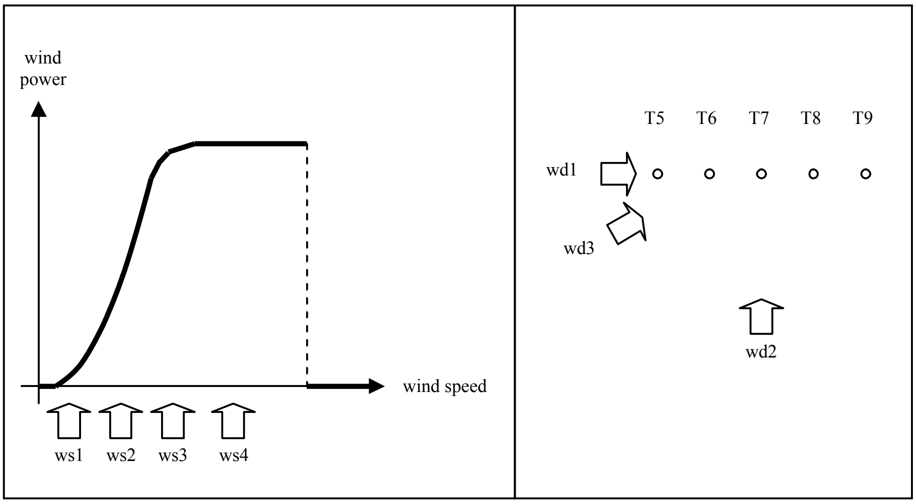


Figure 3 Description of the wind speed ranges (left) and the wind direction ranges (right) in the EWTW

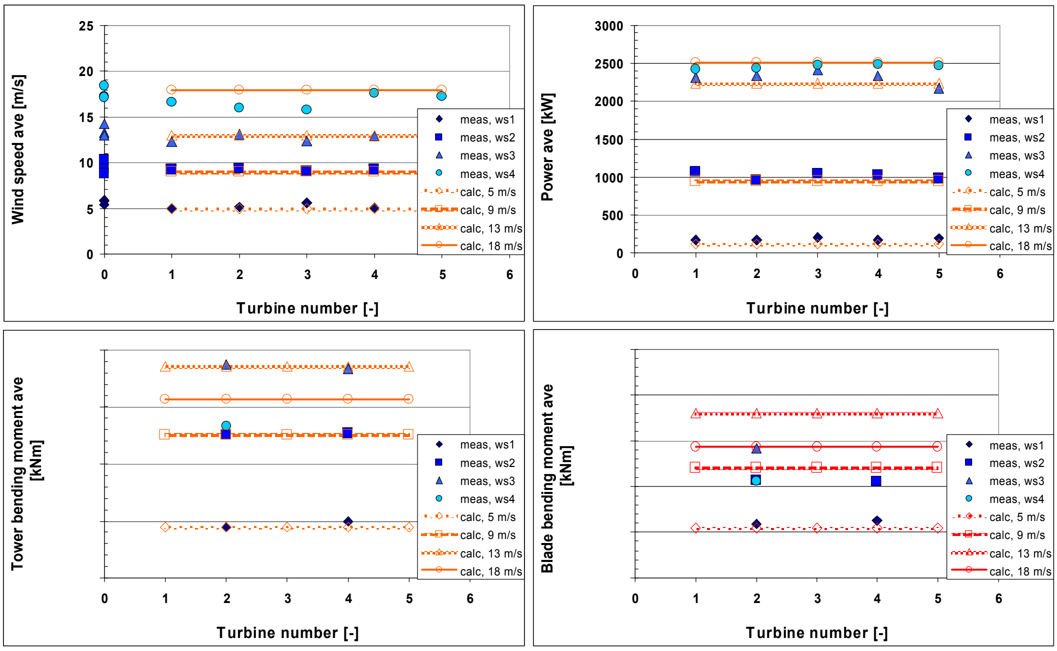


Figure 4 Calculated and measured means of wind speed, power, tower bending moment and blade bending moment in the case of inflow parallel perpendicular to the row of five wind turbines

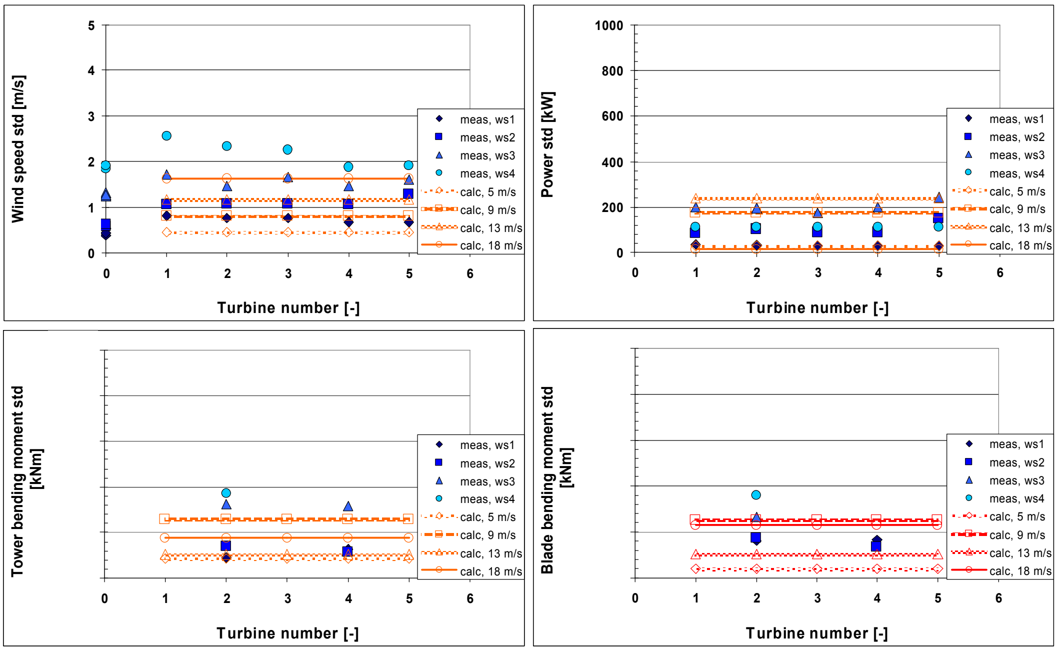


Figure 5 Calculated and measured standard deviations of wind speed, power, tower bending moment and blade bending moment in the case of inflow parallel perpendicular to the row of five wind turbines

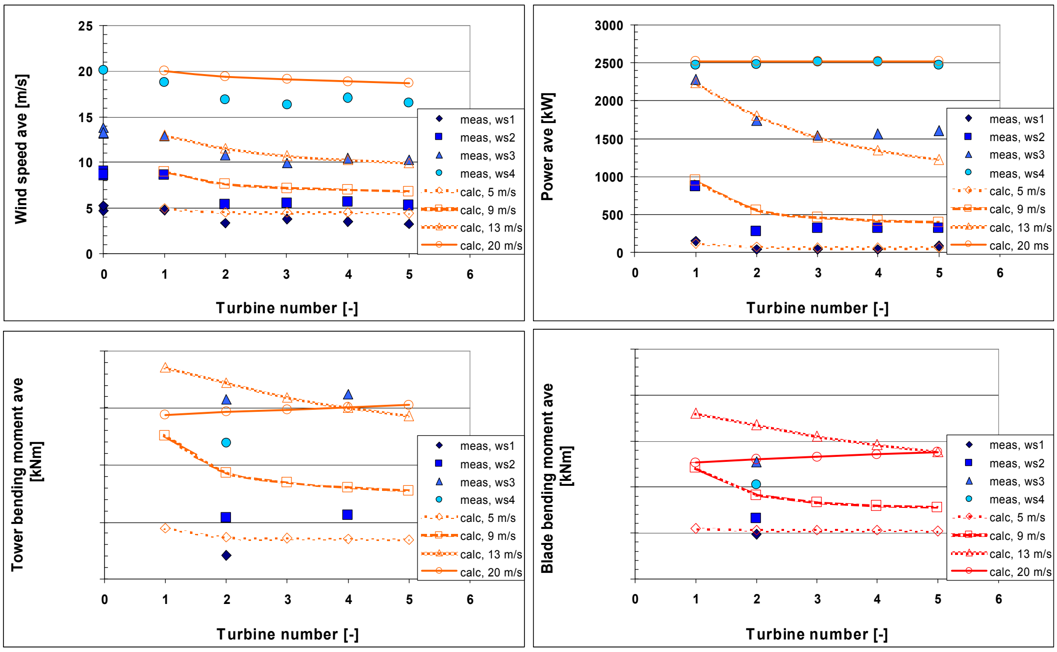


Figure 6 Calculated and measured means of wind speed, power, tower bending moment and blade bending moment in the case of inflow aligned with the row of five wind turbines

