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Energy research Centre of the Netherlands

ECN Wind Energy Presentations at the Dutch Wind Workshops 2008

Delft, October 27-28

ECN-M--08-082

NOVEMBER 2008

Contents

Dutch Wind Workshops, October 2008

Measurements at Offshore Wind farm Egmond aan Zee (OWEZ)

P.J. Eecen

TUDelft

DUWIND

SenterNovem

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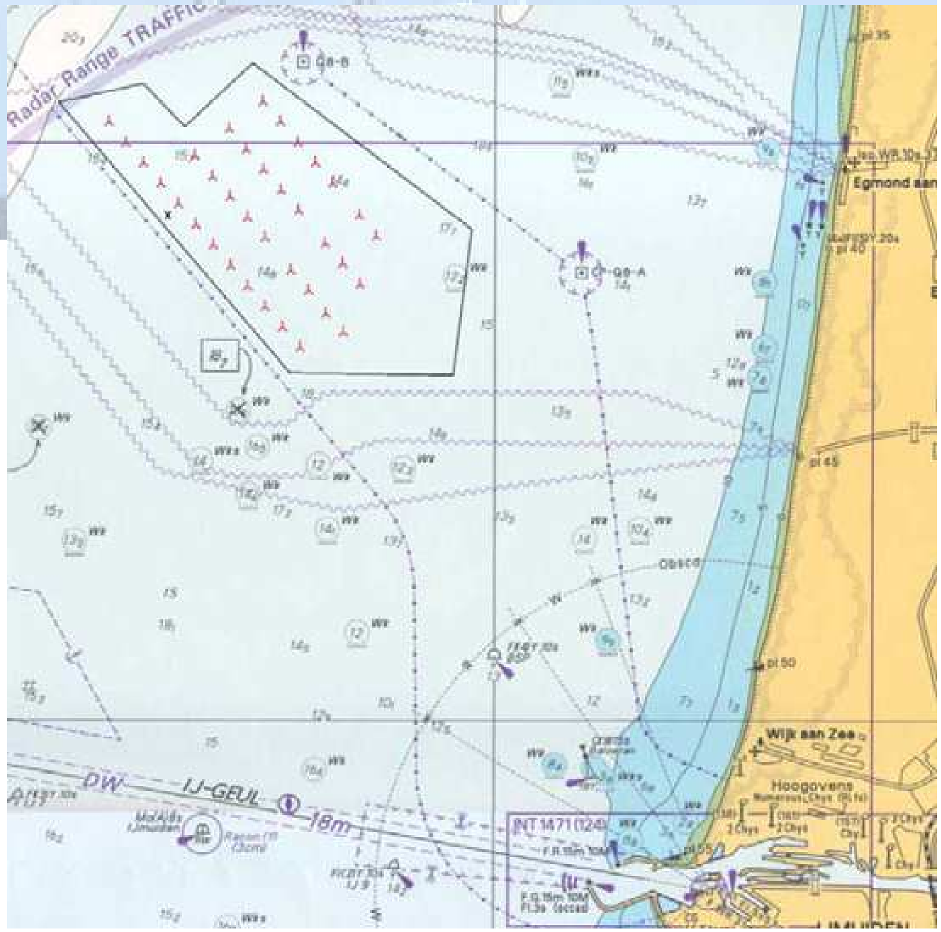
NoordzeeWind

NUON

Contents

OWEZ Wind Farm

- 36 Vestas V90 3MW
- Located 10-18km at the coast near Egmond aan Zee

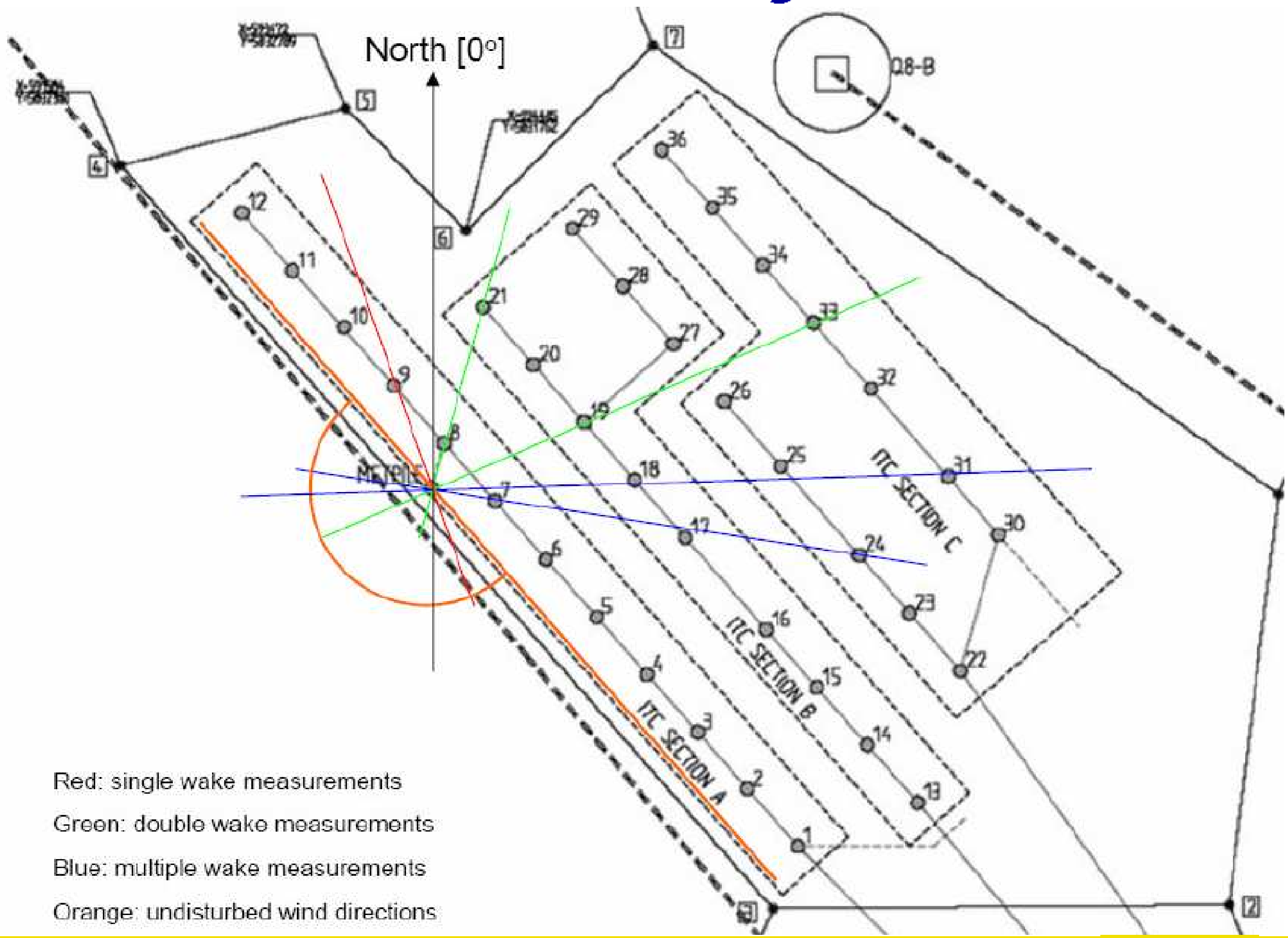


MEP-NSW

- OWEZ is linked to a comprehensive Monitoring and Evaluation Programme (NSW-MEP).
- The NSW-MEP aims to fill the gaps in knowledge and experience in the field of technology, economy, nature, environment and use functions.
- Consequently there are two parts to the NSW-MEP: Ecology and Technology.
- MEP-NSW runs from 2006 to 2012

Measurement of Wind Conditions

A 116m meteorological mast



Red: single wake measurements

Green: double wake measurements

Blue: multiple wake measurements

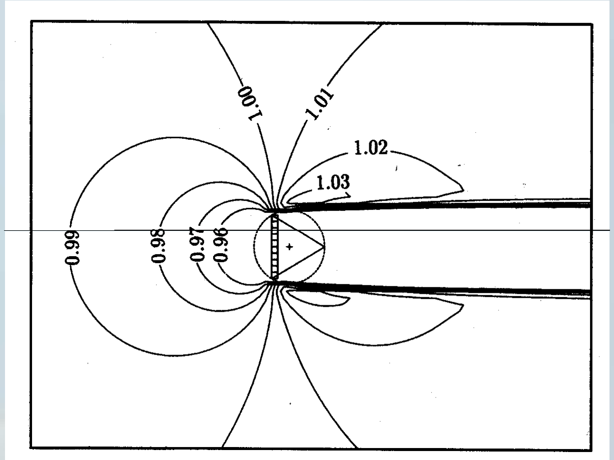
Orange: undisturbed wind directions

116m mast

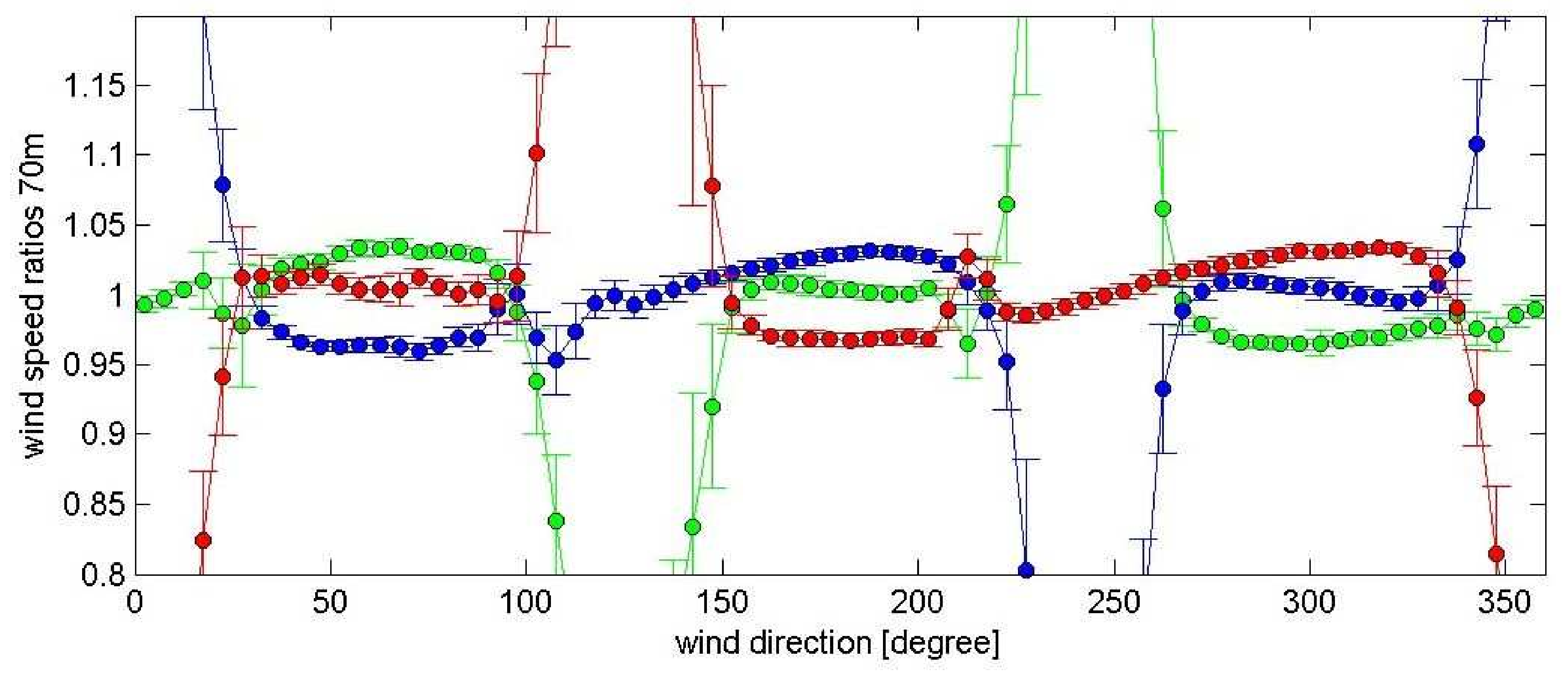
- Wind speed / direction at 21, 70 and 116m
- Air Temperature and humidity at 21, 70 and 116m
- Sea Water Temperature
- Air pressure and precipitation (70m)
- Acceleration measurements in top (116m)

Uncertainties

Flow Distortion due to the mast

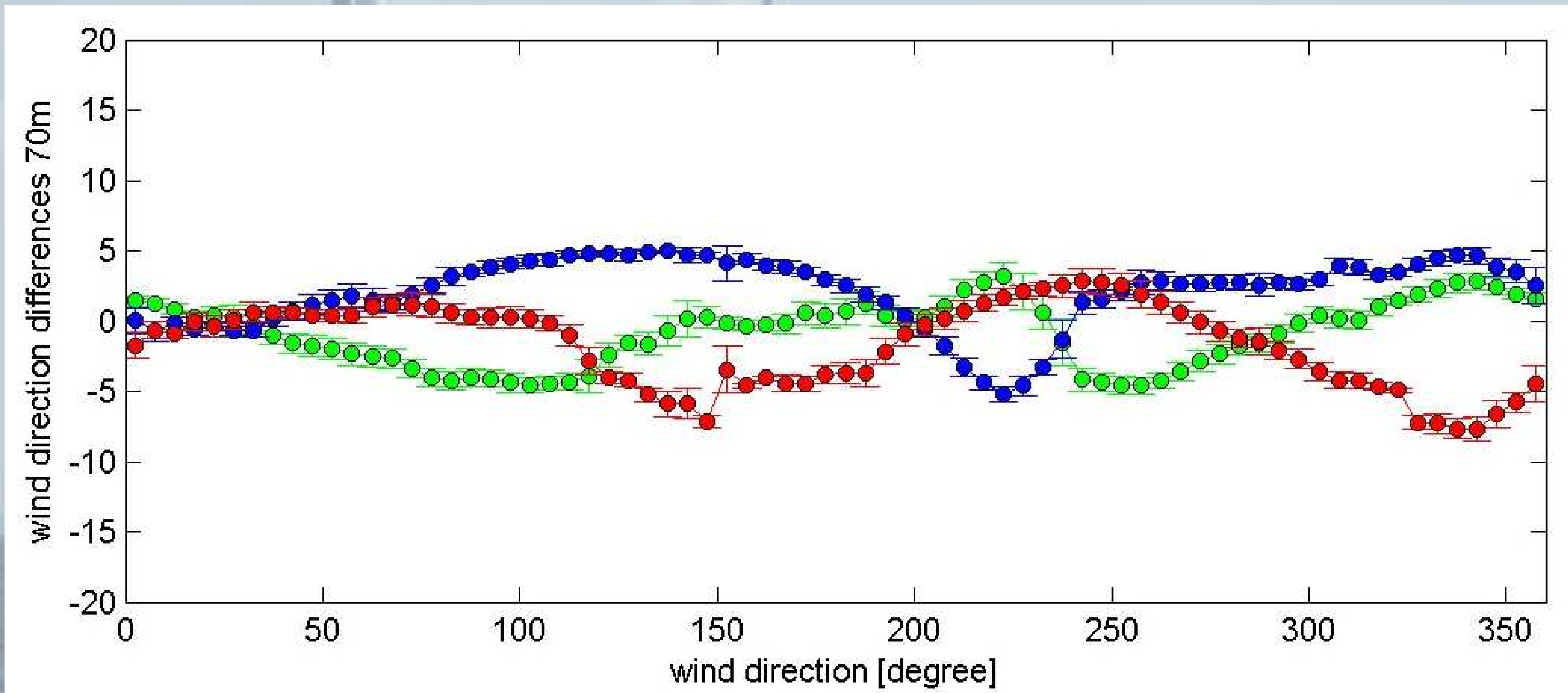


[1] IEA Recommended Practices for Wind Turbine Testing and Evaluation; No 11: Wind Speed Measurement and use of cup anemometry, 1. Edition 1999.