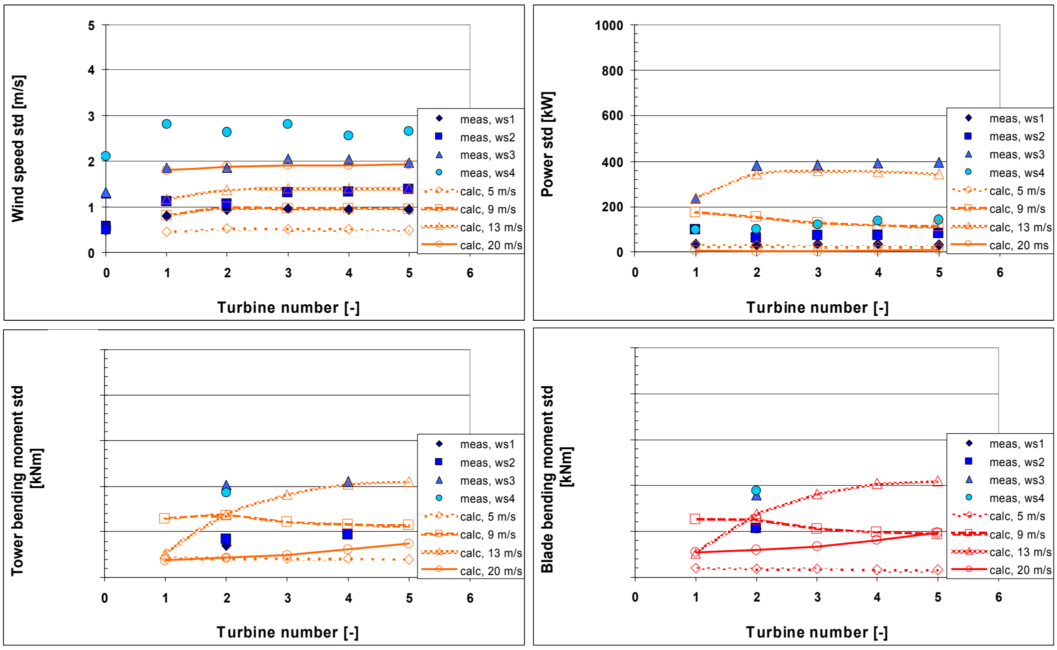


Figure 7 Calculated and measured standard deviations of wind speed, power, tower bending moment and blade bending moment in the case of inflow aligned with the row of five wind turbines

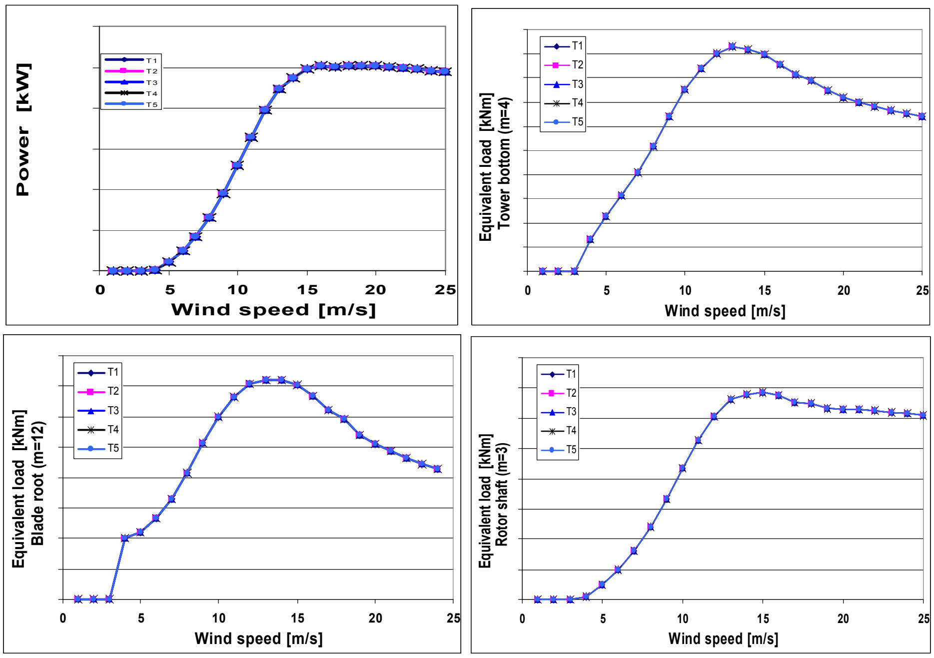


Figure 8 Calculated power and load quantifiers for the turbine tower, the blade and the rotor shaft as a function of wind speed in the case of inflow perpendicular to the row of five wind turbines and a turbulence intensity of 9%

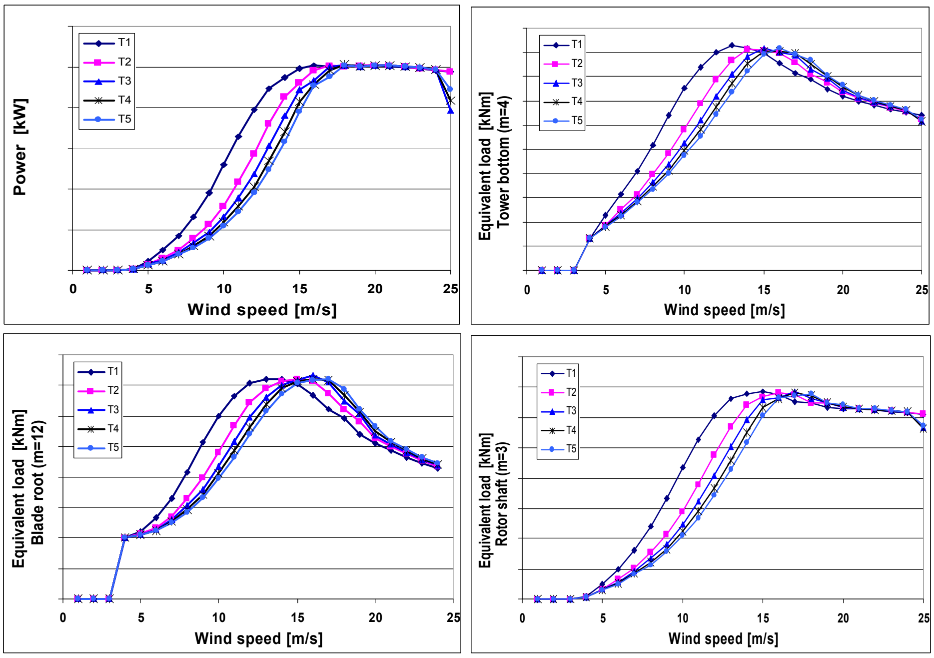
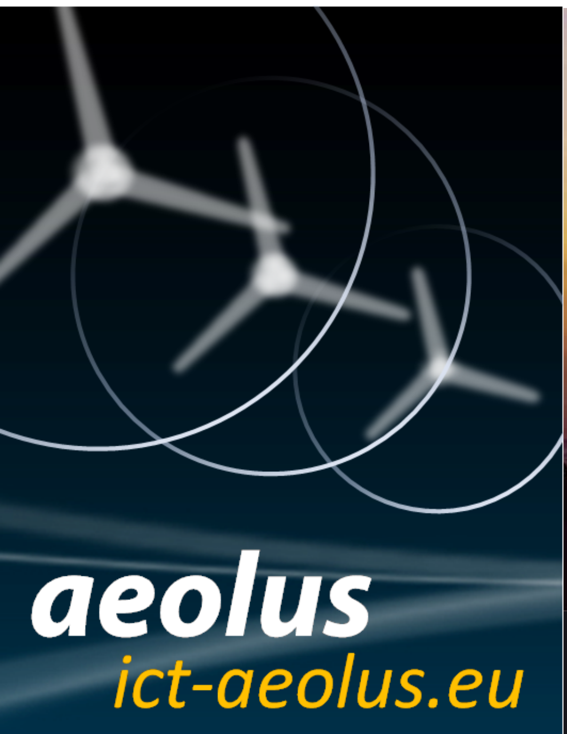


Figure 9 Calculated power and load quantifiers for the turbine tower, the rotor blade and the rotor shaft as a function of wind speed in the case of inflow aligned with the row of five wind turbines and a turbulence intensity of 9%