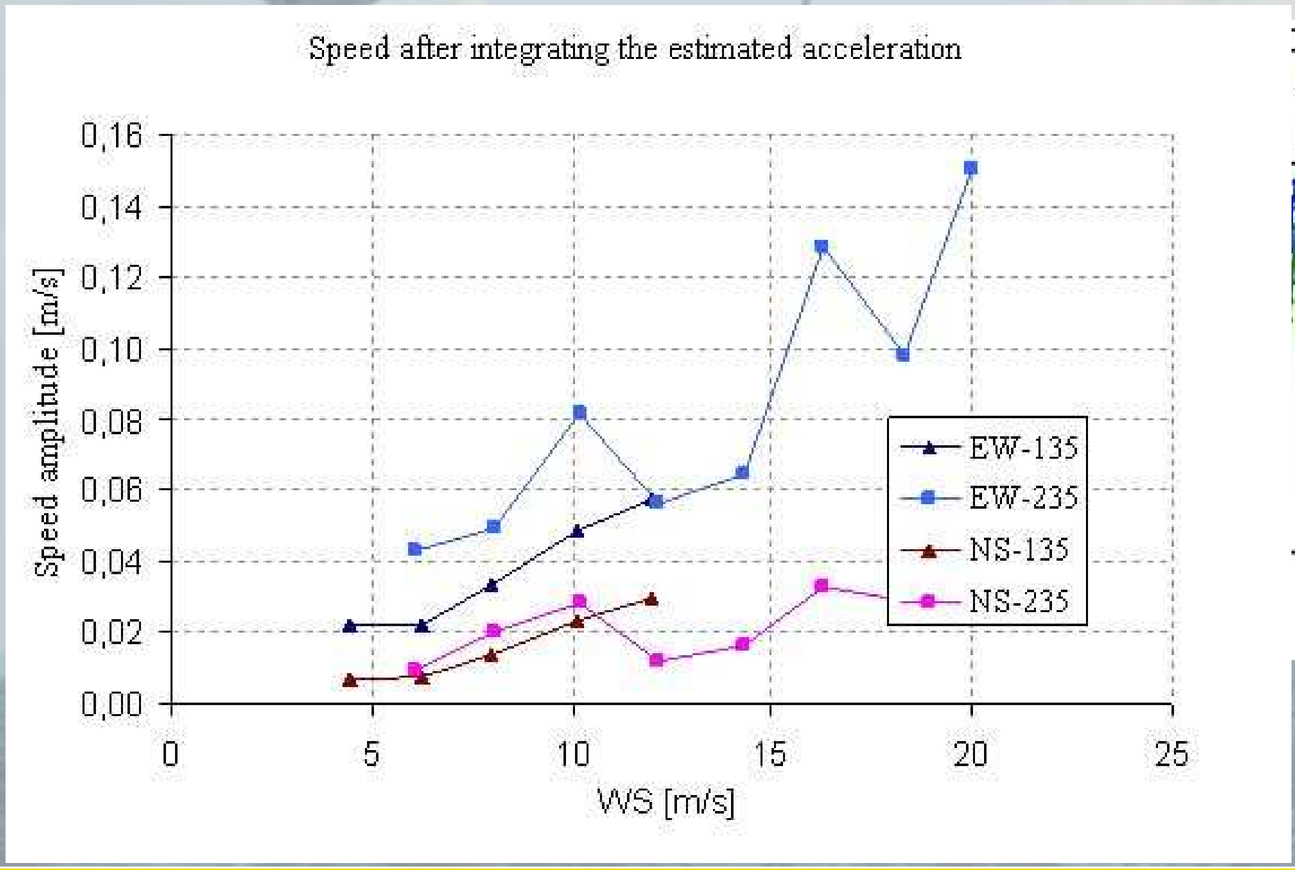
Uncertainties

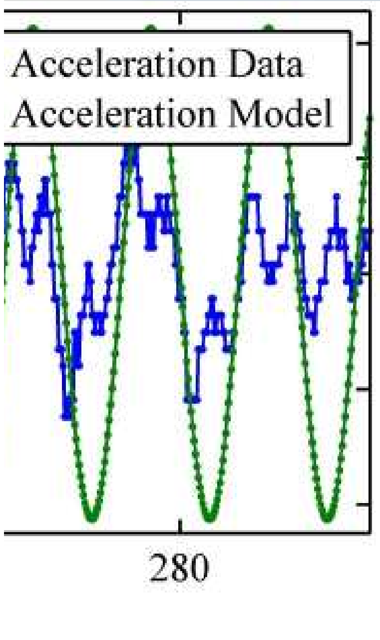
Flow Distortion due to the mast



Uncertainties

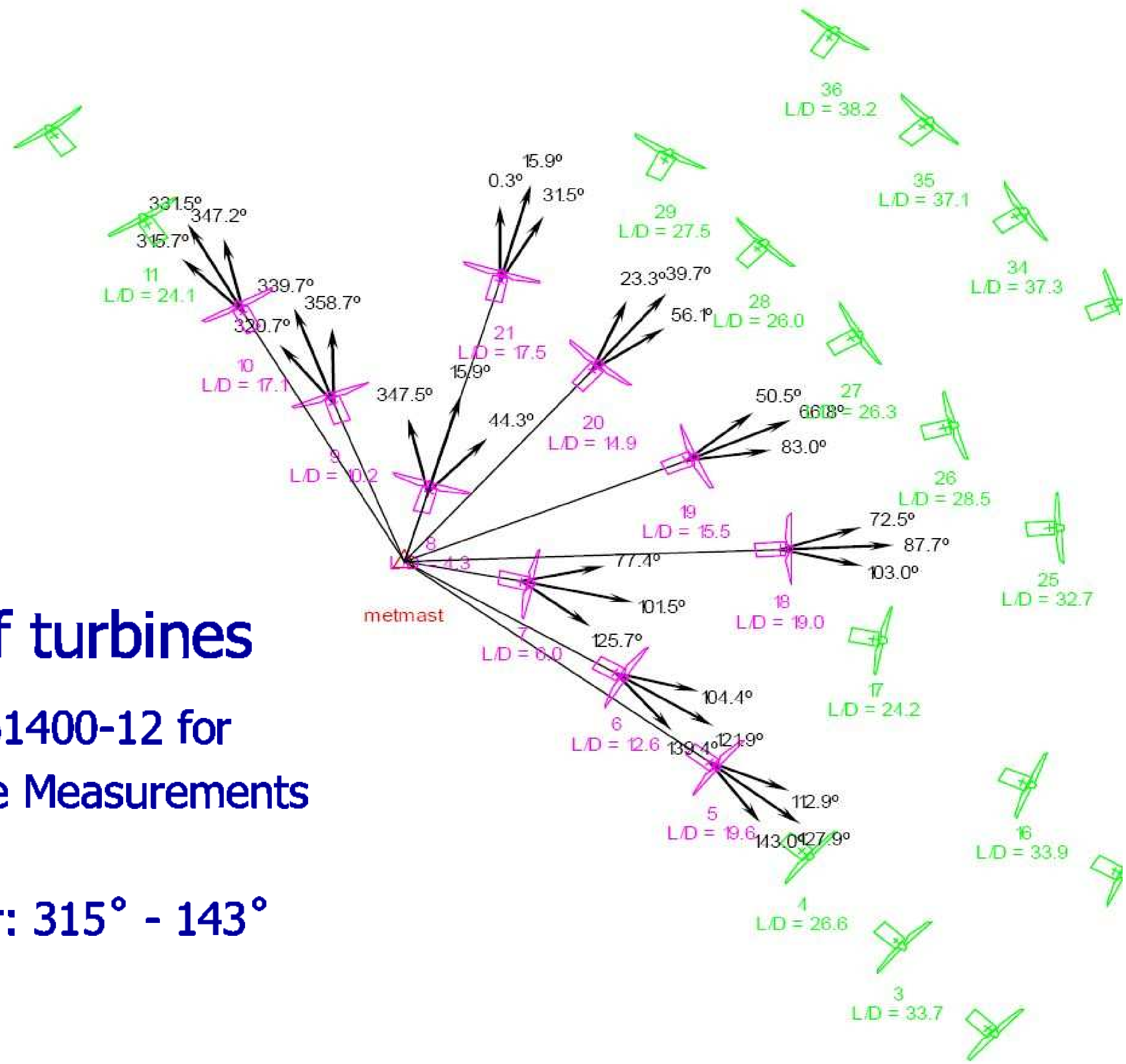
Oscillating movement mast-top





Influence of turbines

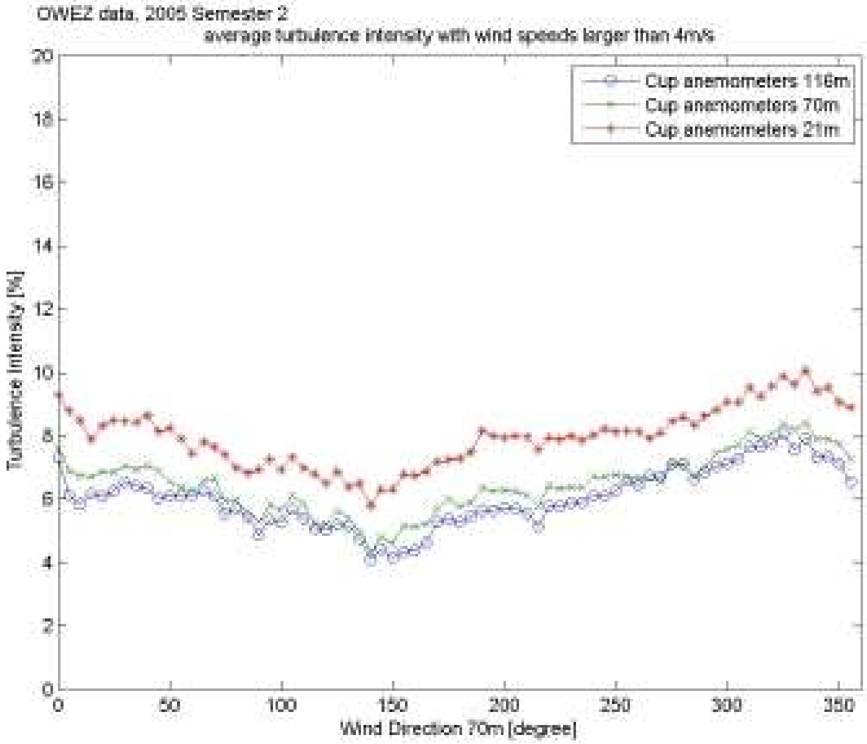
According IEC61400-12 for Power Performance Measurements



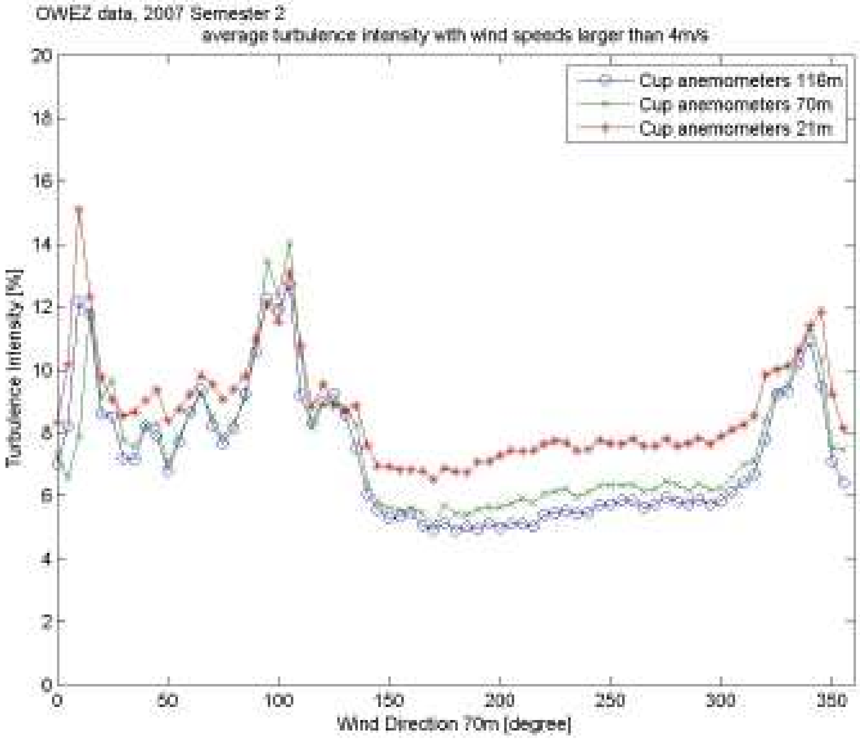
Influenced sector: 315° - 143°

Turbulence

Before Operation (2005)

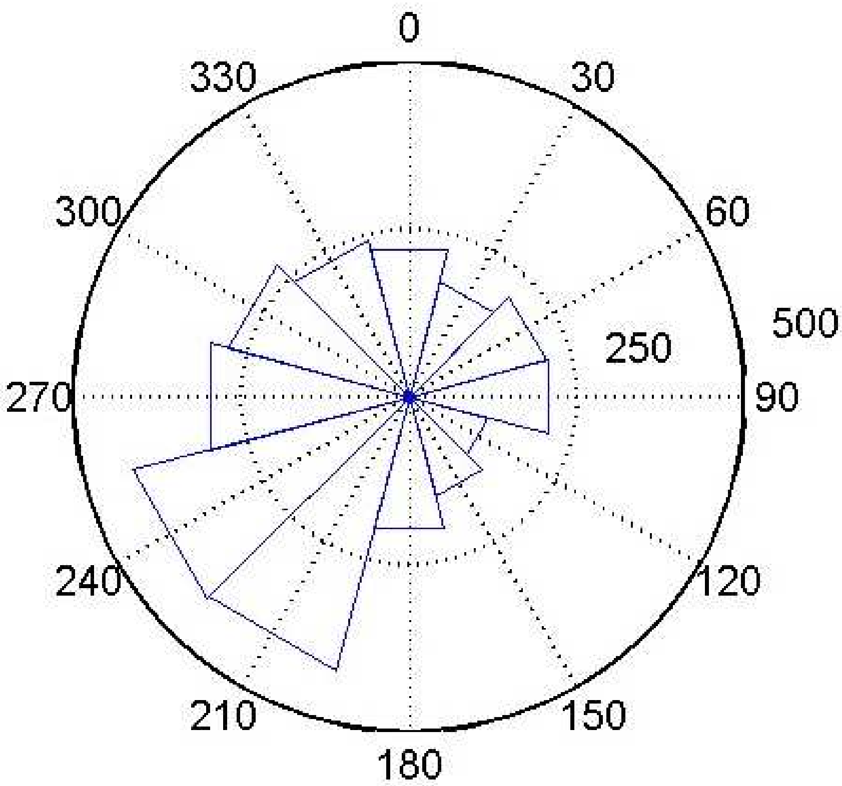


Operating turbines (2007)

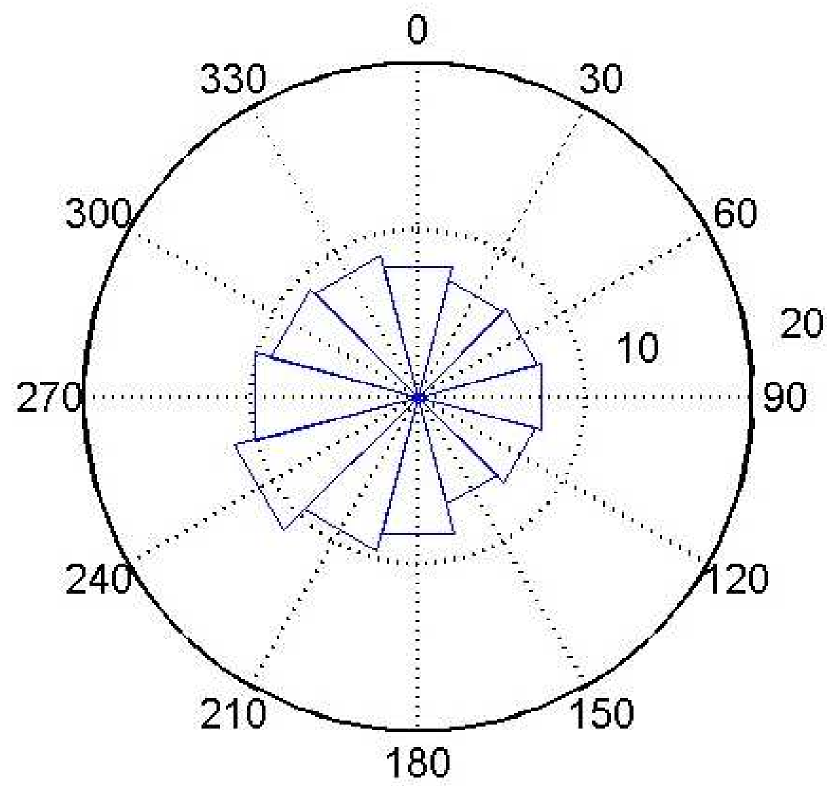


Measured Wind Conditions at 70m (06-2005 – 06-2008)

v_{mean} = 8.9[m/s], $A_{weibull}$ = 10.1[m/s], $k_{weibull}$ = 2.3[-]



mean wind speed at 70m [m/s]



Measurements in Vestas V90

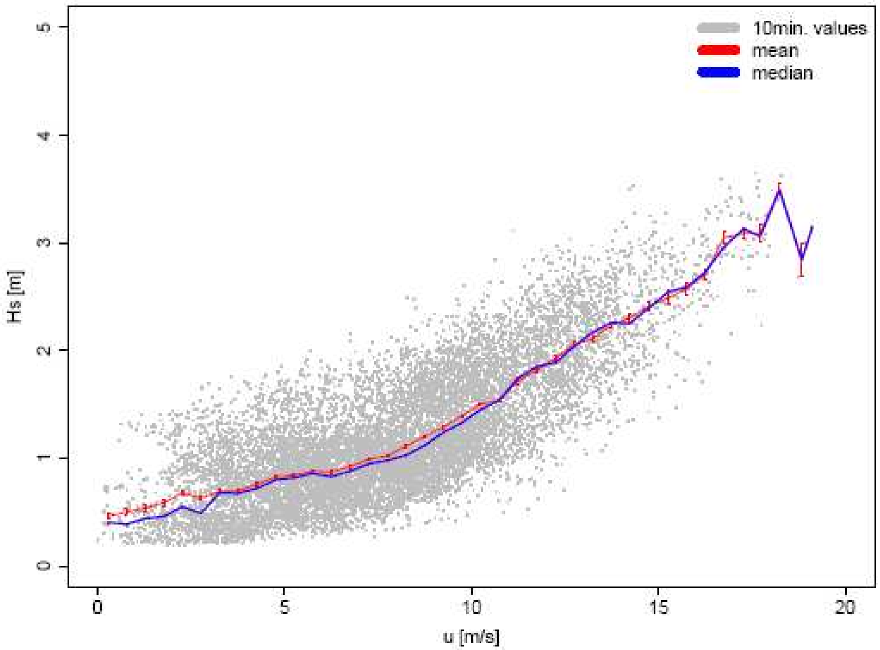
- Measurements in T7 and T8:
  - Rotor azimuth, Rotor rotational speed, turbine power,
  - Nacelle: accelerations, wind speed and direction, yaw angle
  - Blades: Edge-wise & Flap-wise bending moments, pitch angles
  - Tower: Bending moments in tower top and tower base, torsion tower top
  - Turbine operational status

Other Measurements

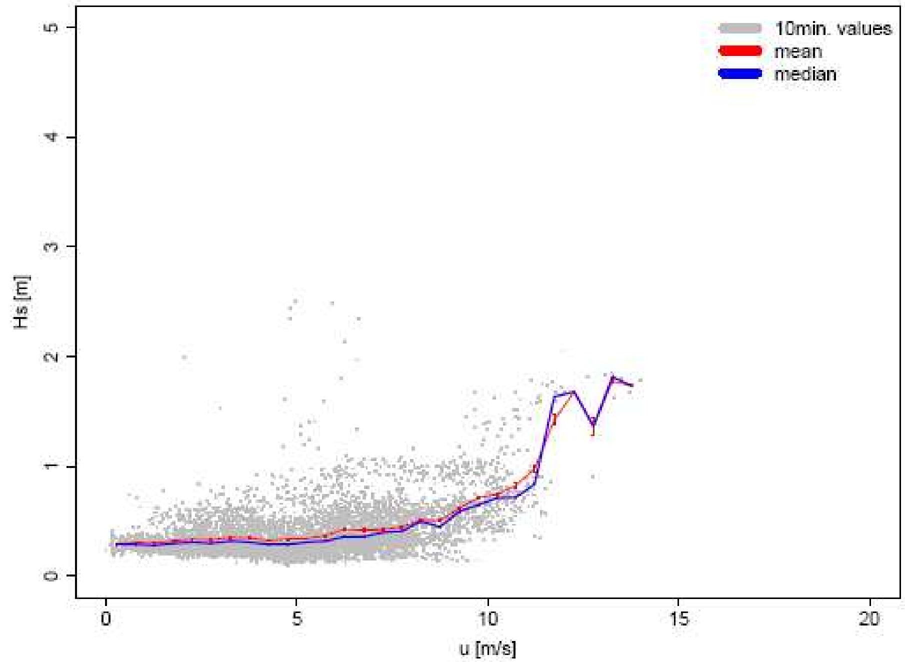
- Reliability of the turbines
- Predictability of the produced power
- Maintenance aspects
- Influence of the wind farm to others – shipping etc.
- Influence of building on fish and birds
- Biological Fouling

Stability analyses - Waves

Unstable atmosphere



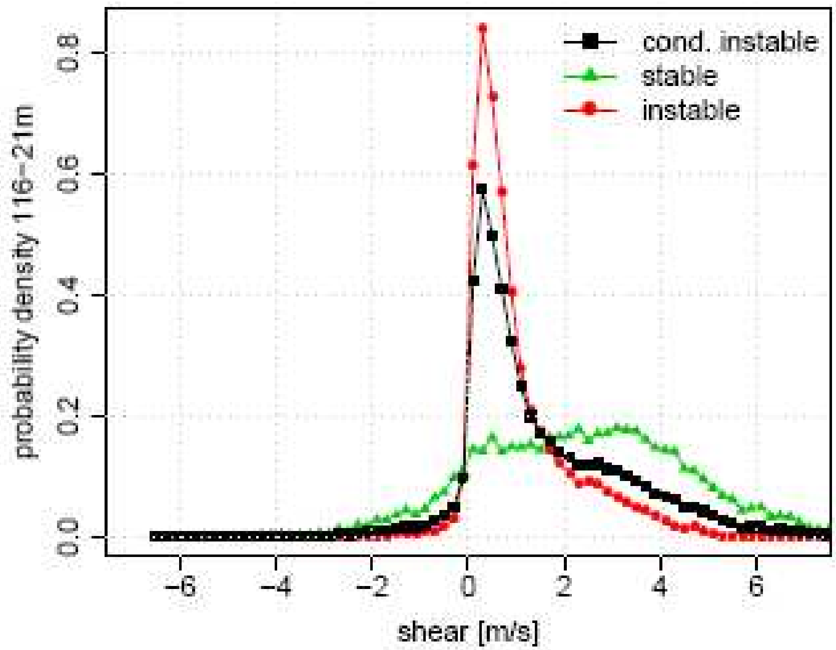
Stable atmosphere



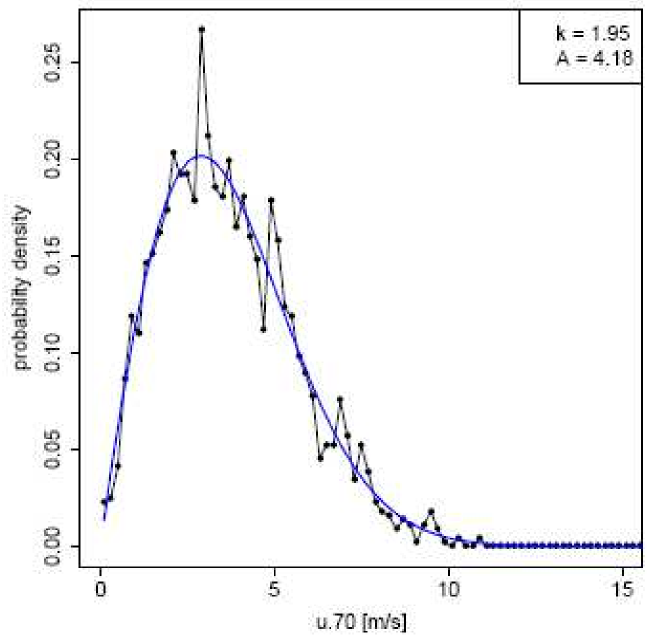
- Stable stratification -> decoupling of different air layers -> the friction on water surface is reduced

Shear

Difference between wind speed at 116m and 21m height

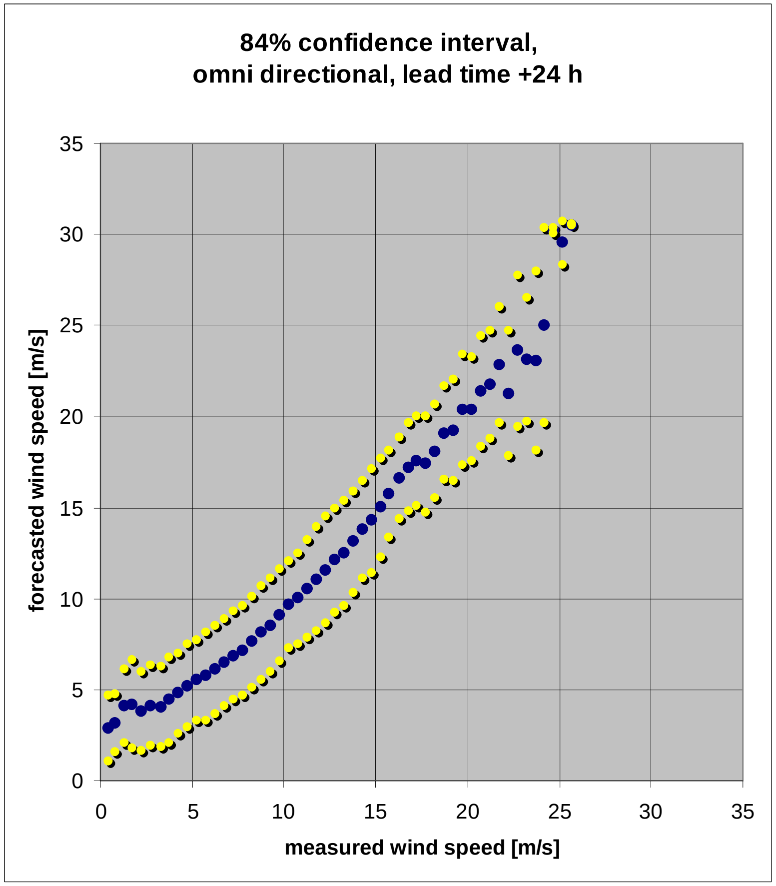


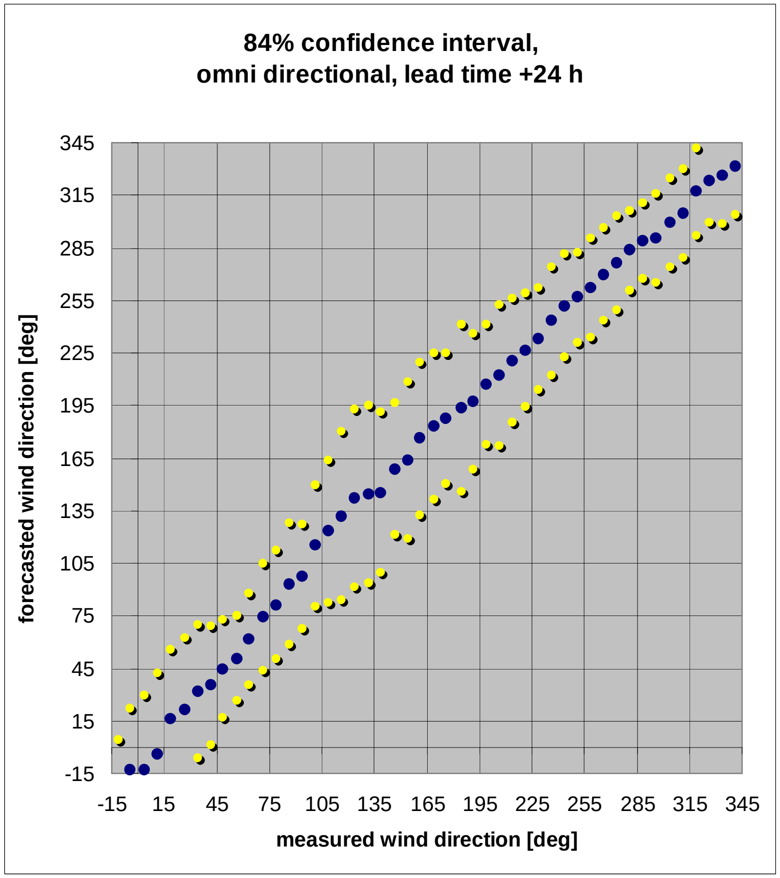
Distribution of negative shear



Results from Wind Power Predictions (+24h)

Prediction for 15-minute periods +24h ahead





Discussion

- An extensive measurement campaign is being carried out at OWEZ in the context of MEP-NSW
- Data and Reports are available at:

www.noordzeewind.nl

- Questions and requests:

mep-manager@noordzeewind.nl

TU Delft

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Measurements at ECN Scale Wind Farm

Peter Eecen

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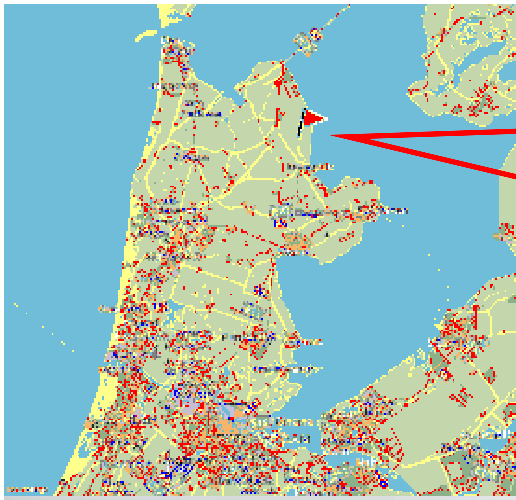
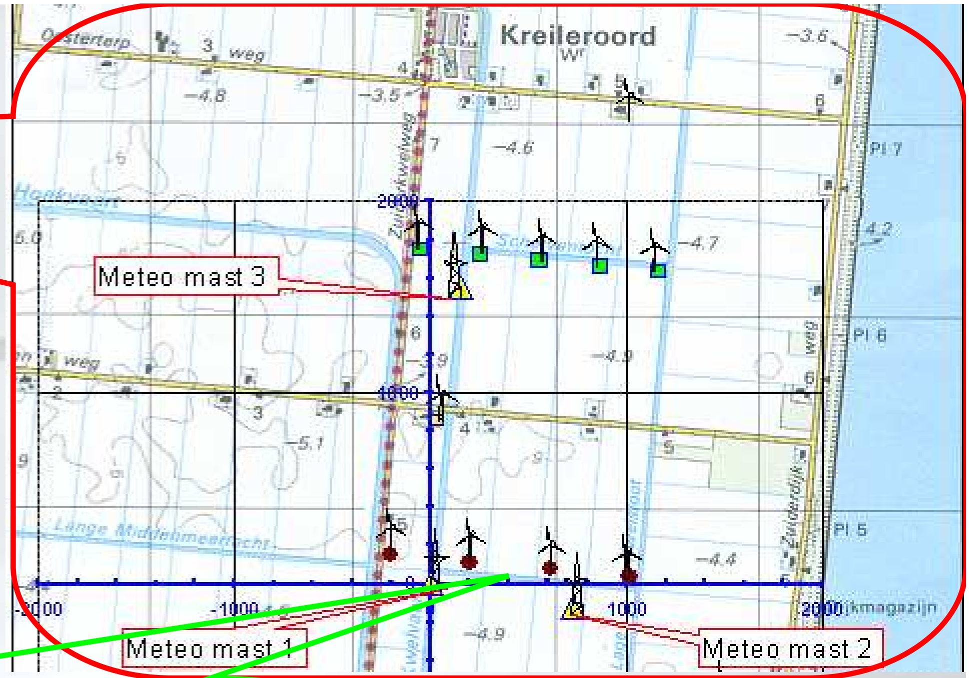
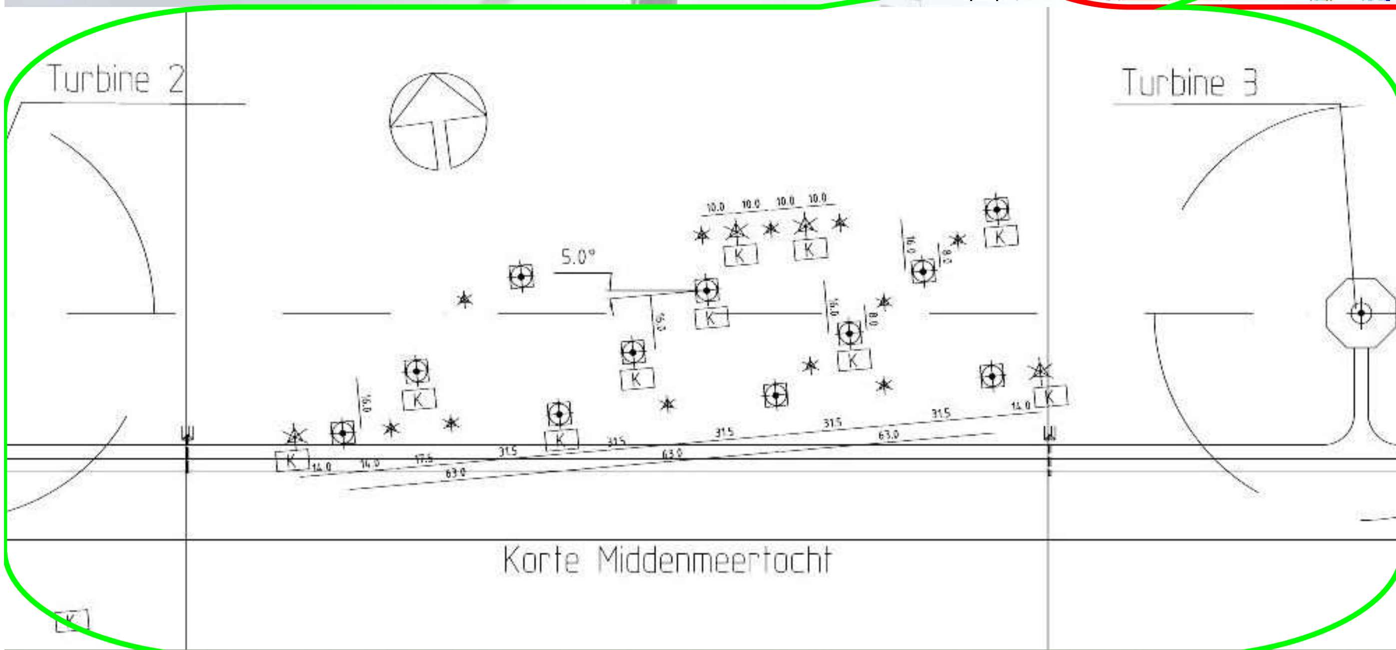
- Overview ECN Wind Turbine Test Site Wieringermeer
- Overview Scale Wind Farm
  - Purpose
  - Turbines
  - Measurement Infrastructure
- Experiments in Scale Wind Farm



ECN Wind Turbine Test site Wieringermeer





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ECN Scale Wind Farm

Purpose ECN Scale Wind Farm

- Future wind farms will grow in size
- Large uncertainties in modeling the wind field
- Lack of measurements of wind field hinders research on wind farm aerodynamics and wind farm control
- The Scale Wind Farm provides high quality measurement data within and around wind farms
- With a better understanding of the wind field
  - Optimised wind farm lay-out
  - Optimised wind farm control strategies

High quality measurements

- Wind tunnel data can give detailed information, however suffers from scaling effects

- Full-scale field data is not hindered by scaling effects, however is limited due to the high costs