ECN

Energy research Centre of the Netherlands

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



Arno J. Brand

Jan Willem Wagenaar

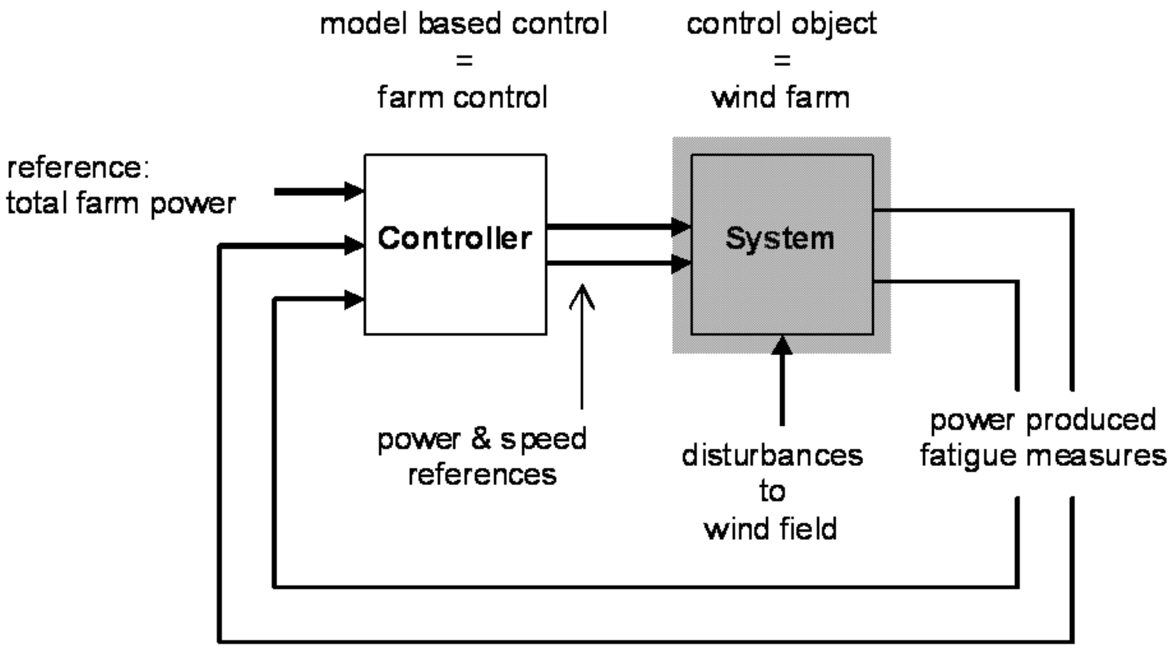
SEVENTH FRAMEWORK PROGRAMME

FP7-ICT STREP 224548 / Aeolus

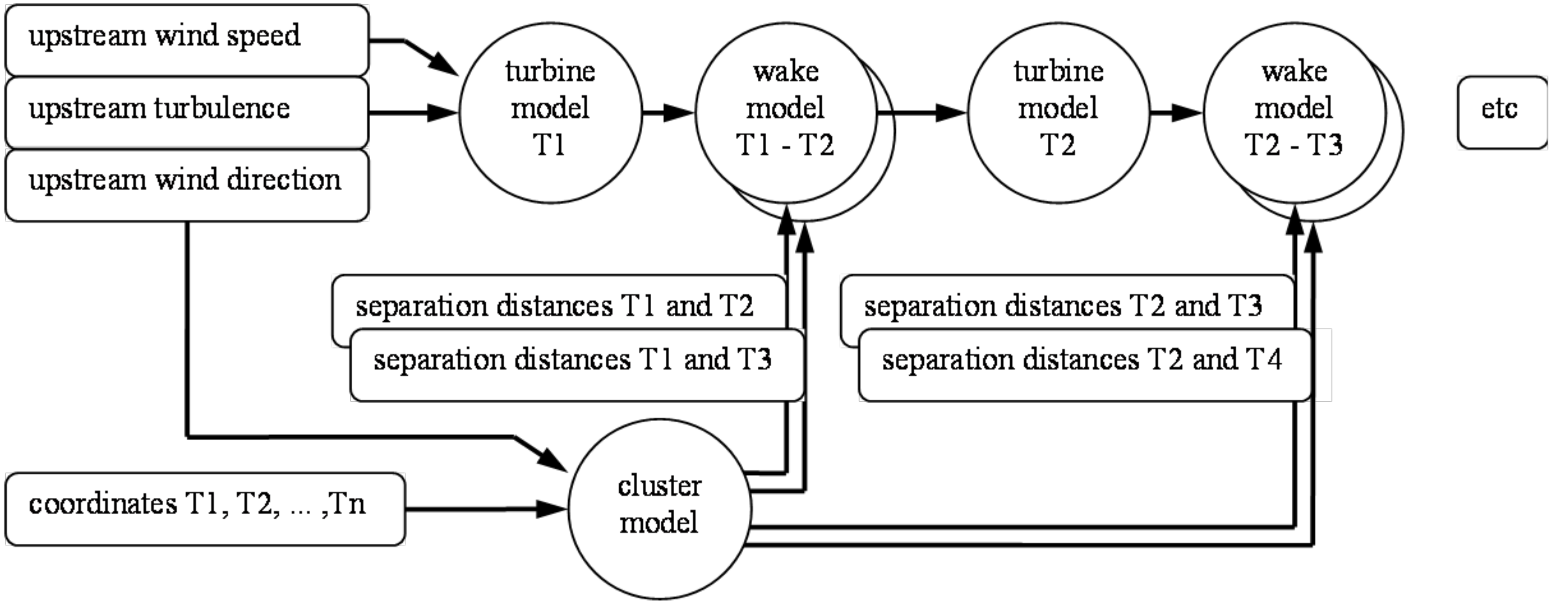
Outline

- Motivation & Objectives
- Method
- Results
- Summary & Outlook

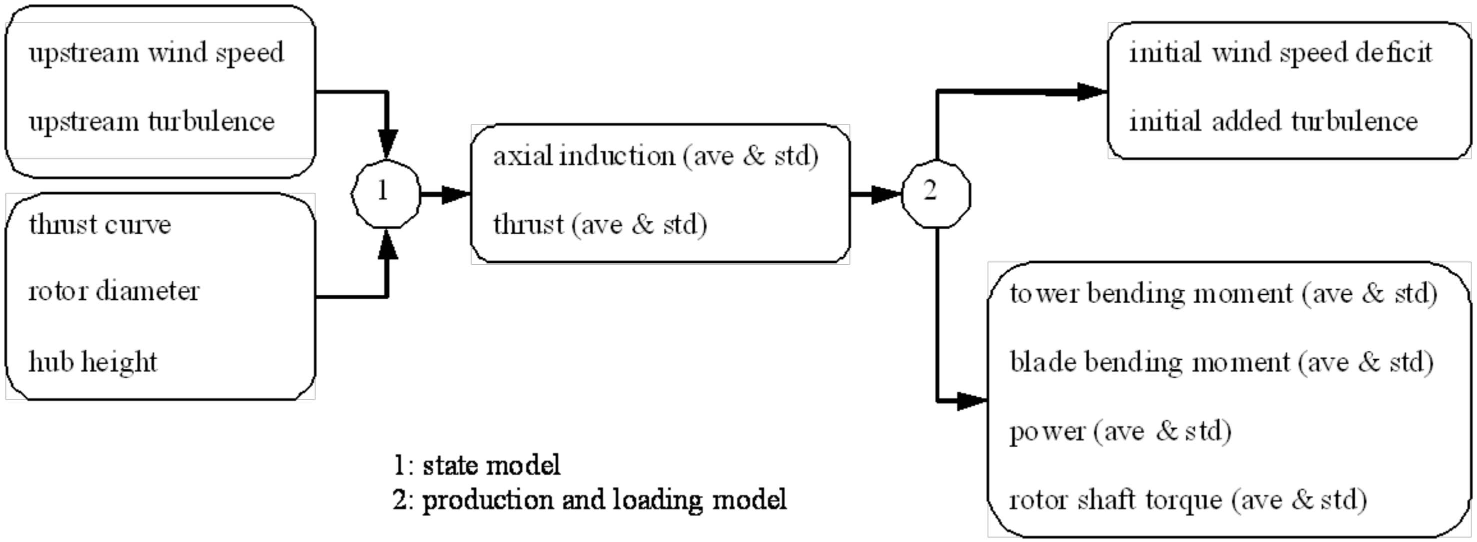
Quasi-steady flow model basic structure



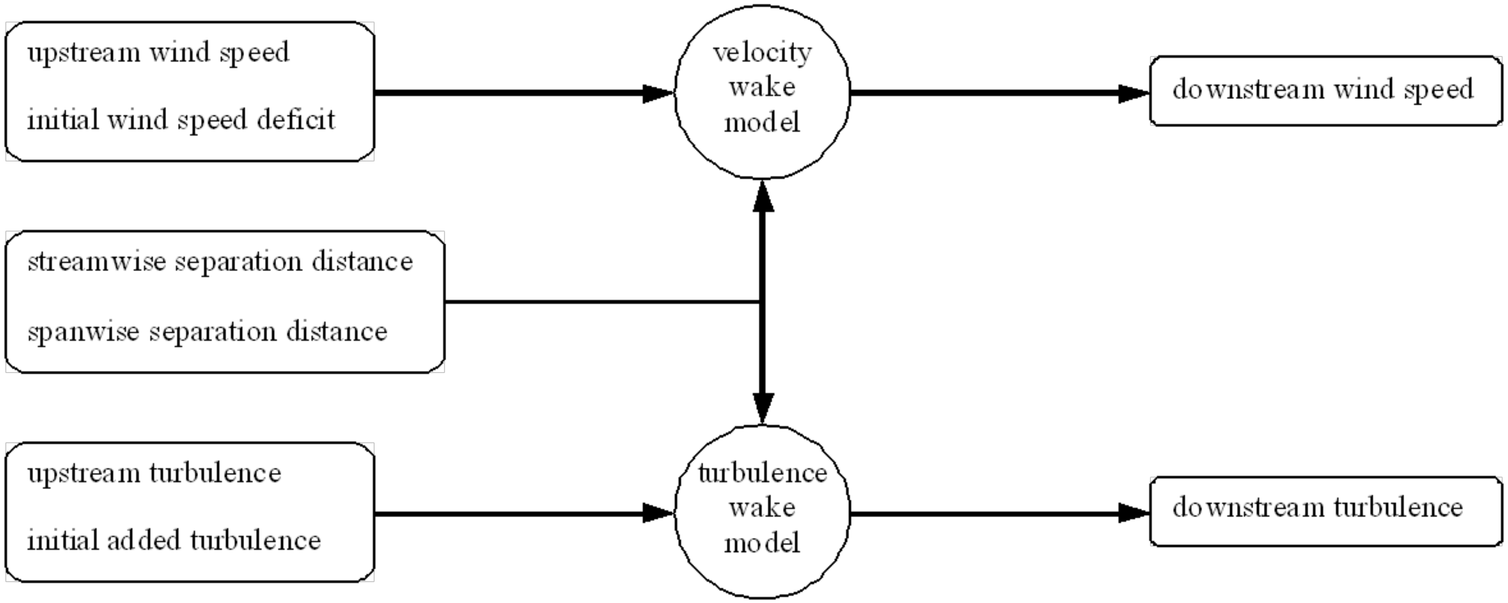
Wind farm flow model



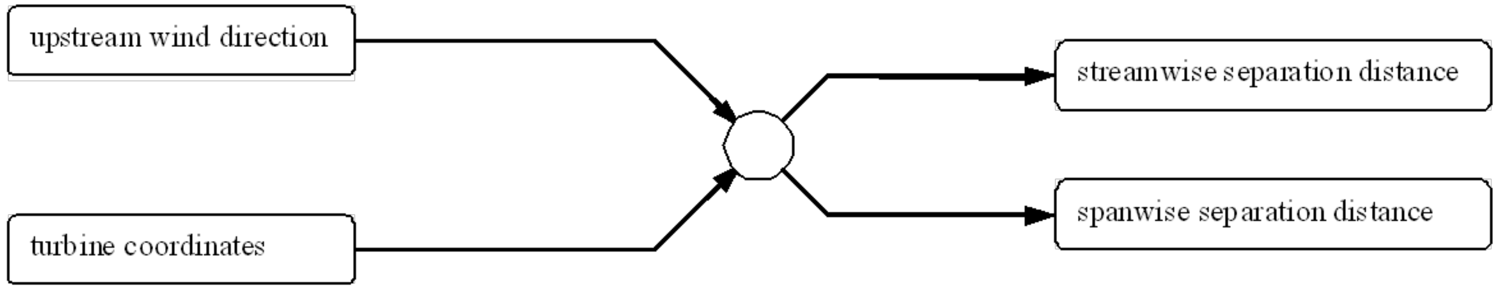
Wind turbine model



Wind turbine wake model



Cluster model



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

Model output

- Forward

  $(\{ \{WS, BPA, RS\}_{iklm}, \{Power, Loads\}_{iklm}) = f(\{WS_k, WD_l, TI_m\})$

  state **output** **external conditions**

- Inverse

  $(\{WS_k, WD_l, TI_m\}, \{WS, BPA, RS\}_{iklm}, \{Loads\}_{iklm}) = g(\{Power\}_{iklm})$

  external conditions **state** **loads** **power reference**

WS = Ambient wind speed

WD = Ambient wind direction

TI = Turbulence intensity

BPA = Blade pitch angle

RS = Rotor speed

Assumptions

- Momentum theory for wind turbine states and wakes
- Ten minute wind speed normally distributed