Solution: Scale Wind Farm

Measurements with many measurement masts and limited scaling problems

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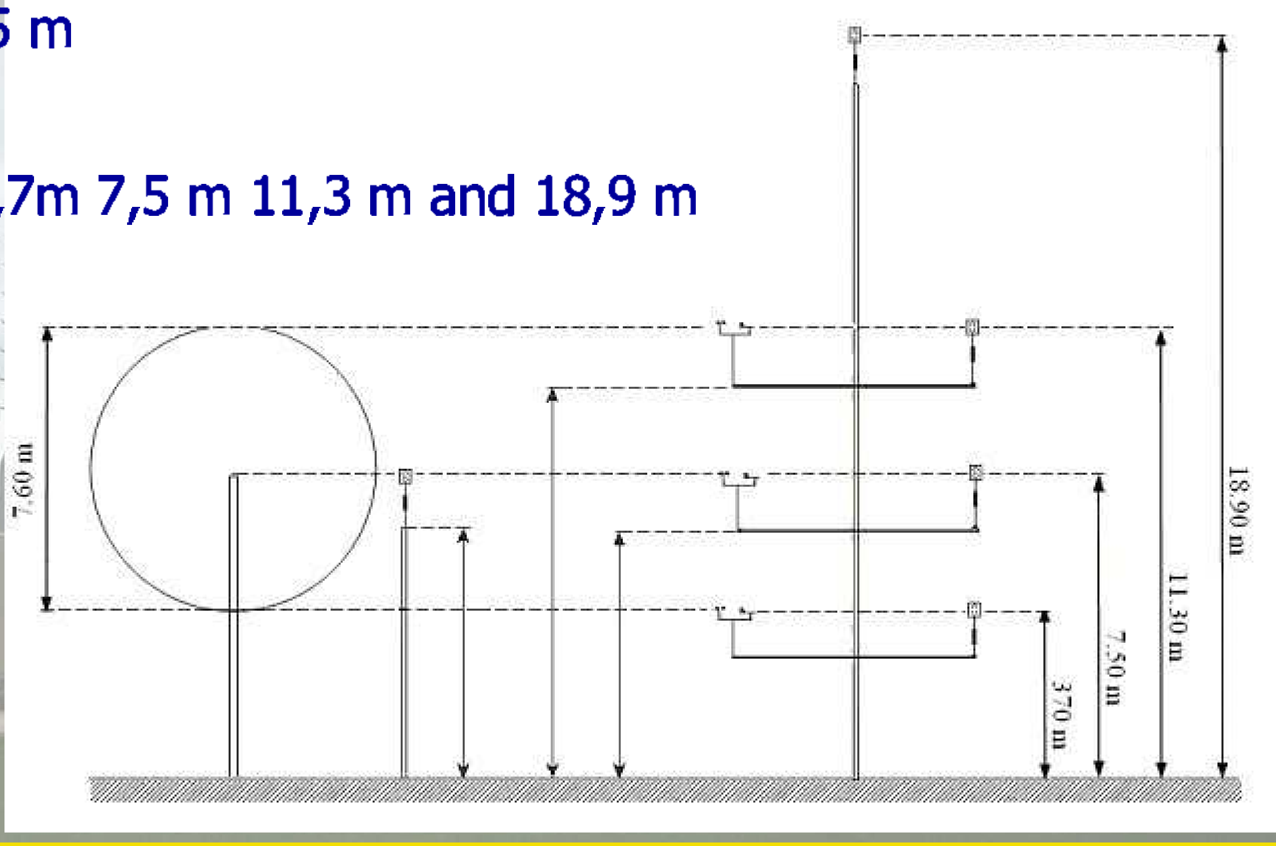
Aircon Wind Turbine

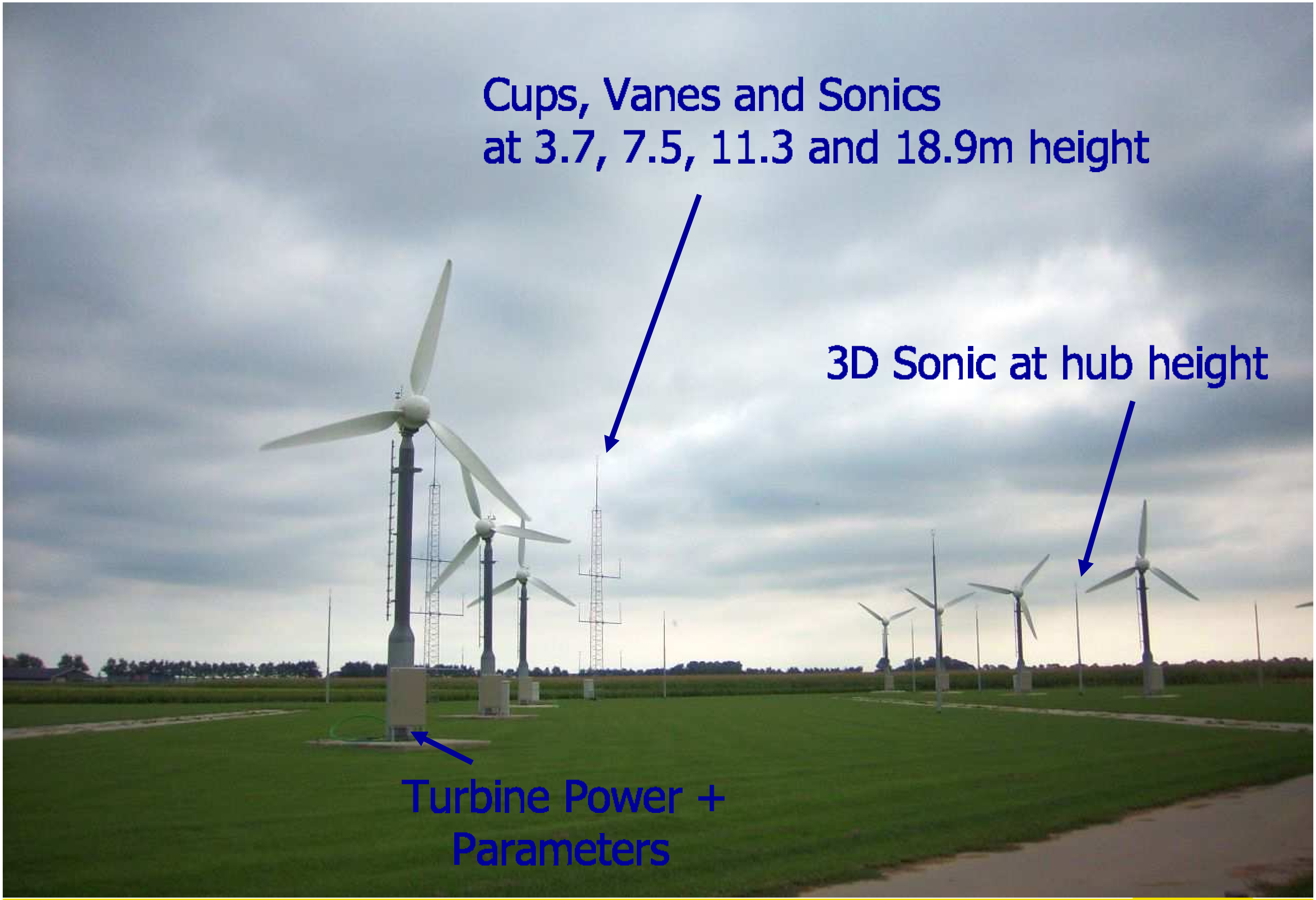
- 10 AIRCON P10 turbines
- Rotor diameter 7,6 m
- Hub height 7,5 m
- Rated power 9,8 kW
- Erected in March 2008

- 11th turbine 'at request'

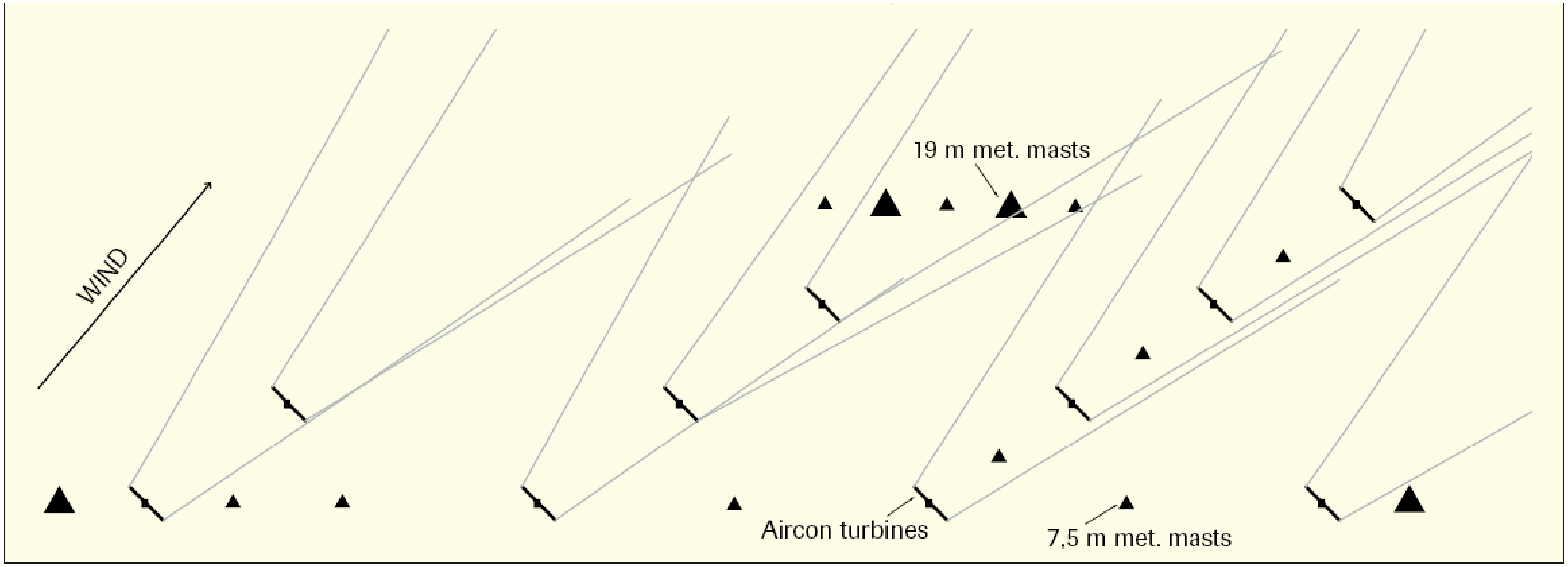
Measurements of the wind field

- **Meteo masts**
- 10 masts at 7,5 m
  - Meas. height 7,5 m
- 4 masts at 19m
  - Meas. heights 3,7m 7,5 m 11,3 m and 18,9 m




Cups, Vanes and Sonics
at 3.7, 7.5, 11.3 and 18.9m height
3D Sonic at hub height
Turbine Power +
Parameters

Experiments



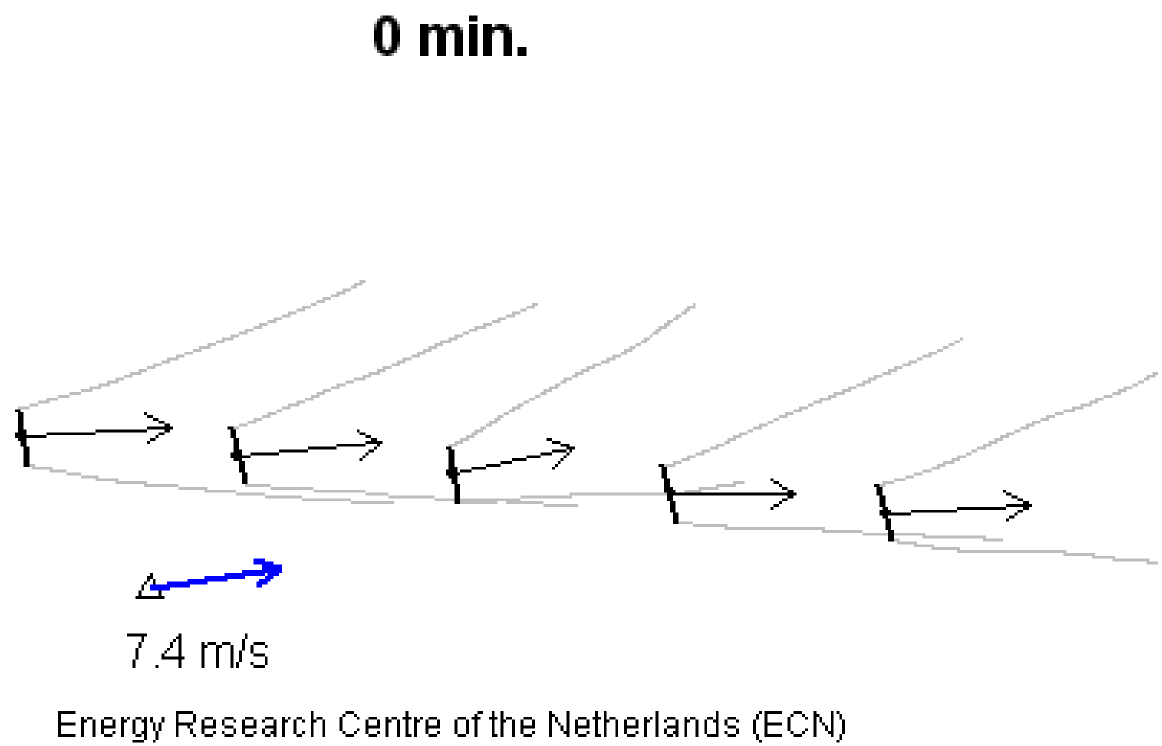
Side by side row comparison

experiments in wind farm control strategies

Side by side turbine comparison

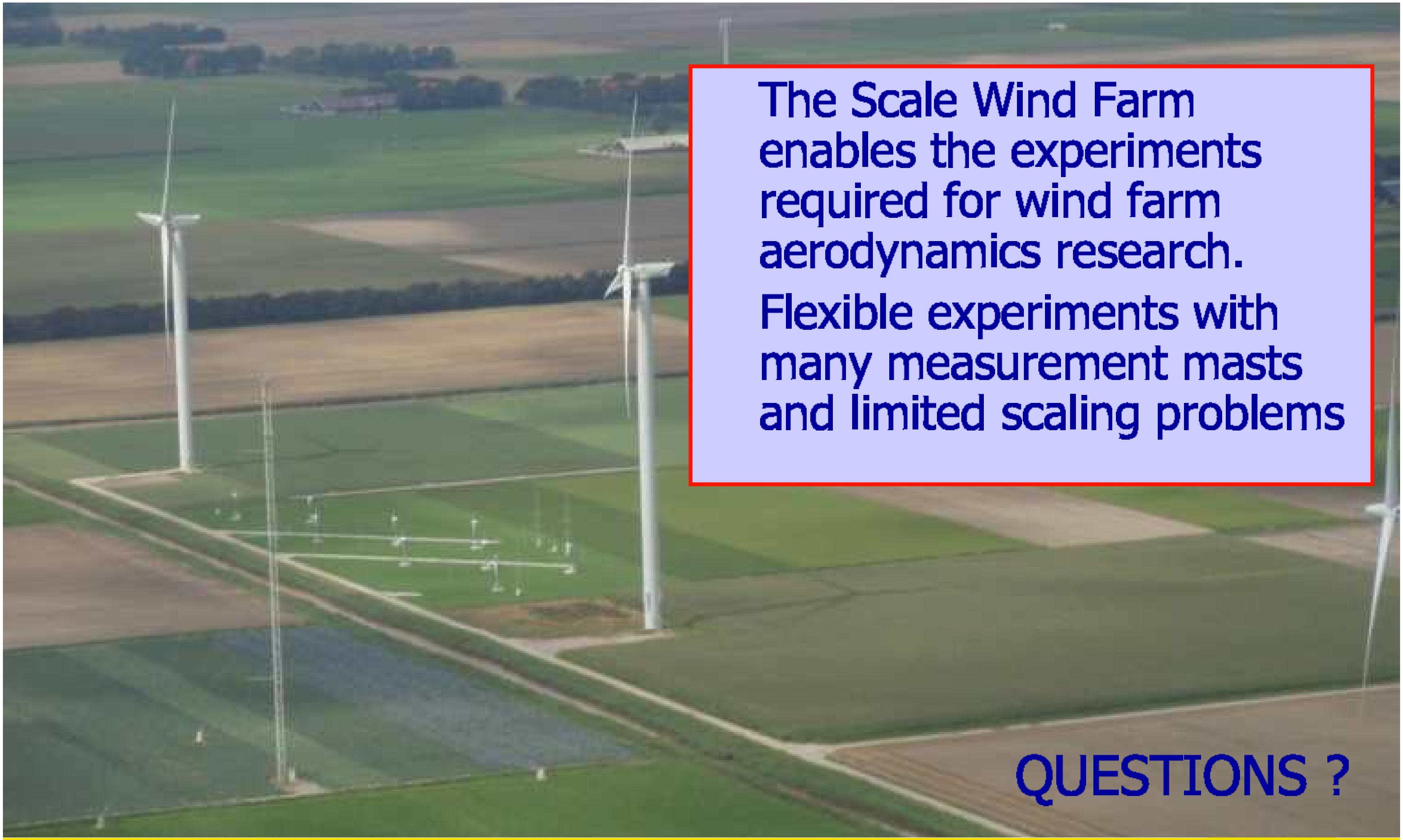
experiments to demonstrate turbine improvements

Full control of turbines is required!