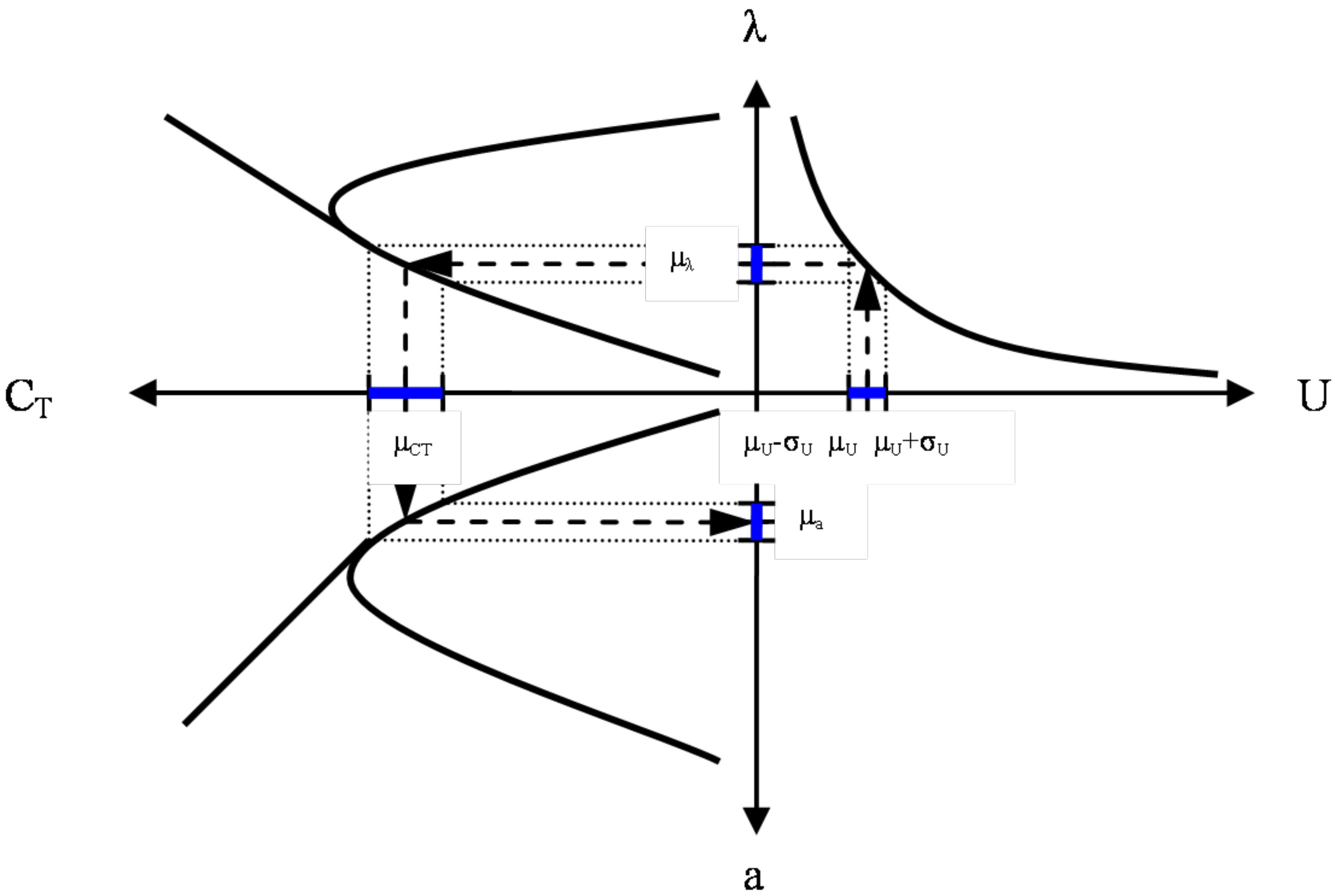
$$U : N(\mu_U, \sigma_U)$$

- Derived quantities normally distributed

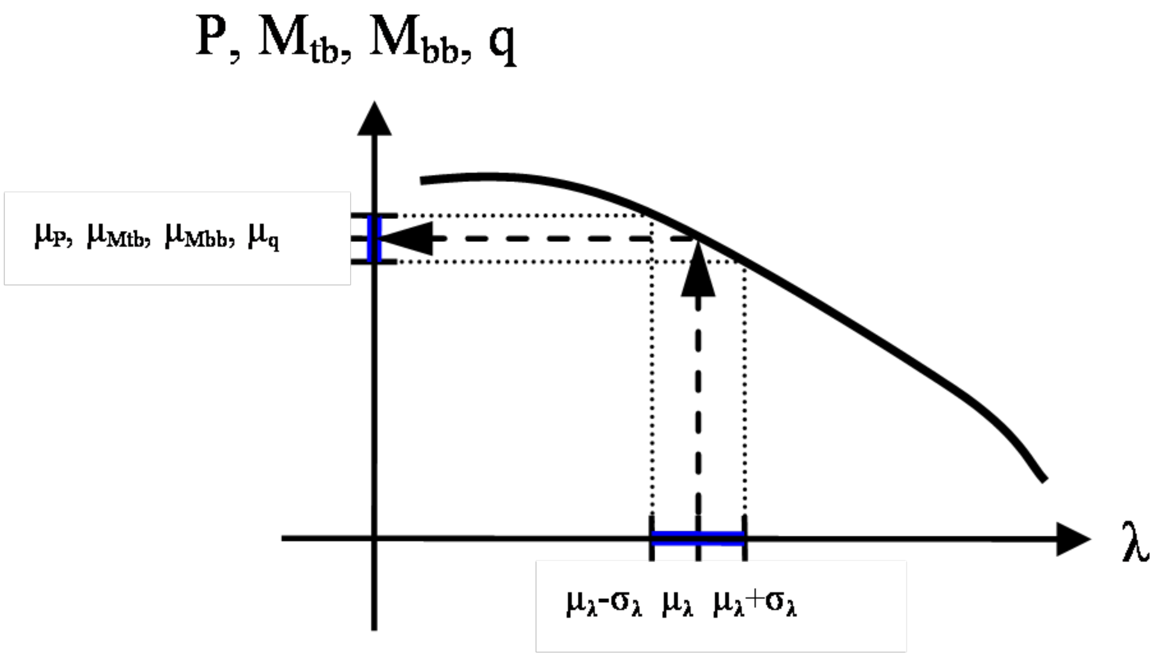
$$x = f(U) \quad x : N(\mu_x, \sigma_x) \quad \mu_x = g_1(\mu_U, \sigma_U) \quad \sigma_x = g_2(\mu_U, \sigma_U)$$

- Load quantifier depending on μ_x and σ_x

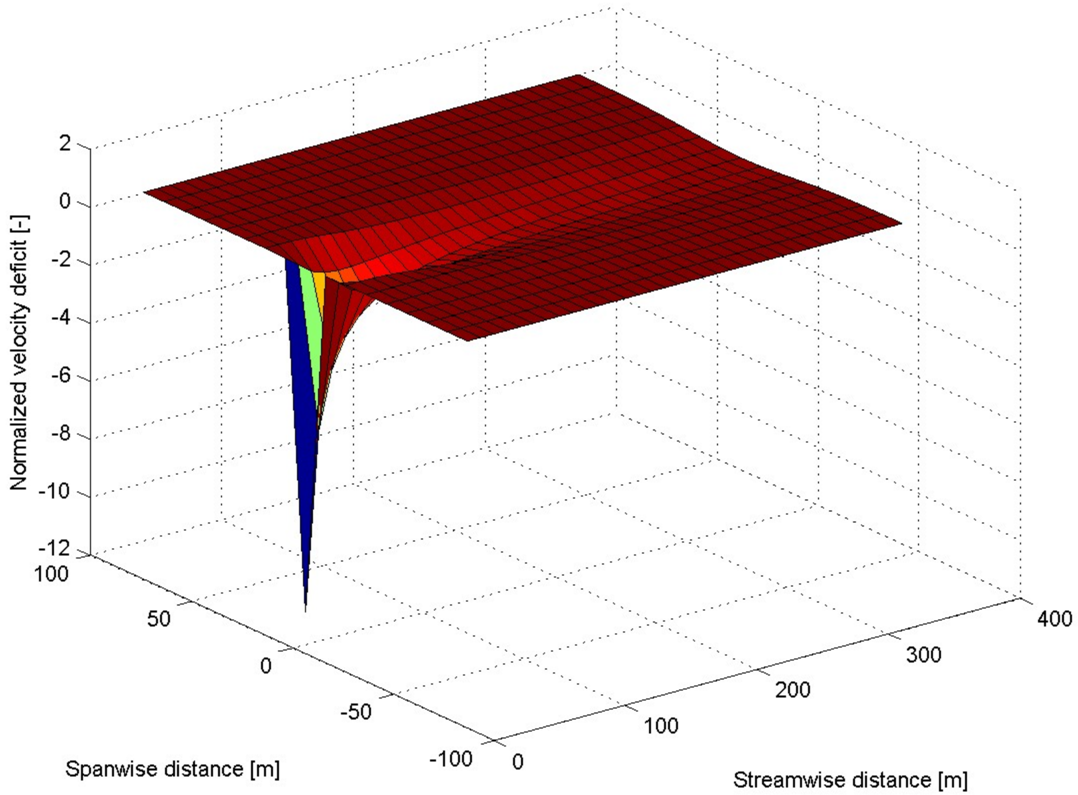
Wind turbine state



Wind turbine production and loading



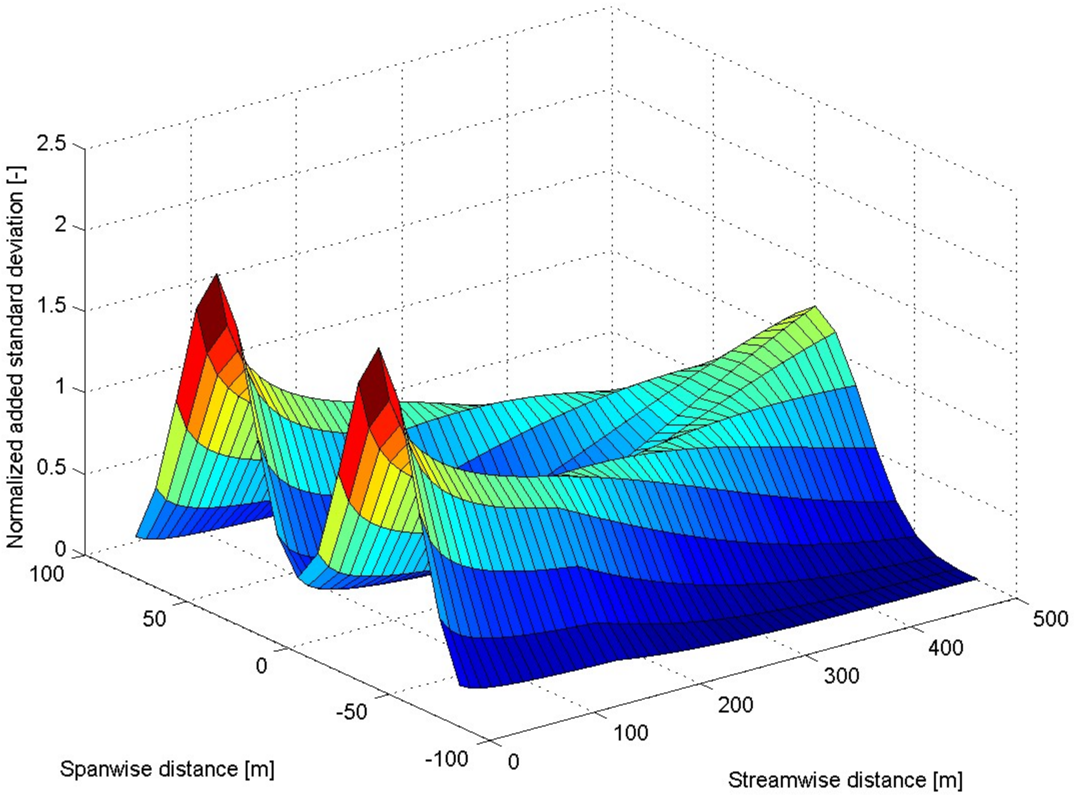
Velocity deficit



D = 80 m

a = 1/3

Added turbulence



D = 80 m

a = 1/3

Load quantifier

- Equivalent load L_{eq}

$$L_{eq}^{m} \equiv \frac{1}{N}\sum_{i} n_i L_i^{m} = \frac{1}{N}\sum_{j} L_j^{m} = f(\mu_L, \sigma_L)$$