In order to compare experiments with theory, it is essential to reduce the degrees of freedom

ECN Scale Wind Farm

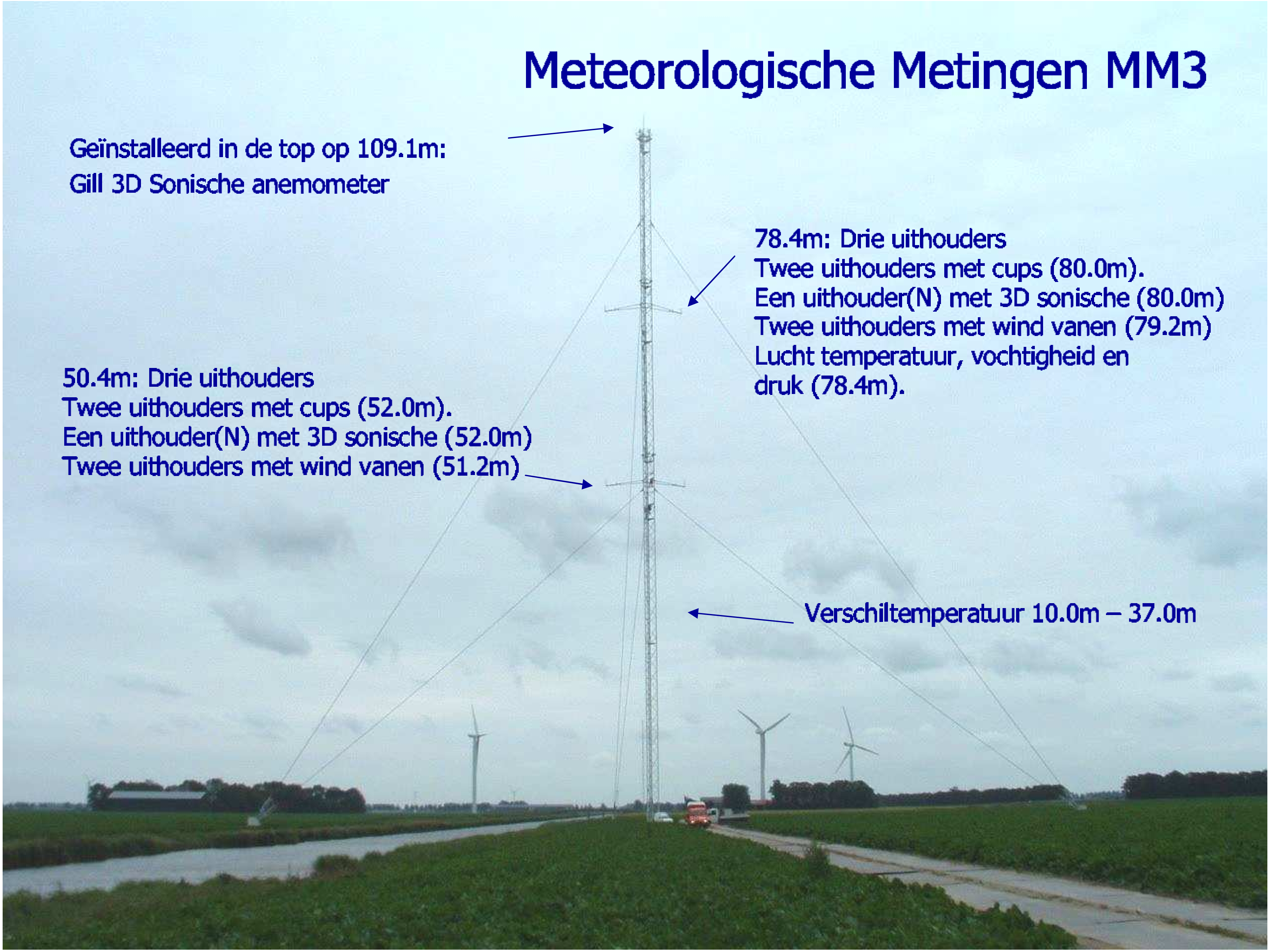


The Scale Wind Farm enables the experiments required for wind farm aerodynamics research.

Flexible experiments with many measurement masts and limited scaling problems

QUESTIONS ?

Meteorologische Metingen MM3

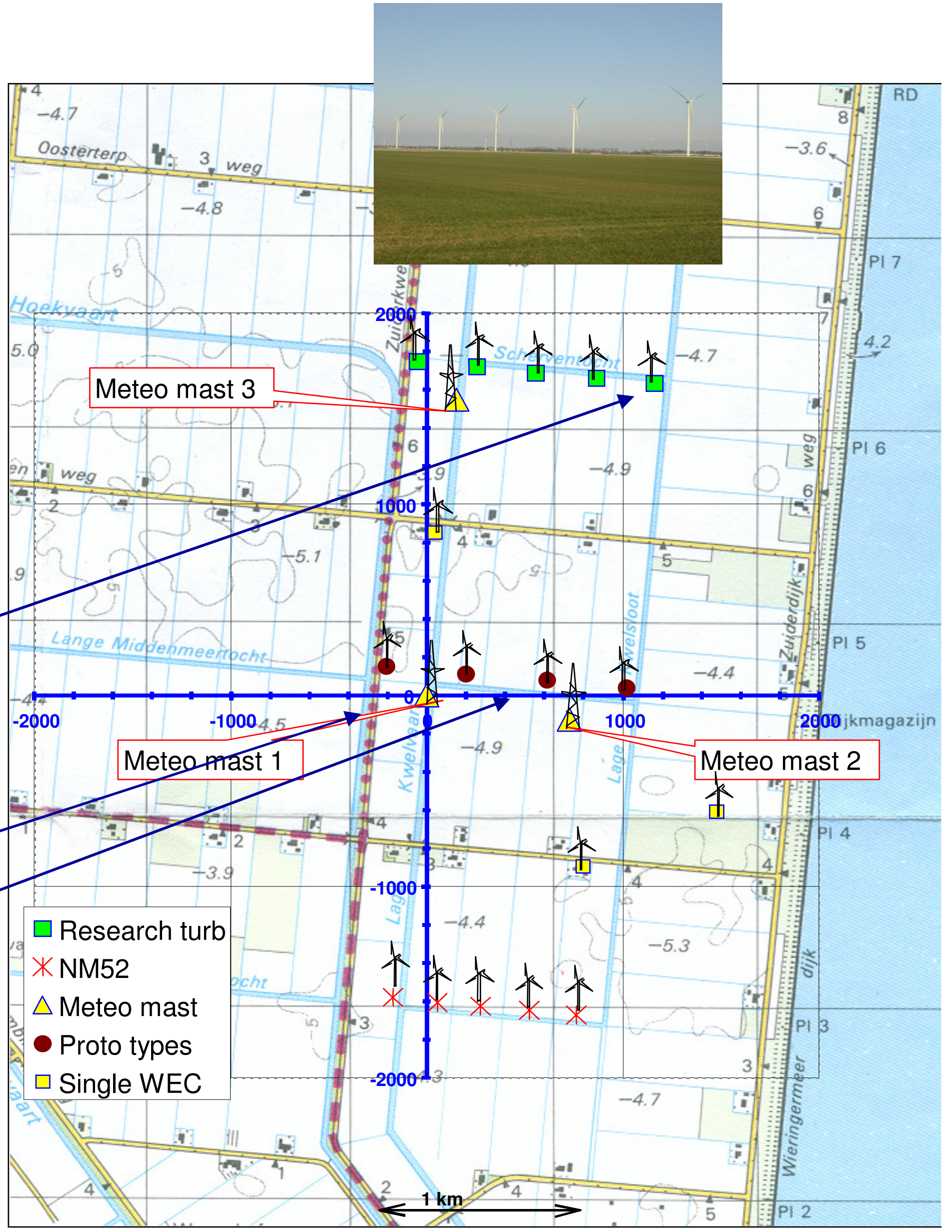


ECN-MW Testfield measurements

Gerard Schepers

ECN Wind Turbine Test Farm Wieringermeer (EWTW)

- Two rows:
    - Five **research** turbines with one 108m high meteorological mast (mm3)
    - Four **prototype** turbines with two 108m high meteorological masts (mm1 and mm2)
    - Scaled farm
- Measurement Infrastructure
- Measurement Pavilion



Research Turbines at EWTW

- EWTW Research Turbines:
- Five turbines in a single line
- Mutual distance: 3.8 D

Hub height: 80m

Rotor diameter: 80m

Rated. Power: 2.5MW

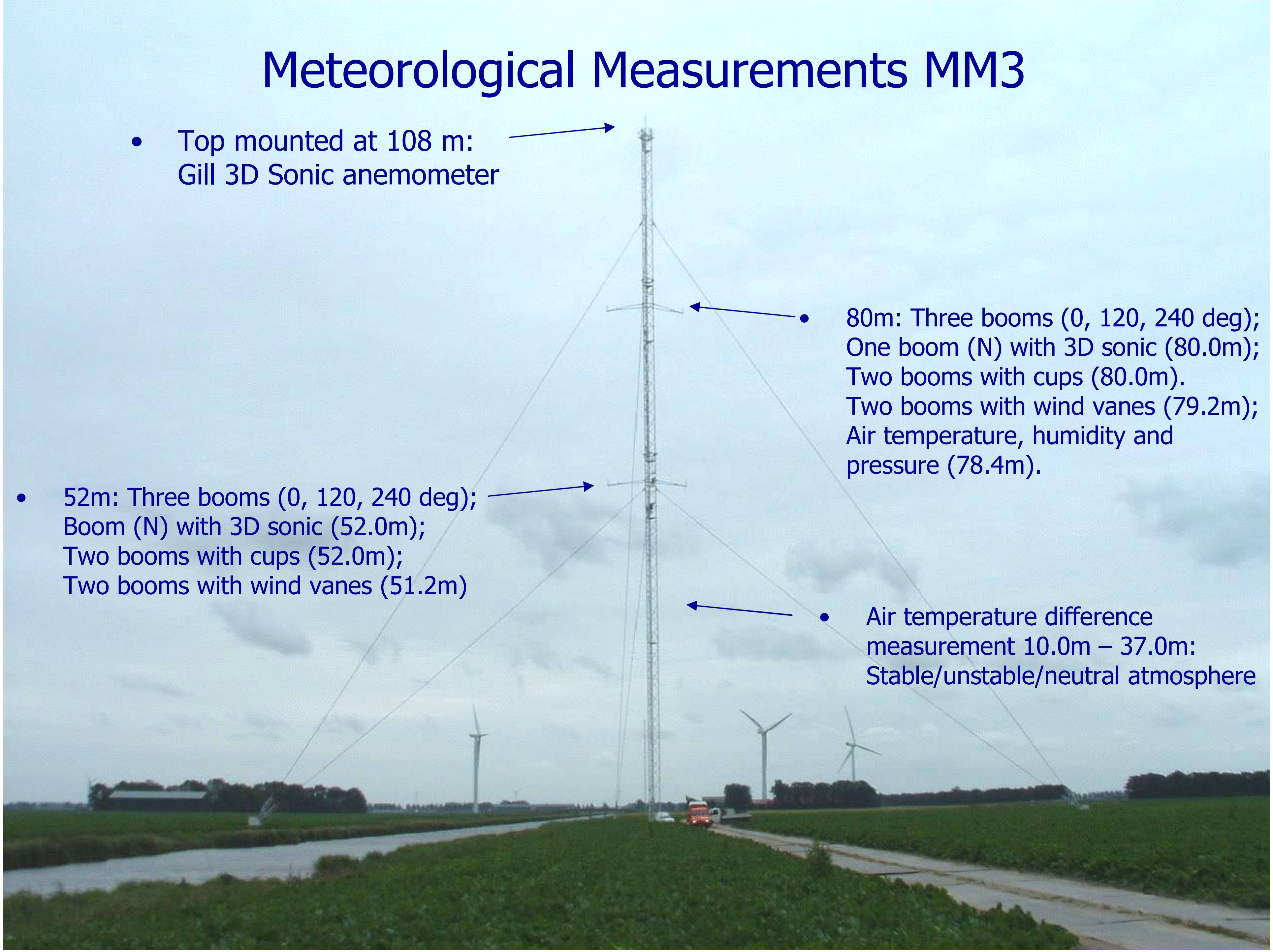
- A 108m high mast is installed with equipment at 52m, 80m and 108m heights.

ECN Wind Turbine Test site Wieringermeer, EWTW

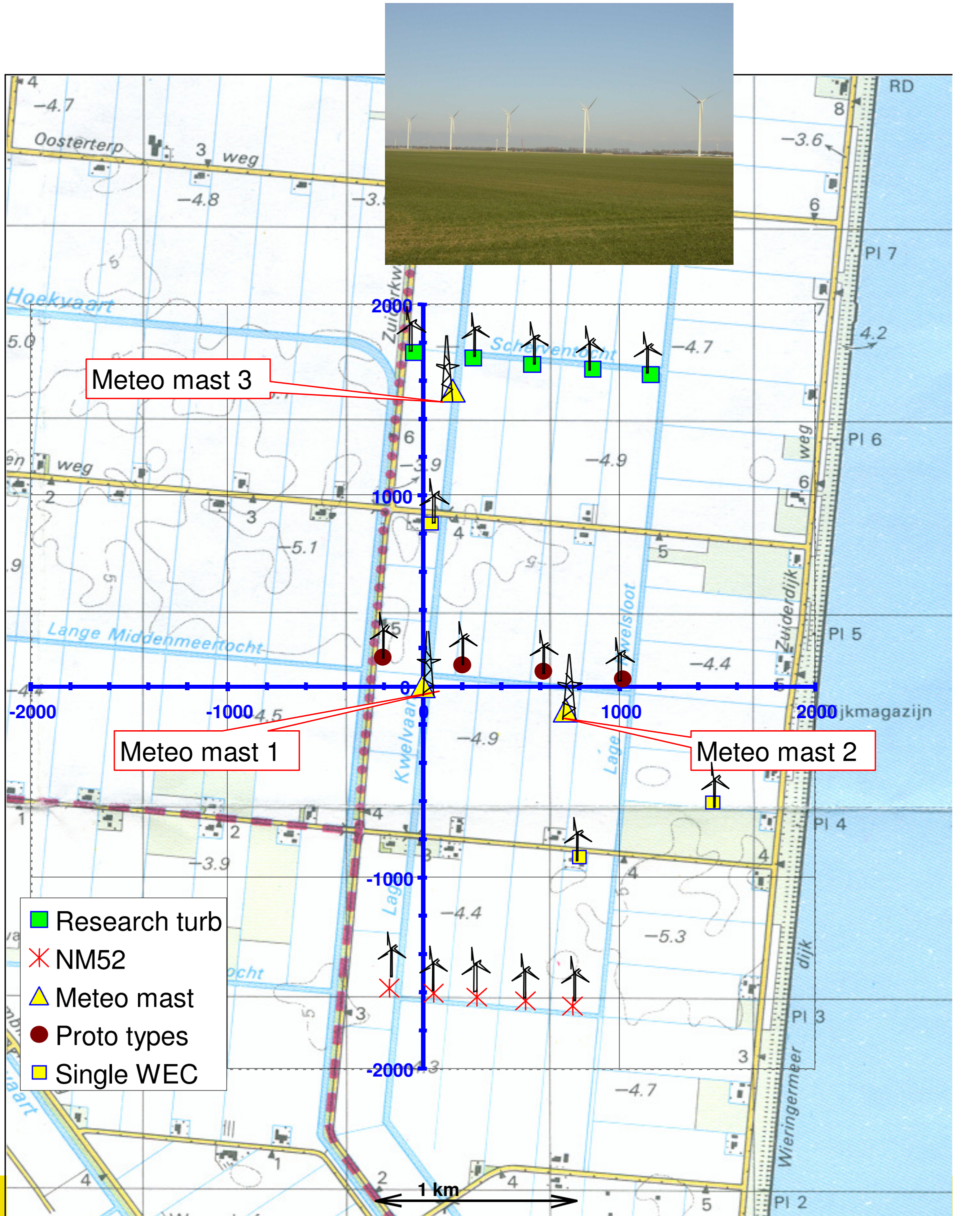
– State of the art turbines
– Research farm
– Turbine data available

Meteorological Measurements MM3

- Top mounted at 108 m:
  Gill 3D Sonic anemometer
- 80m: Three booms (0, 120, 240 deg);
  One boom (N) with 3D sonic (80.0m);
  Two booms with cups (80.0m).
  Two booms with wind vanes (79.2m);
  Air temperature, humidity and
  pressure (78.4m).
- 52m: Three booms (0, 120, 240 deg);
  Boom (N) with 3D sonic (52.0m);
  Two booms with cups (52.0m);
  Two booms with wind vanes (51.2m)
- Air temperature difference
  measurement 10.0m – 37.0m:
  Stable/unstable/neutral atmosphere



- Research turbines numbered from 5 (most Westerly) to 9 (most Easterly)
- Wind farm line: 95-275 degrees
- MM3 at 3.5 D and 315 degrees from turbine 5
- MM3 at 2.5D and 31 degrees from turbine 6
- Sonic anemometers on boom in Northern direction, well suited for wake measurements



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Measurements at research turbines

- Five turbines are equipped to measure a variety of signals
- From PLC (25Hz). All turbines:
  - Electric active power PLC
  - Generator speed PLC
  - Wind speed nacelle PLC
  - Wind direction nacelle PLC
  - Nacelle position PLC
  - Pitch angle axis 1 PLC
  - Pitch angle axis 2 PLC
  - Pitch angle axis 3 PLC
  - Operation mode (0-24) PLC
- On a daily basis, files are received with 10-minute averaged statistics (avg, min, max, std) of 132 signals measured with SCADA system