- Equivalent tower bottom bending moment

$$L_{eq} = \left(\mu_L^4 + 6\mu_L^2\sigma_L^2 + 3\sigma_L^4\right)^{\frac{1}{4}}$$

- Equivalent blade root bending moment

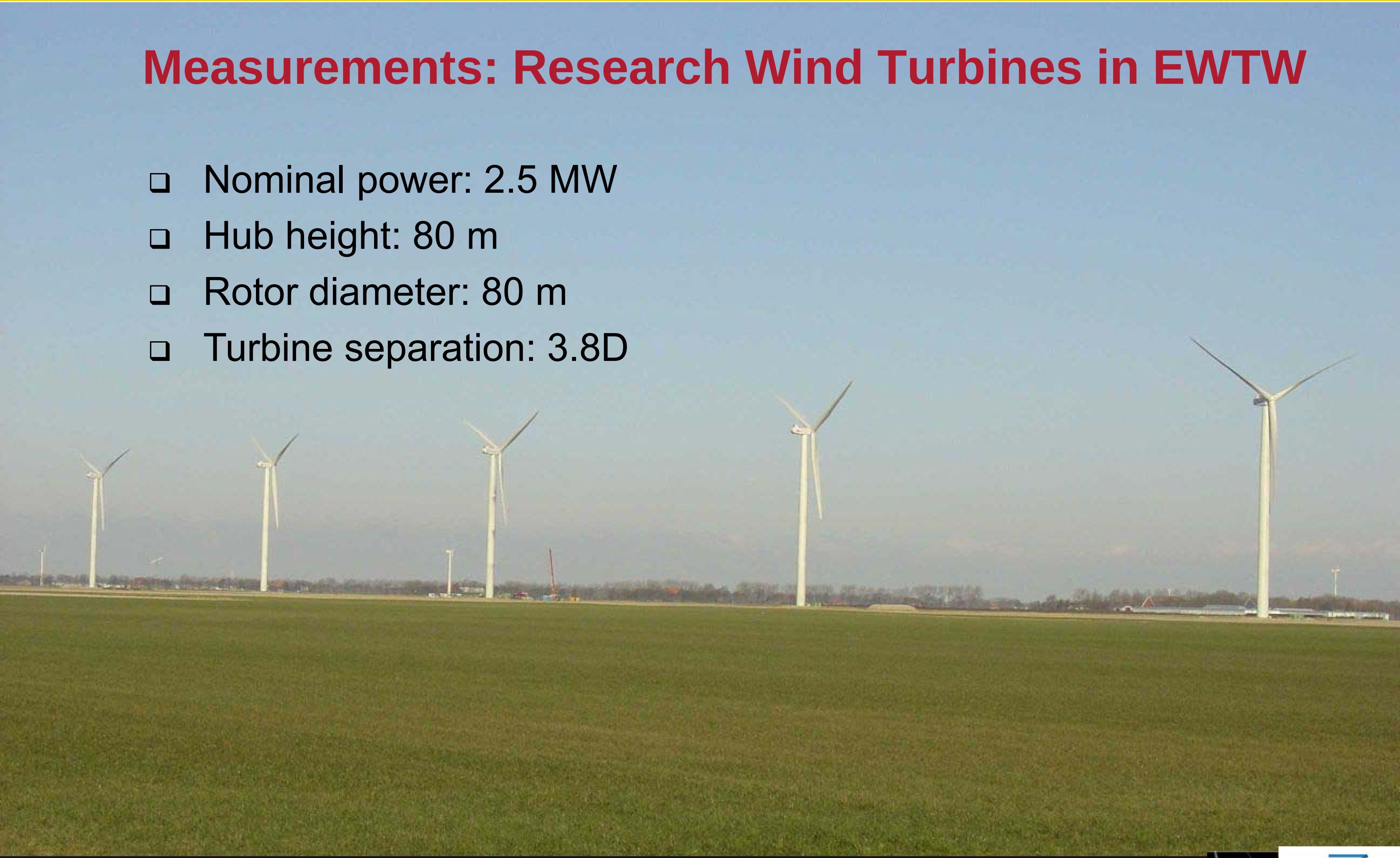
$$L_{eq} = \left(\mu_L^{12} + 66\mu_L^{10}\sigma_L^2 + 1485\mu_L^8\sigma_L^4 + 13860\mu_L^6\sigma_L^6 + 51975\mu_L^4\sigma_L^8 + 62370\mu_L^2\sigma_L^{10} + 10395\sigma_L^{12}\right)^{\frac{1}{12}}$$

- Equivalent rotor shaft torque

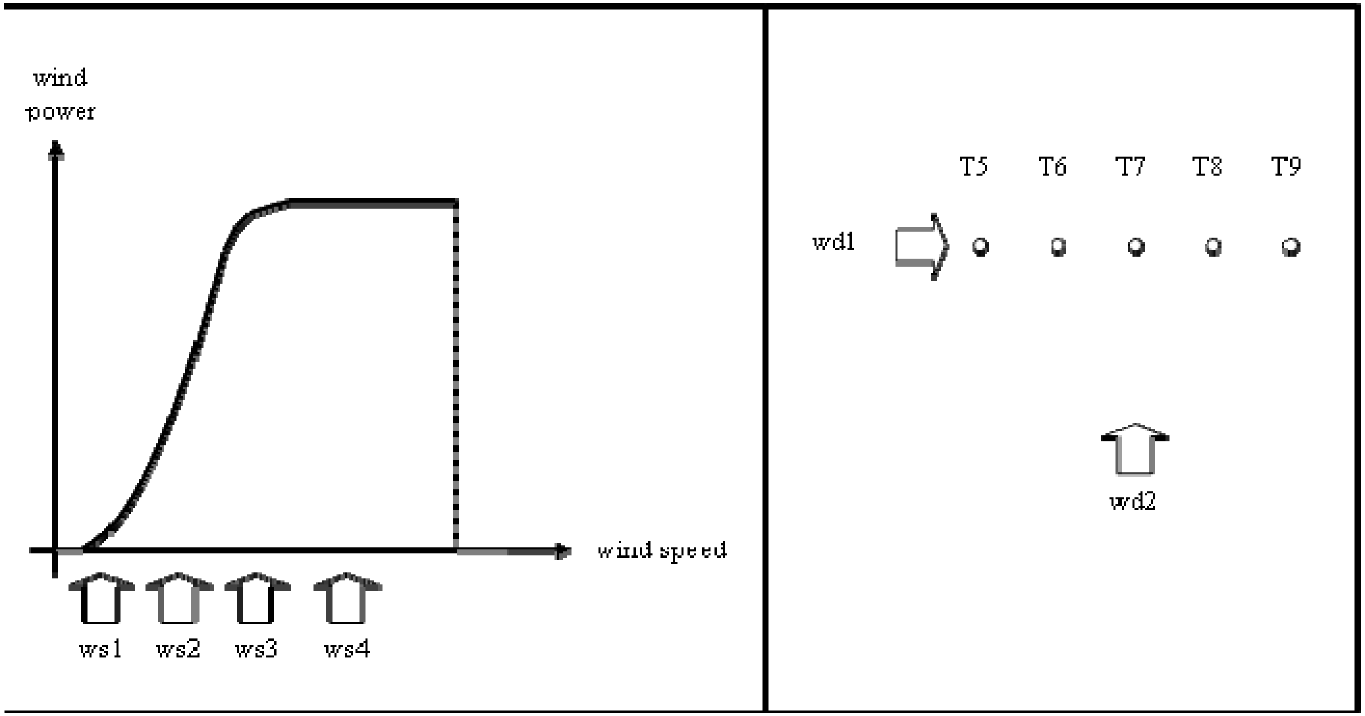
$$L_{eq} = \left(\mu_L^3 + 3\mu_L\sigma_L^2\right)^{\frac{1}{3}}$$

Measurements: Research Wind Turbines in EWTW

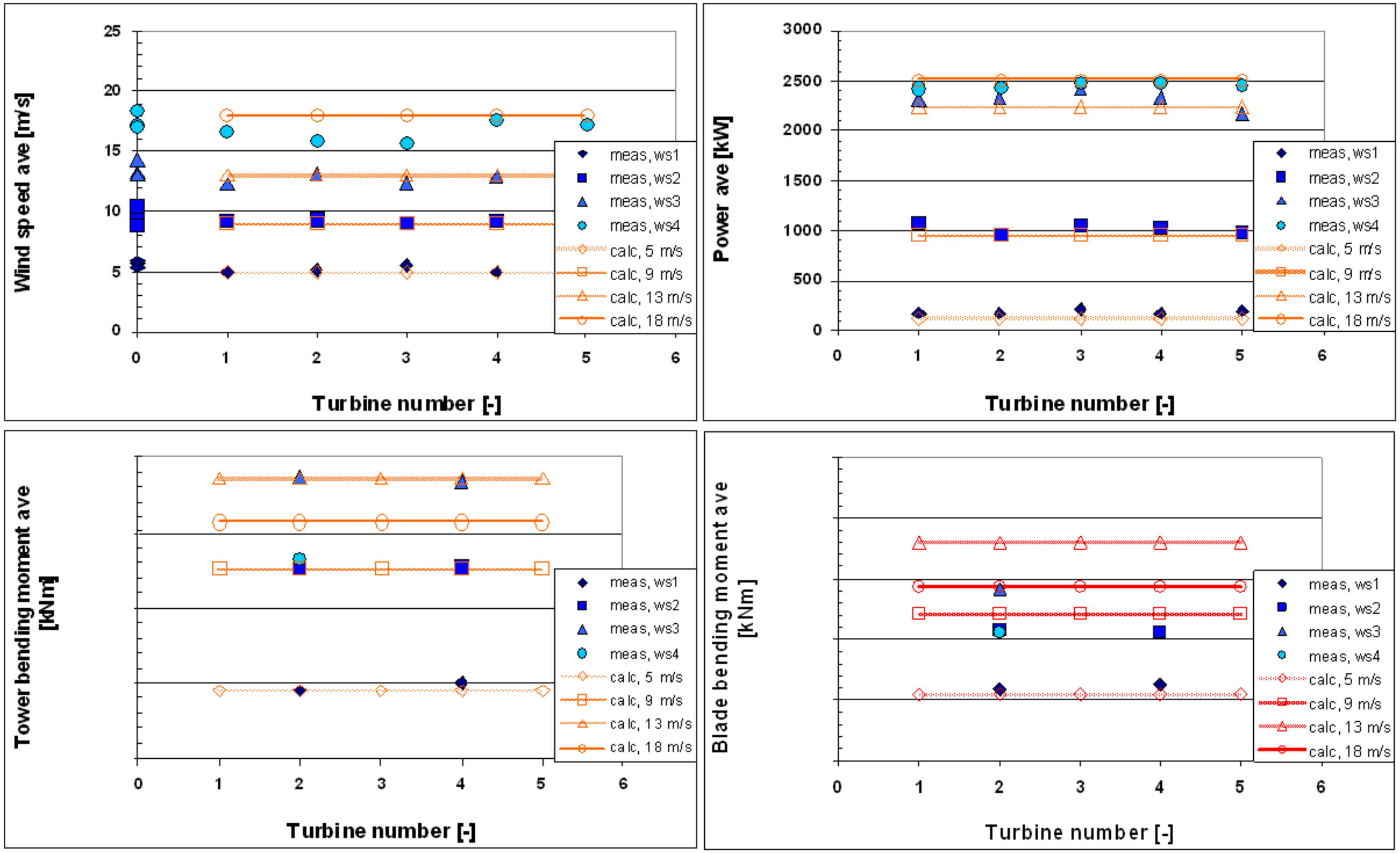
- Nominal power: 2.5 MW
- Hub height: 80 m
- Rotor diameter: 80 m
- Turbine separation: 3.8D