Measurements at research turbines

- Load measurements at turbine #6 with 32 Hz:
  - blade 1, Root, Flap moment
  - blade 1, Root, Edge moment
  - blade 2, Root, Flap moment
  - blade 2, Root, Edge moment
  - blade 3, Root, Flap moment
  - blade 3, Root, Edge moment
  - Tower bottom bending N-S
  - Tower bottom bending E-W
  - Tower bottom bending, +45 deg.
  - Tower bottom bending, -45 deg.
  - Rotor Azimuth

- Autumn 2007-Spring 2008: Load measurements are also performed on turbine #8 and torque on high speed shaft and main shaft strain measurements on both turbines

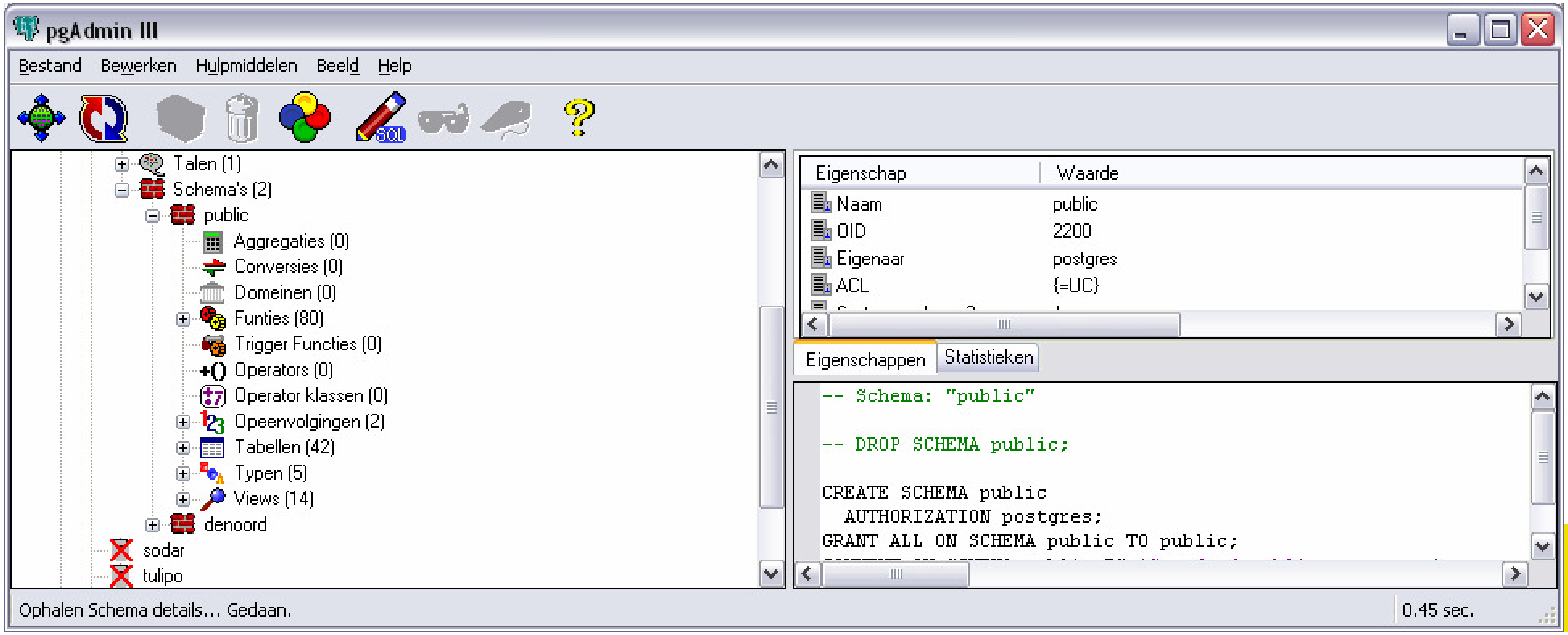
Database

- ECN has developed a database in SQL 4 years of data (Some data were added a later stage)
  - Meteorological data of masts
  - Turbine data from PLC's
  - Turbine data from SCADA
  - Load measurements
  - Pseudo signals (functions)

Standardised database structure

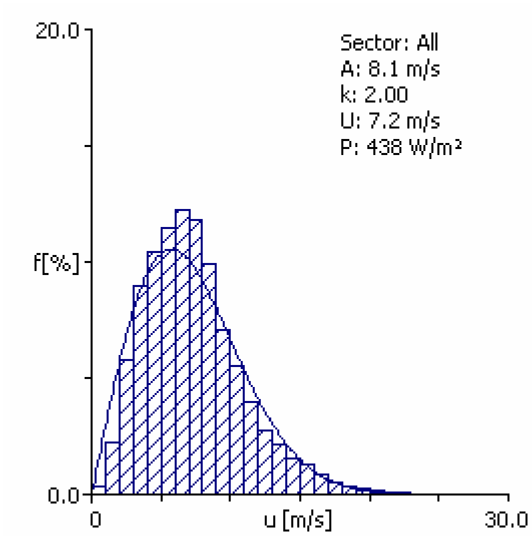
The data are synchronised and easily accessible/selectable on 10-minute statistics data.

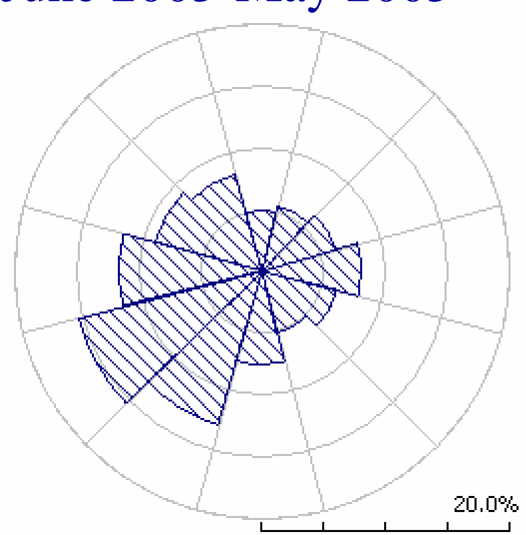
The raw data are also easily accessible.

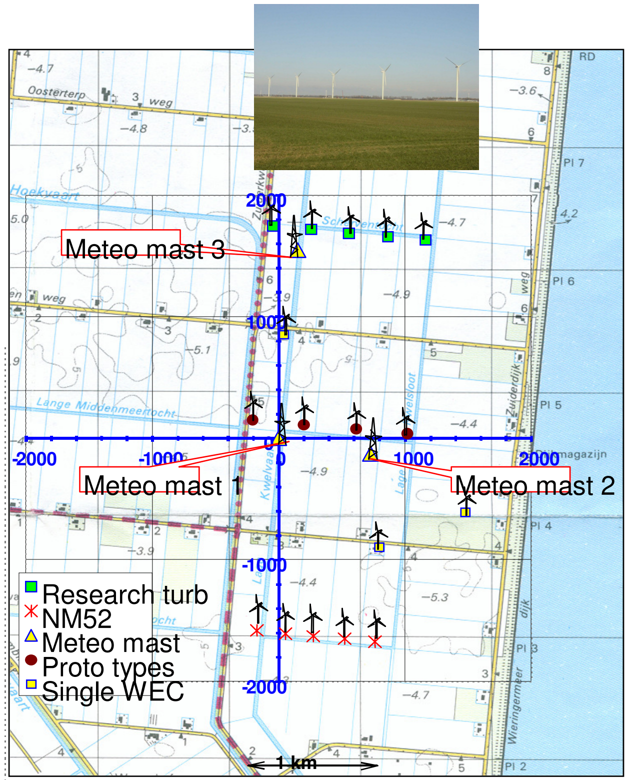


Wind Climate

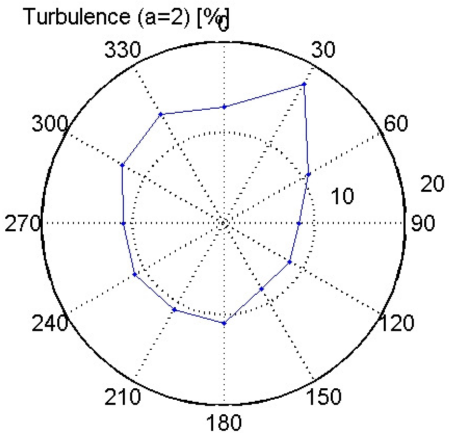
MM1: H=71.6 m, June 2003-May 2005

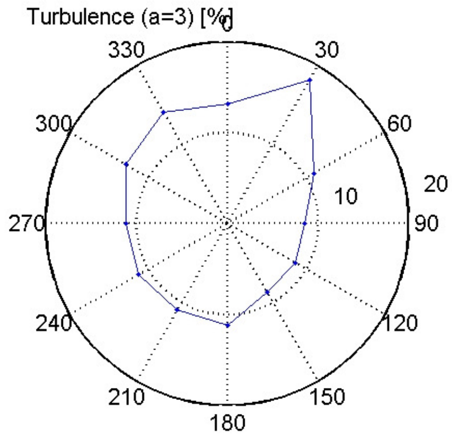






MM 3:H=80m, Turb. Int. according to IEC 61400-1





Turbine 1: 315 deg.;

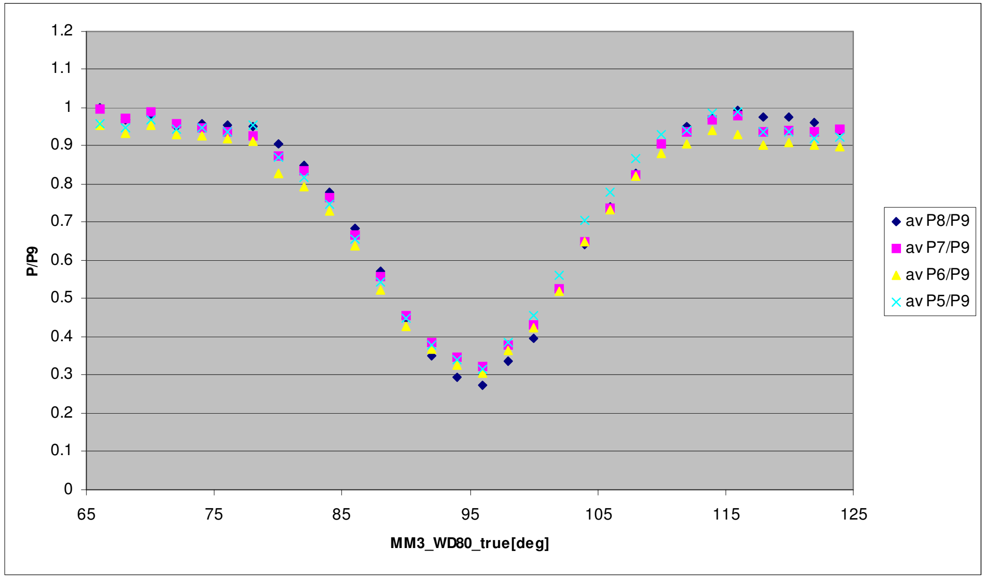
Turbine 2: 31 deg.;

Turbine 3-5: 71-85 deg

Research projects at EWTW

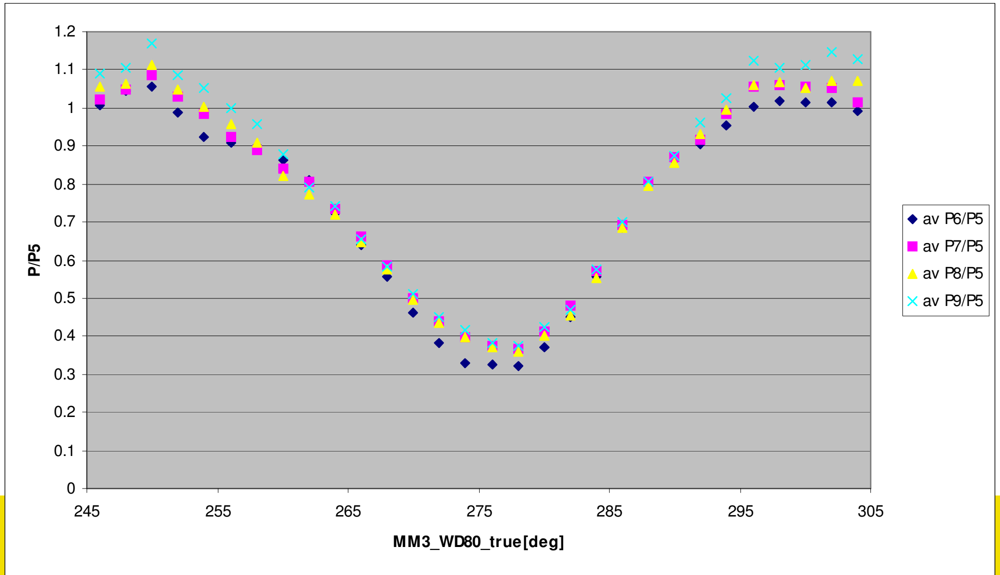
- WT-Bird: A method for registration of bird collisions using video cameras and microphones triggered by acoustic vibration measurement
- FOBM: Measurement methods to monitor wind turbine blades by means of fiber optic measuring systems
- O&M Cost Estimator: Methods to analyze SCADA data, loads data and O&M data for estimating future O&M costs
- Flight Leader: Methods to monitor and assess the equivalent loads on main components of any turbine in a wind farm. Such method can be used to determine the most heavily loaded turbines and components
- PROTEST: procedures for designing mechanical components (viz. gearbox, pitch system, and yaw system) and specifying the loads on these components.
- Sirocco: Silent Rotors by Acoustic Optimisation
- Extrapolation of extreme loads
- Crisp: An EU project to investigate, develop and test advanced intelligence by ICT technologies to reduce costs of integration and control of distributed generation and RES to the EU power grid. Includes a considerably wake investigation
- Aeolus: A project from the EU ICT program coordinated by University of Aalborg to develop models that allow real-time predictions of flows and incorporate data from a network of sensors, and control paradigms that acknowledges the uncertainty in the modelling and dynamically manages the flow resource in order to optimise specific control objectives. Includes a Wake work package!
- Project on (time dependant) meteorological characterisations
- Wake reducing concepts (Heat and Flux)
- Projects on wake characterisation(national project ‘LTVM database’ and supply of data to the partners in the EU project Upwind (WP8: flow))

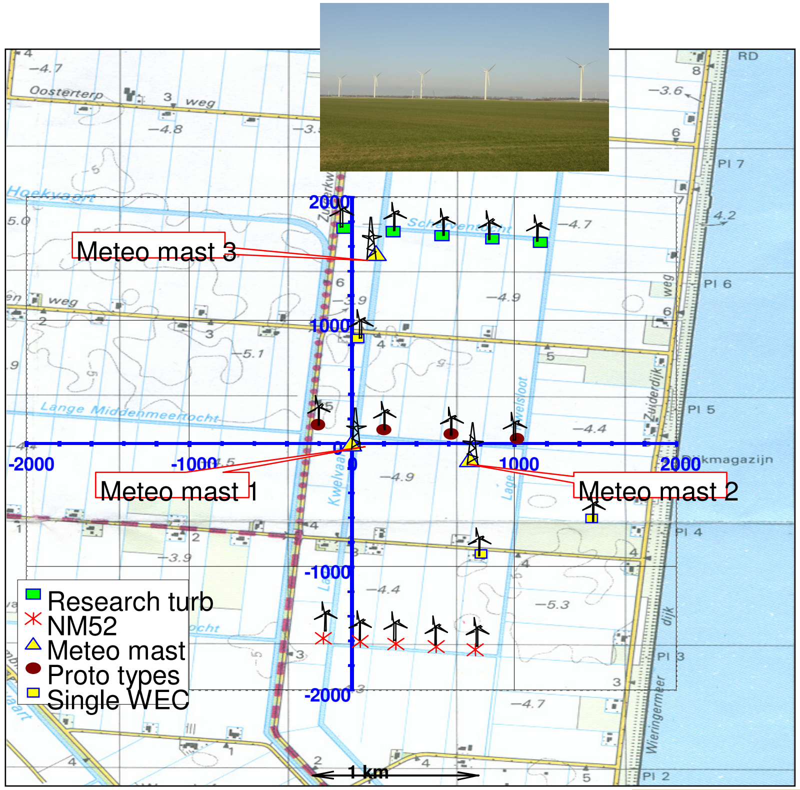
Relative power production ($V_w < V_{rated}$)



Single/double/triple/quadruple: Single wake gives largest power deficits, other deficits are similar

Slightly larger deficit when wind blows from the East, i.e. at low turbulence level





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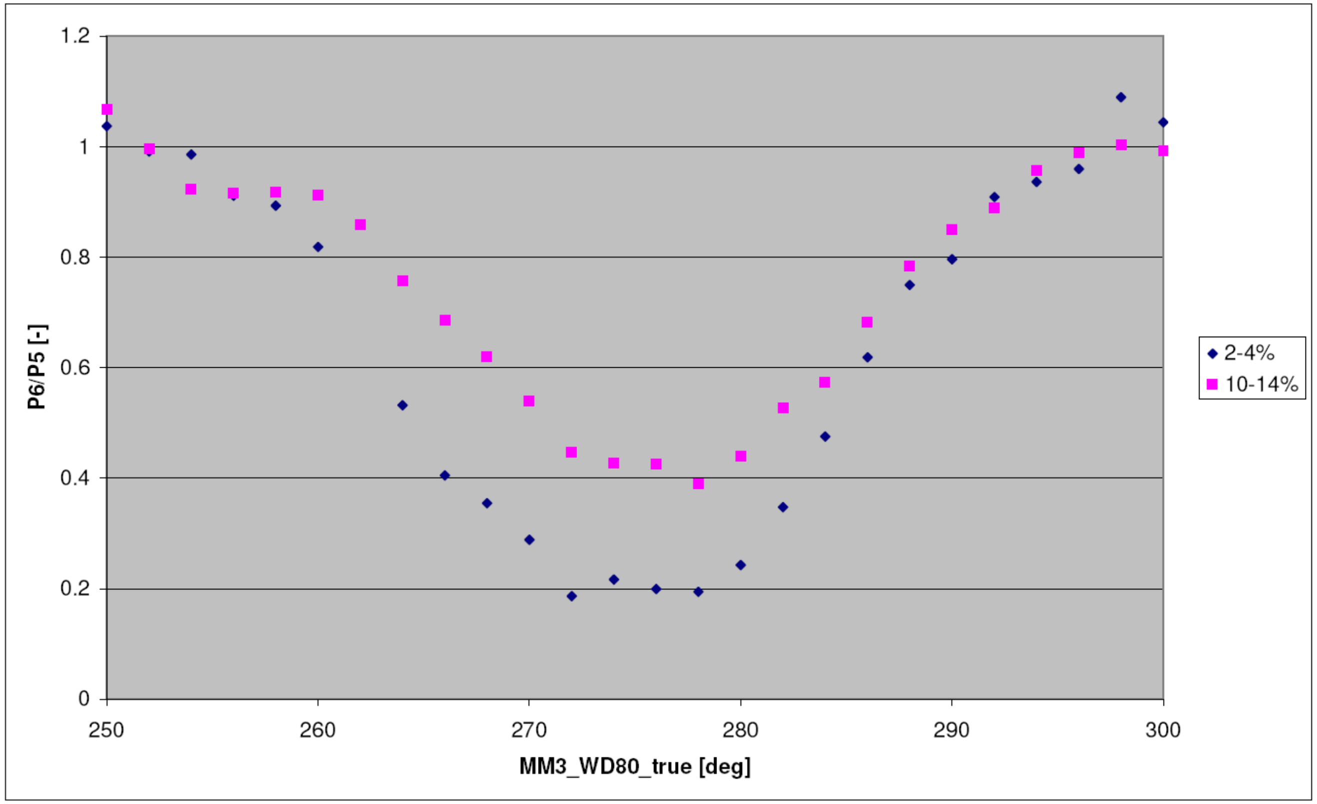
Effect of ambient turbulence intensity on relative production of second turbine

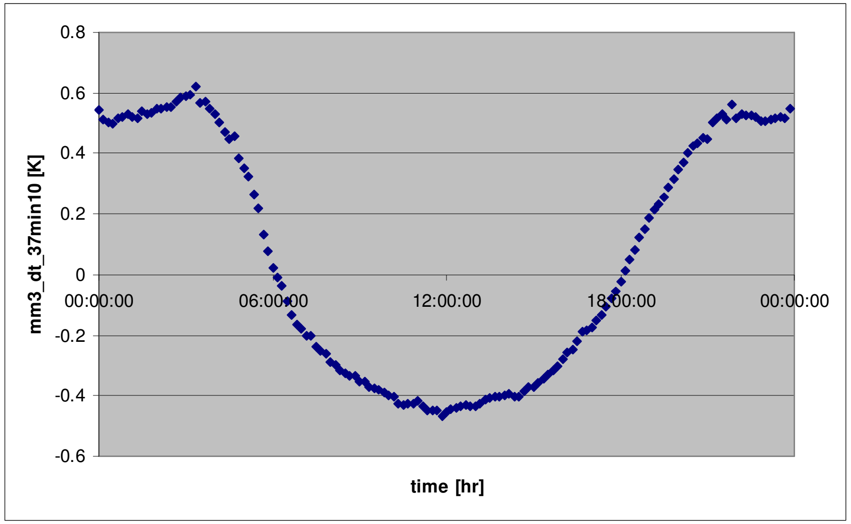
Low ambient turbulence intensity: P_6/P_5 much lower



Summer: Diurnal cycle of temperature difference, wind shear (V108-V52/V80) and turbulence intensity (h=80m)

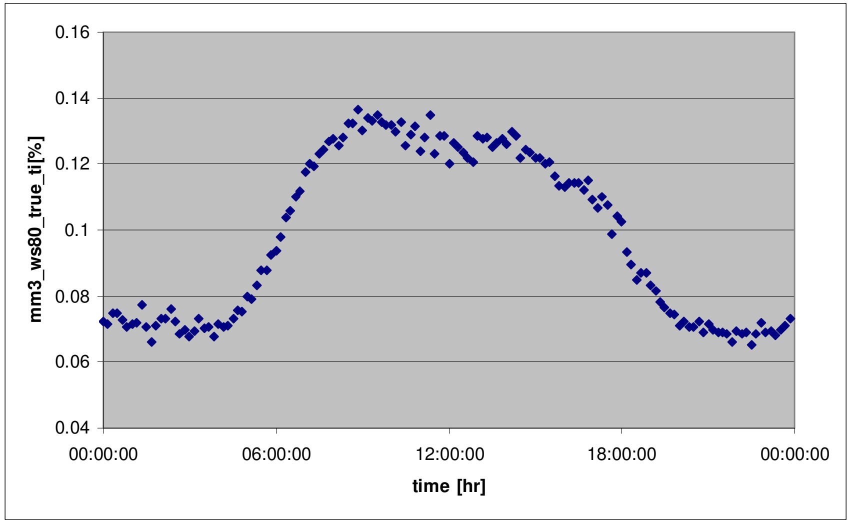
- 2005-2008
- Summer period [1])
- V(h=80m) <12 m/s
- Binning interval: 10 min.

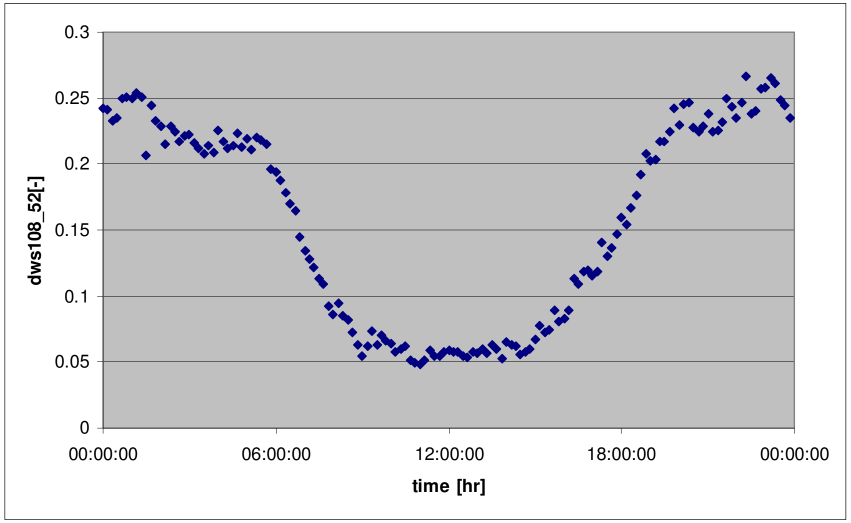
Temperature difference $T_{37m} - T_{10m}$



Wind shear

Turbulence intensity

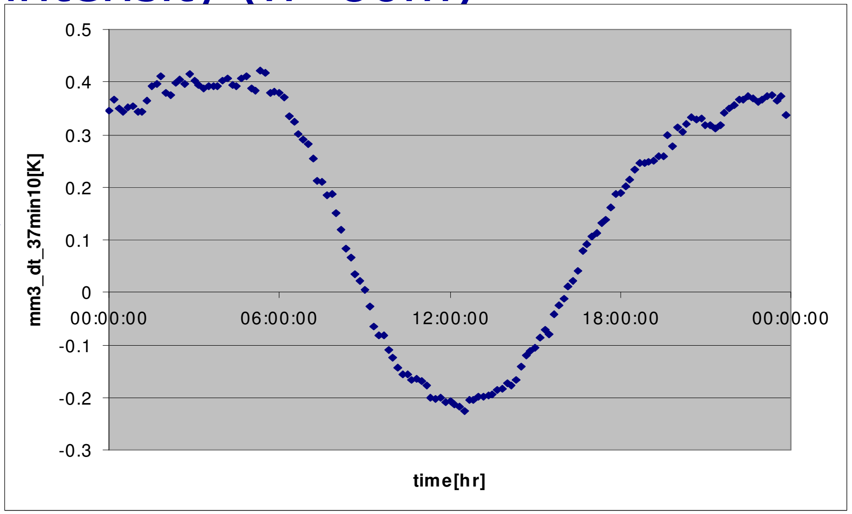




Winter: Diurnal cycle of temperature difference, wind shear (V108-V52/V80) and turbulence intensity (h=80m)

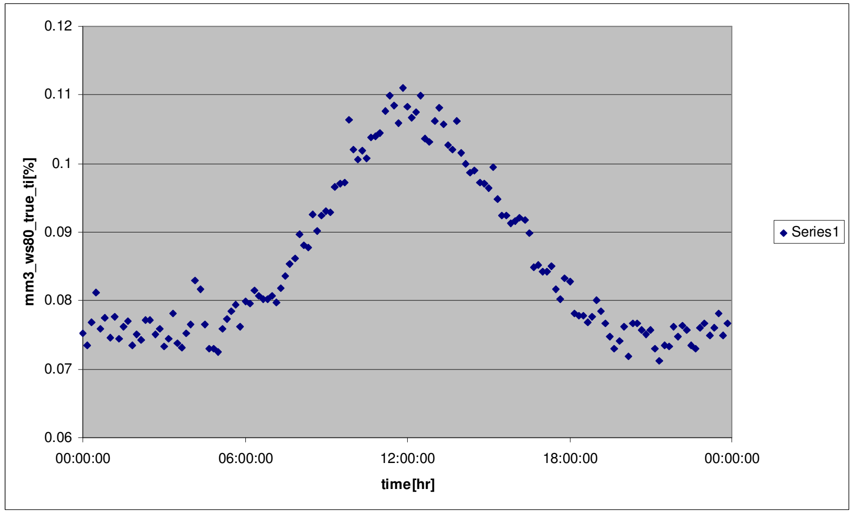
- 2005-2008
- Winter period [1])
- V(h=80m) <12 m/s
- Binning interval: 10 min.

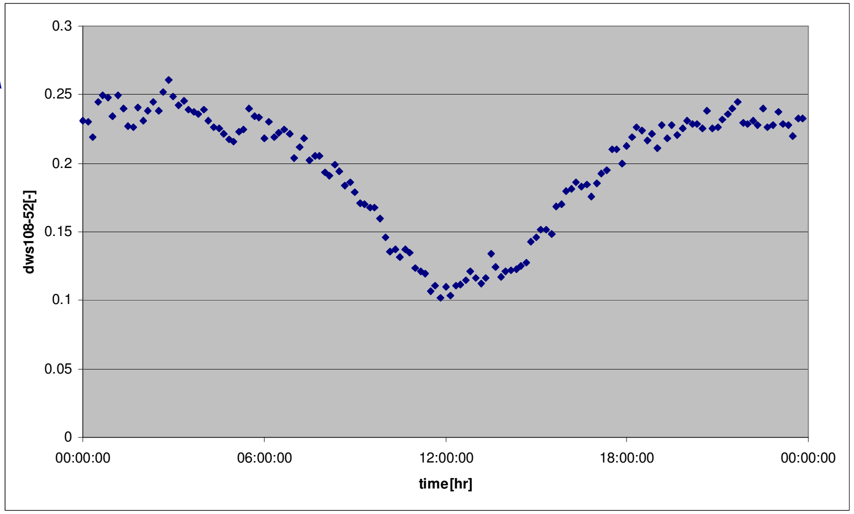
Temperature difference $T_{37m} - T_{10m}$



Wind shear

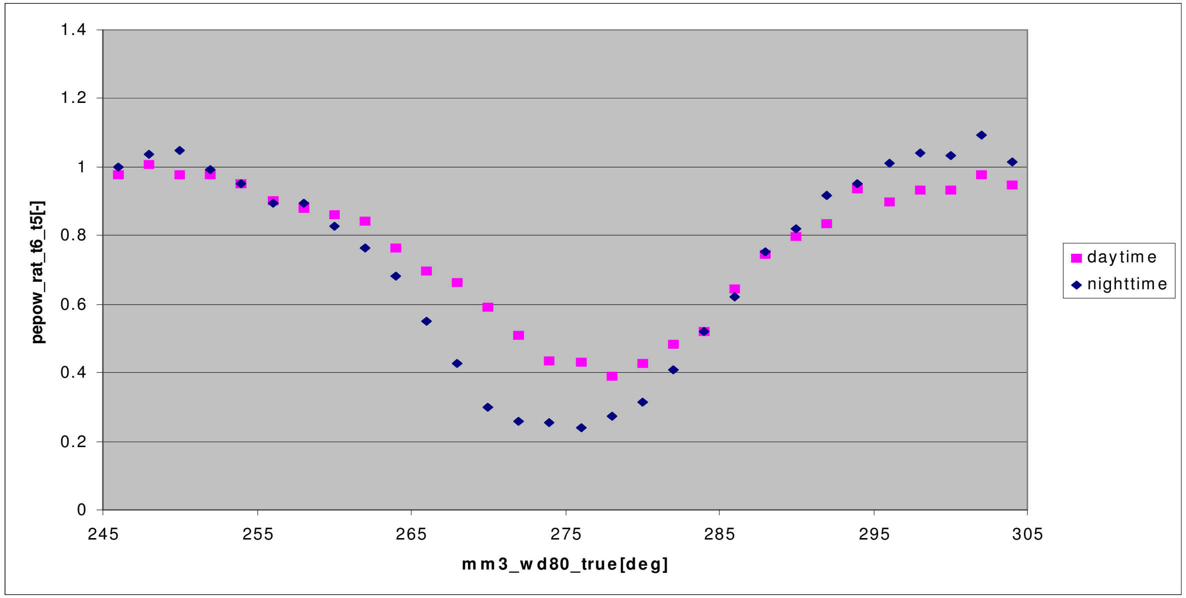
Turbulence intensity

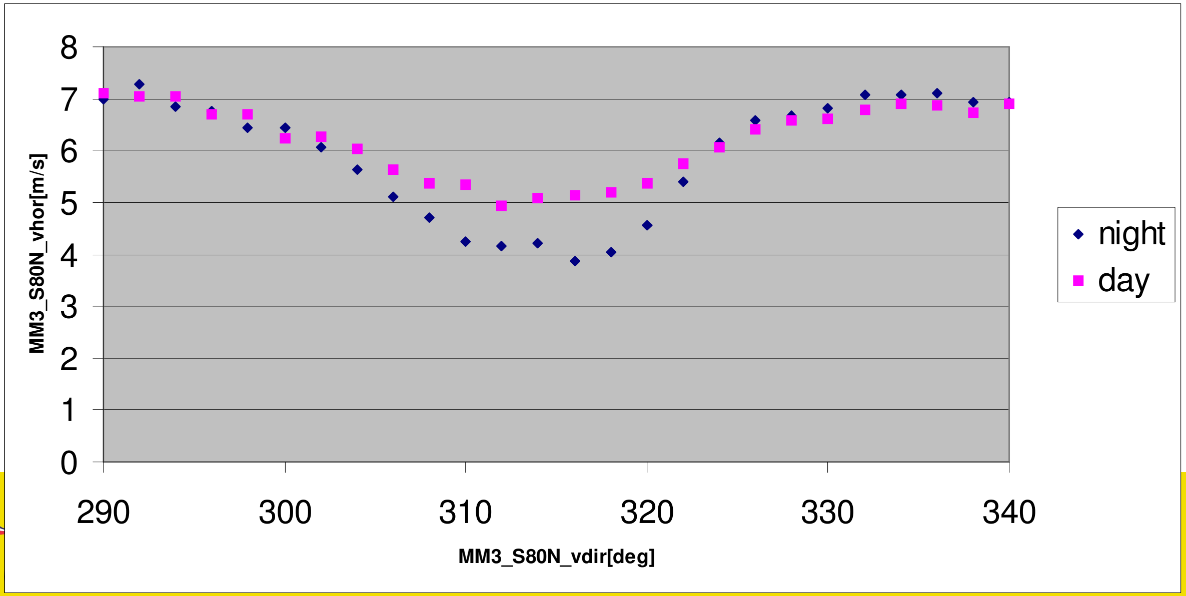




[1]) October 15 – April 15

Relative production of second turbine and velocity deficit at 3.5D (summer period) at day and night time