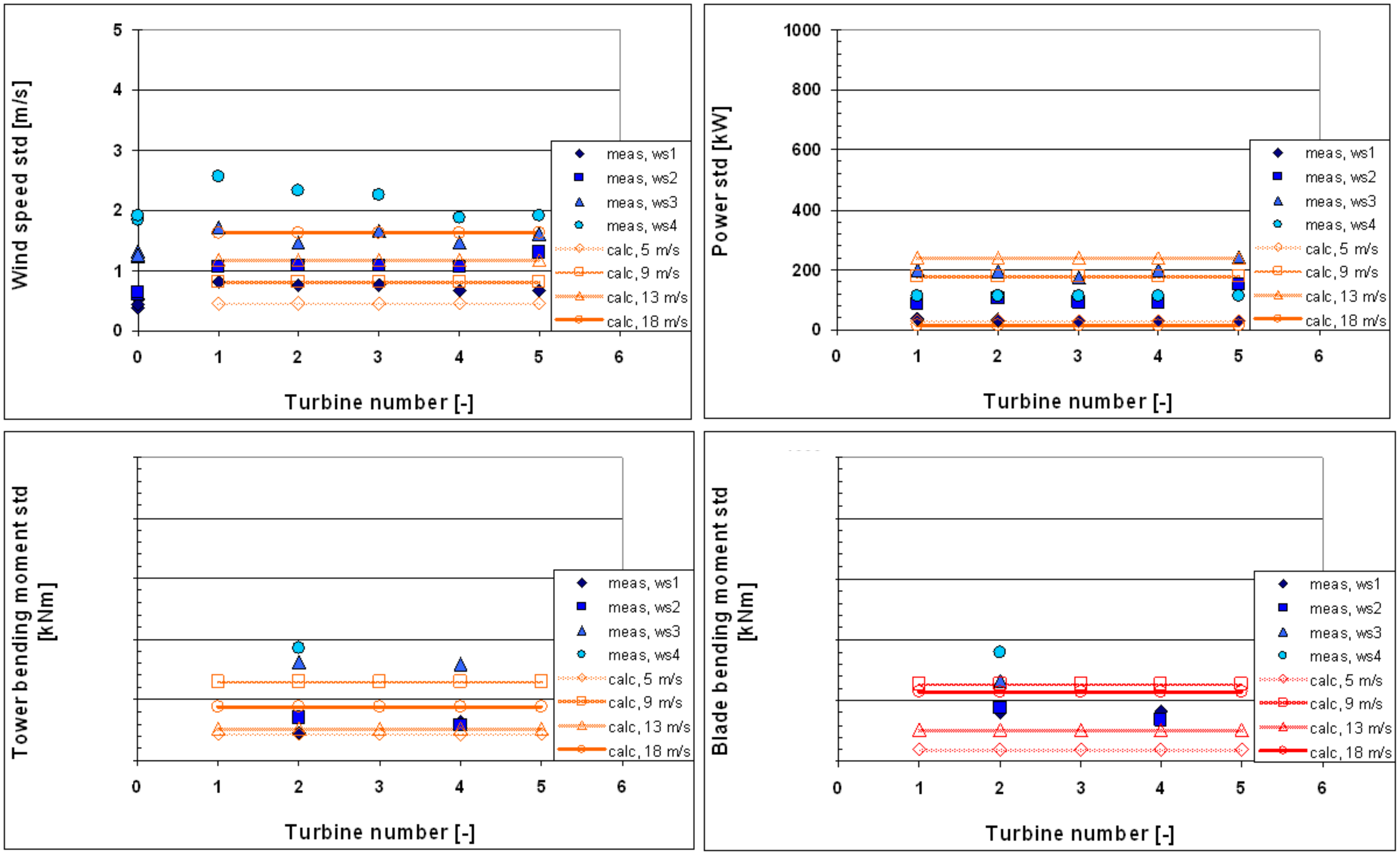
Wind speed and wind direction cases



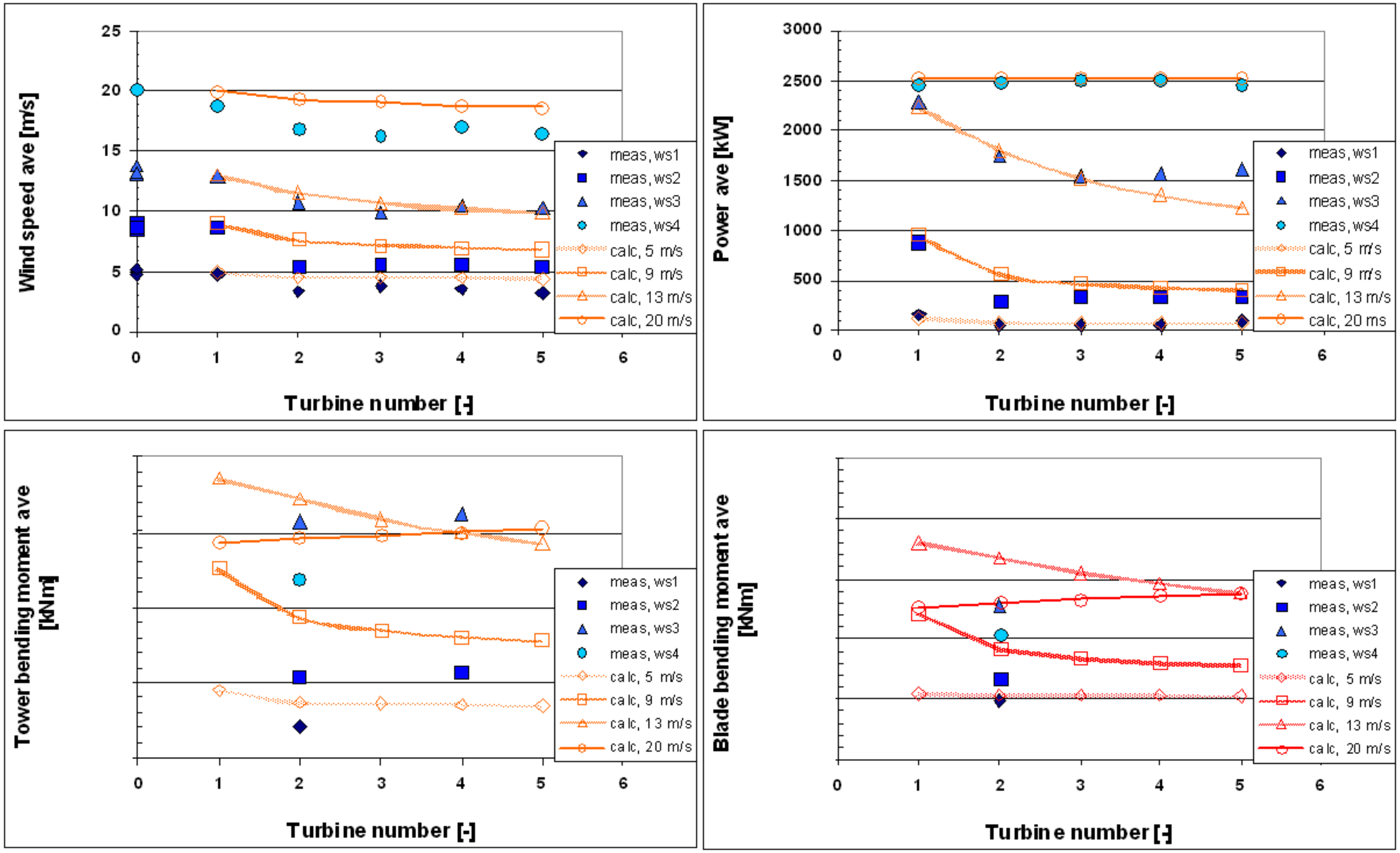
Perpendicular inflow: averages



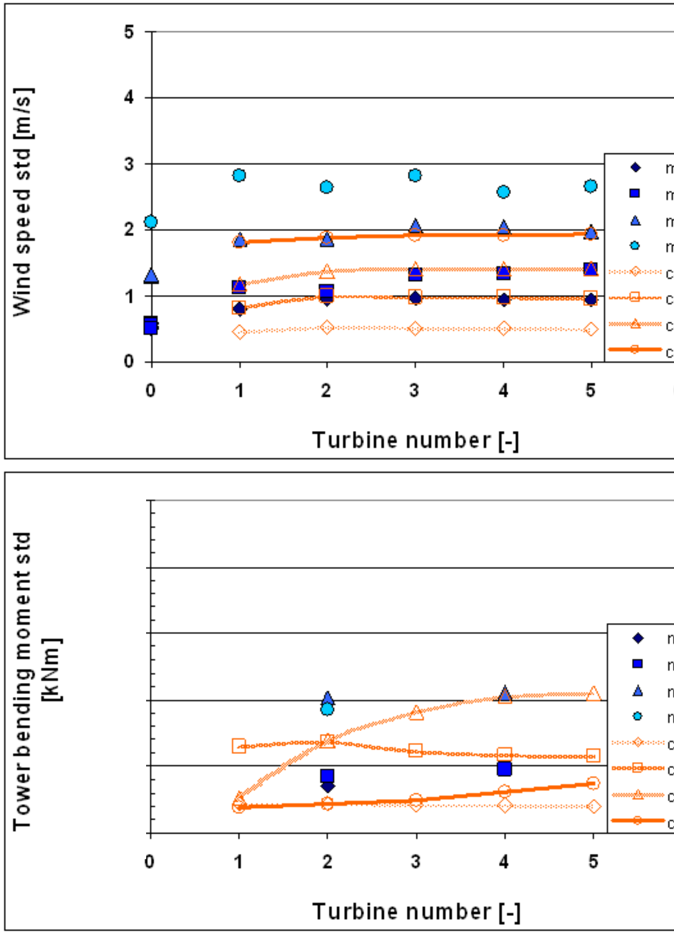
Perpendicular inflow: standard deviations



Parallel inflow: averages

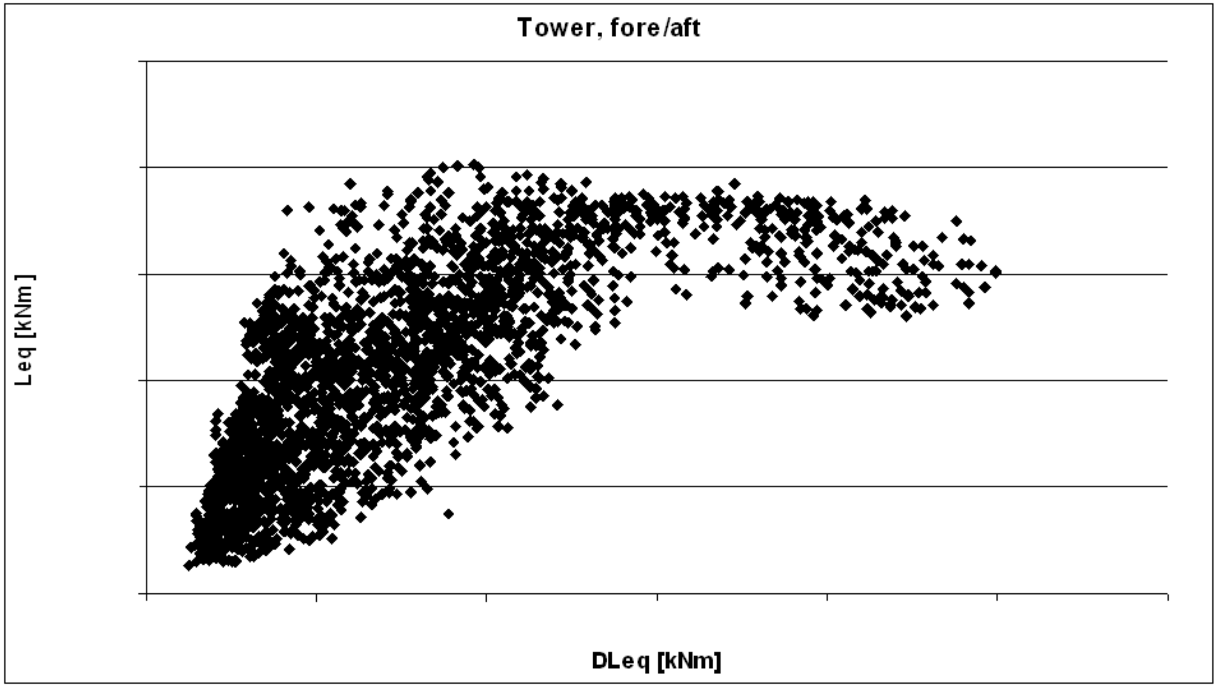


Parallel inflow: standard deviations



Load quantifier versus fatigue quantifier

- Equivalent load L_{eq}
- Fatigue equivalent load range ΔL_{eq}



Conclusion

- Main difference measurements and predictions due to:
  - * Un-modelled spatial variations in wind speed, and
  - * Too gradually modelled decay of wind speed
- Equivalent load:
  - * Promising load quantifier

Summary and outlook

- Quasi-steady wind farm flow model
- Model output comparison with data from EWTW
- Various modelling issues

- Model output to be compared to data from ESWF
- Modelling issues to be addressed:
  - * Decay of velocity deficit and added turbulence
  - * Loads and load quantifier
  - * Power reference

Contact

Arno J. Brand

ECN Wind Energy
Wind turbine rotor and Wind farm Aerodynamics

M: P.O. Box 1, NL 1755 ZG Petten, Netherlands
E: brand@ecn.nl
T: +31 224 56 4775
F: +31 224 56 8214
I: linkedin.com/in/arnobrand