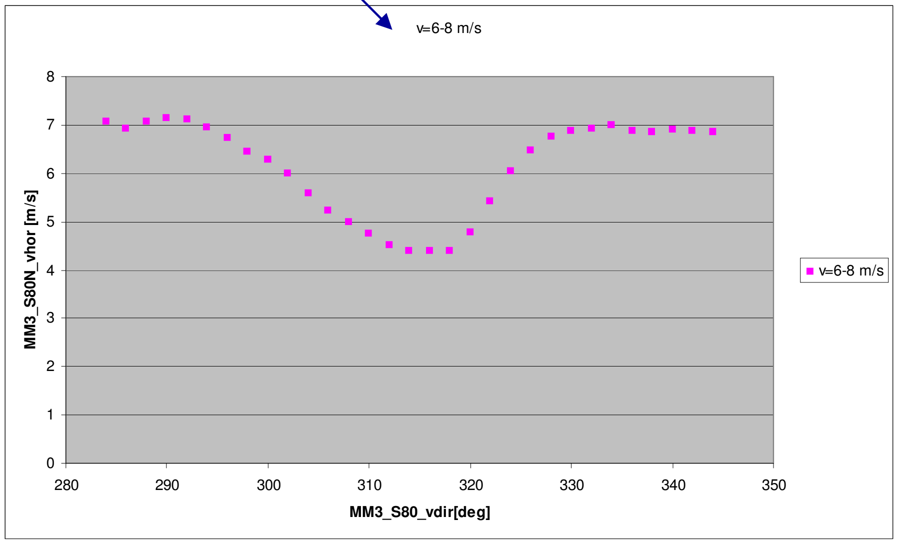


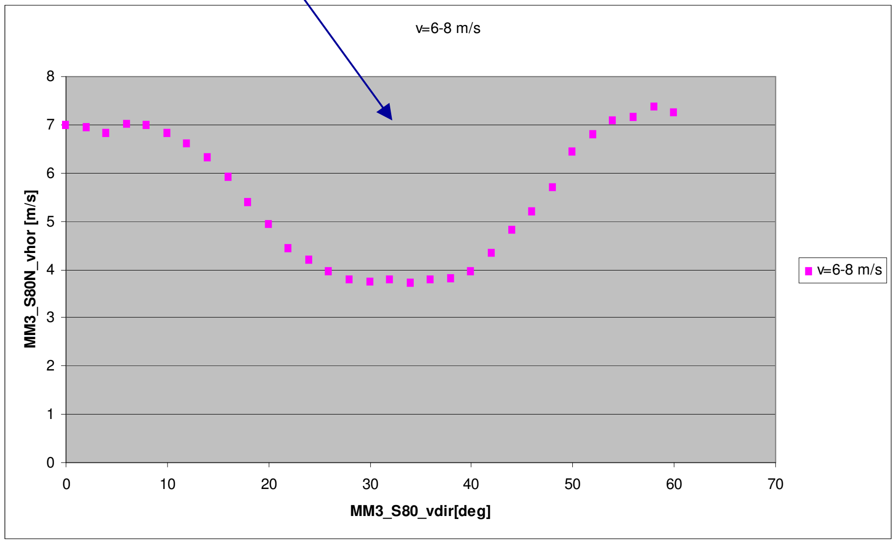


Night time: Much stronger wake effects

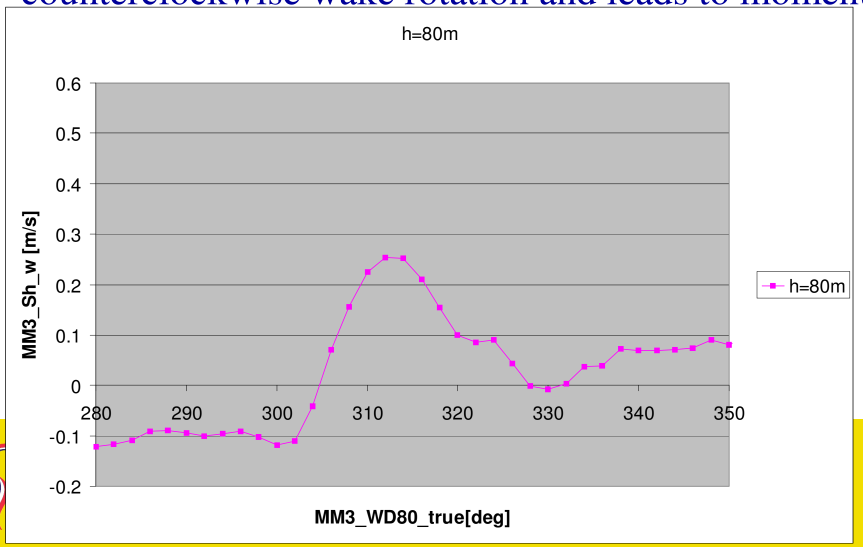
ECN Energy research Centre of the Netherlands

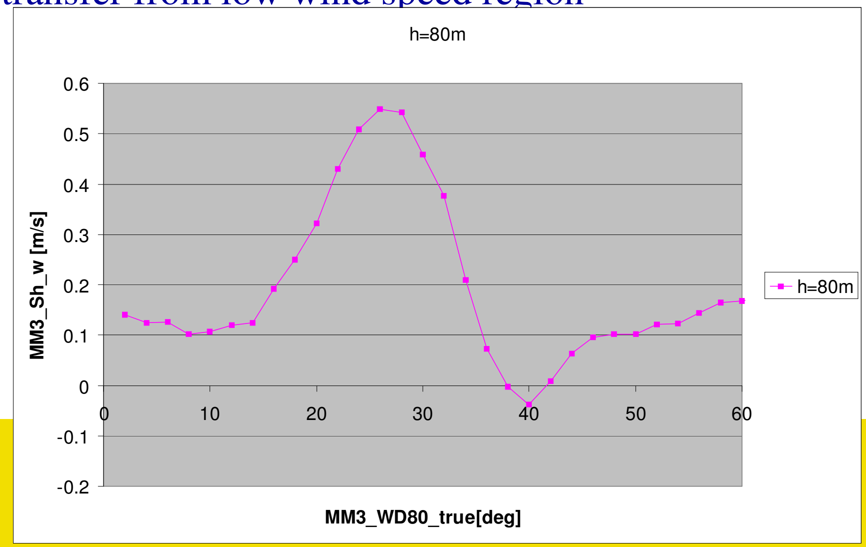
Meteorological wake measurements: Velocity deficit at hub height as function of wind direction
MM3 at 3.5D(315 degrees) from turbine 5 and 2.5D(31 degrees) from turbine 6
V_{free} between 6-8 m/s, derived from P(V) curve





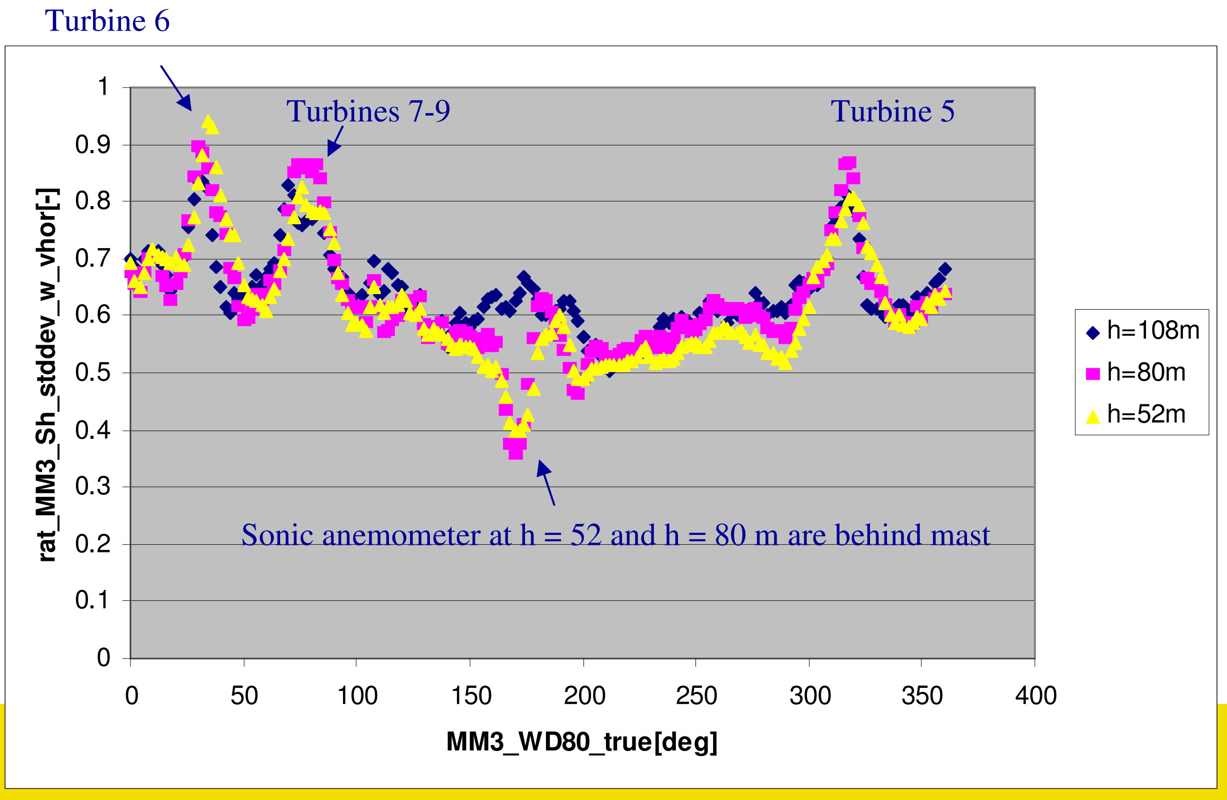
'Asymmetry' in wake profile, with lower velocities 'left' may be caused by wake rotation, see vertical velocity at hub height as function of wind direction:
Larger vertical velocity at 'left' part of the rotorplane (looking from downwind) is consistent with counterclockwise wake rotation and leads to momentum transfer from low wind speed region





Anisotropy in wake: σ_w/σ_{hor} (sonic) at h=52m, h=80m and h =108 m as function of wind direction

- Free stream: σ_w/σ_u ~0.6 (Panofsky Dutton: 0.52)
- In wake: Turbulence more isotropic
- Mast disturbance visible at h =52m and h=80m

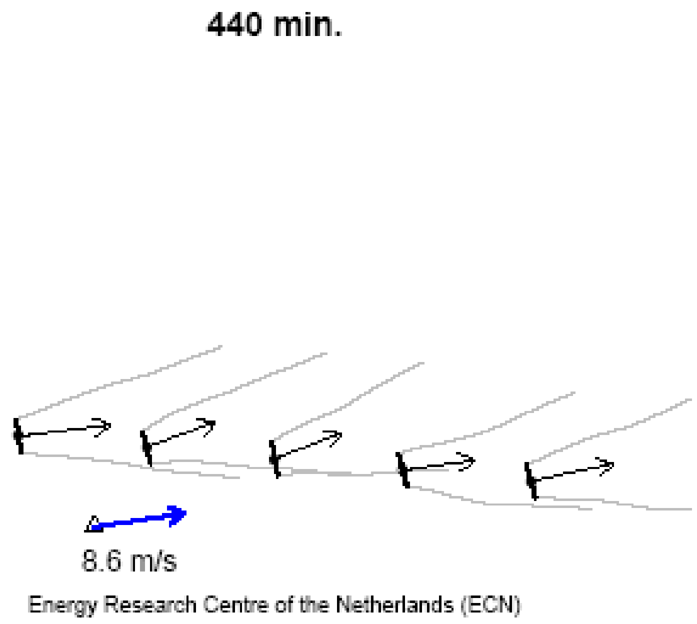


Animation showing wind direction variation (+wakes)

$$\overline{\mathbf{x}}(\mathrm{T},\tau) = \int_{\mathrm{T}}^{\mathrm{T}-\tau} \overline{\mathbf{u}}(\mathrm{t})\,\mathrm{dt}$$

Sampled with 2 Hz
Empirical wake expansion

Courtesy to Stephan Barth



Conclusions from EWTW wake measurements

- Largest power deficit is found at 2nd turbine. The power deficit from the 3rd to the 5th turbine is slightly lower
- At low ambient turbulence intensities:
  Power deficit > 80%
- Turbulence becomes more isotropic in wake
- Effect of wake rotation visible in measurements of vertical velocity at hub height at 2.5 and 3.5D which results in assymmetric wake profile
- A clear diurnal cyle appears in temperature difference, wind shear, turbulence and resulting wake effects. Wake effects are much stronger at night time
- Data are used for validation of different types of (stationary) wake models in EU project Upwind.
- Wakes are very instationary

Statement: Field measurements on full scale MW turbines form the best basis for the final validation of aerodynamic (wake) models since they are the only type of measurements taken at representative conditions

Proposed adaptations for BEM

Herman Snel

Contents

- Introduction
- Description of shear flow, present treatment, and adaptations with cylindrical wake model
- Inflow formulae for harmonic distribution of trailed vorticity
- Equations for the determination of blade loads, first harmonics
- Mutual interaction between blades
- Validation possibilities
- Summary and **statements**

Introduction

- For wind turbine design and certification calculations, the Blade Element Momentum remains the only option, notwithstanding the rapid improvement of CFD based methods
- Hence further improvement of BEM is a necessity, to reduce uncertainties
- BEM is based on the analysis of annular regions, in which for each blade, often a annular symmetry is assumed for the determination of conditions at the particular blade.
- For some non-symmetric conditions, better estimations can be made for the inflow distribution over the annulus, c.q. the entire rotor plane. Moreover, in non-symmetry there is a mutual interaction between the blades: bound vortex induction.
- **Work presented here is 'Work in progress', open to suggestions, but meant to show directions of thought. Part of UPWIND**

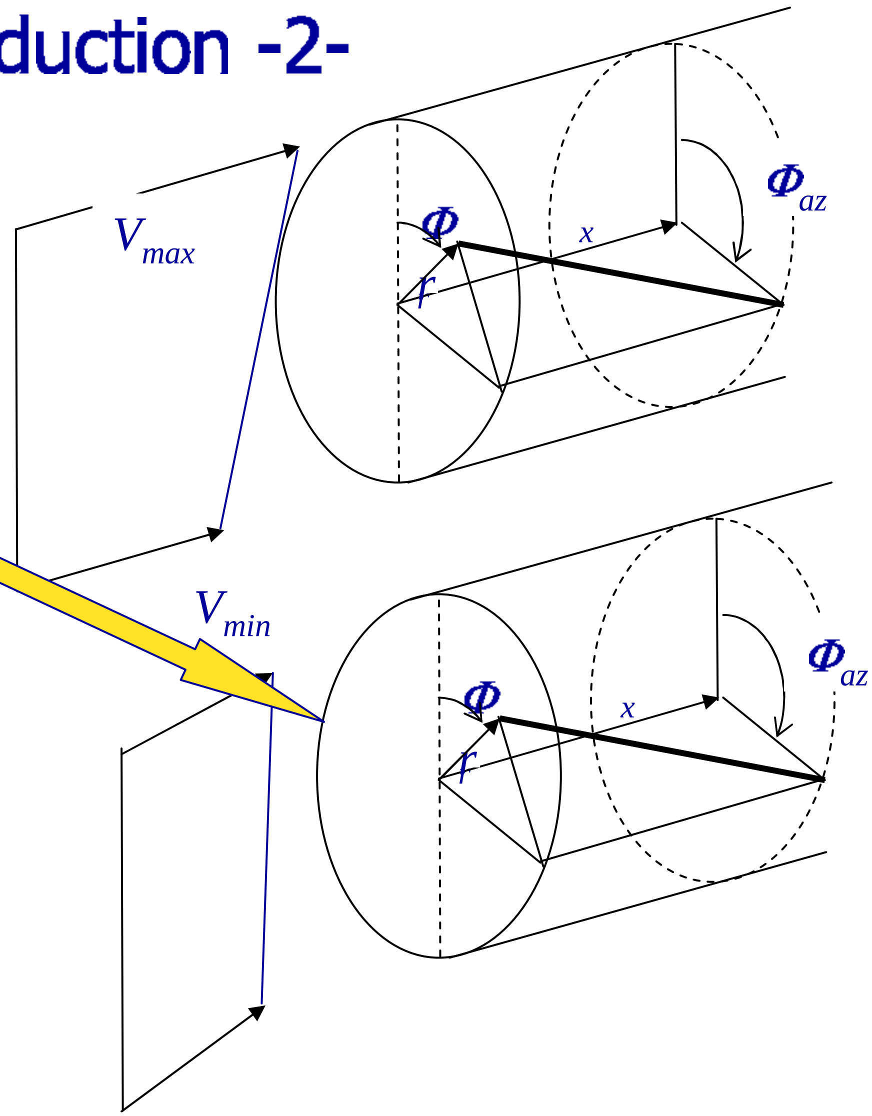
Introduction -2-

Two cases will be looked at:

1. The shear or extreme shear situation;
2. The oblique inflow, yawed situation (not in detail).

Concentration in presentation is on shear

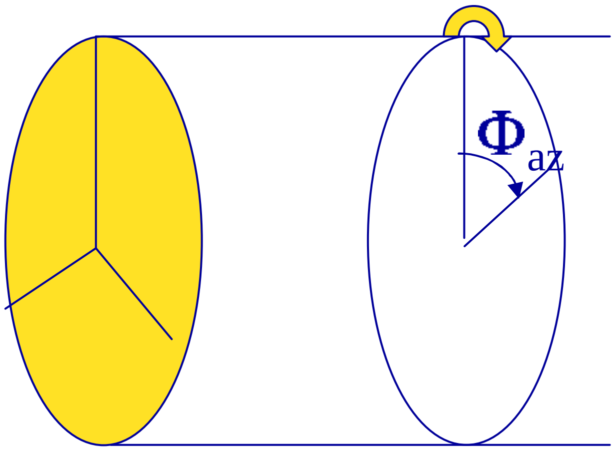
Part of the ideas can be extended to general non-symmetry.



Sheared flow (steady)

- Simplify the wake to a vorticity cylinder, resulting from the vorticity trailed from the blades and concentrated into a tip vortices.
- The vorticity distribution on this wake cylinder will at least be harmonic, for the time being we assume an even distribution, but extension to odd terms is not a problem.

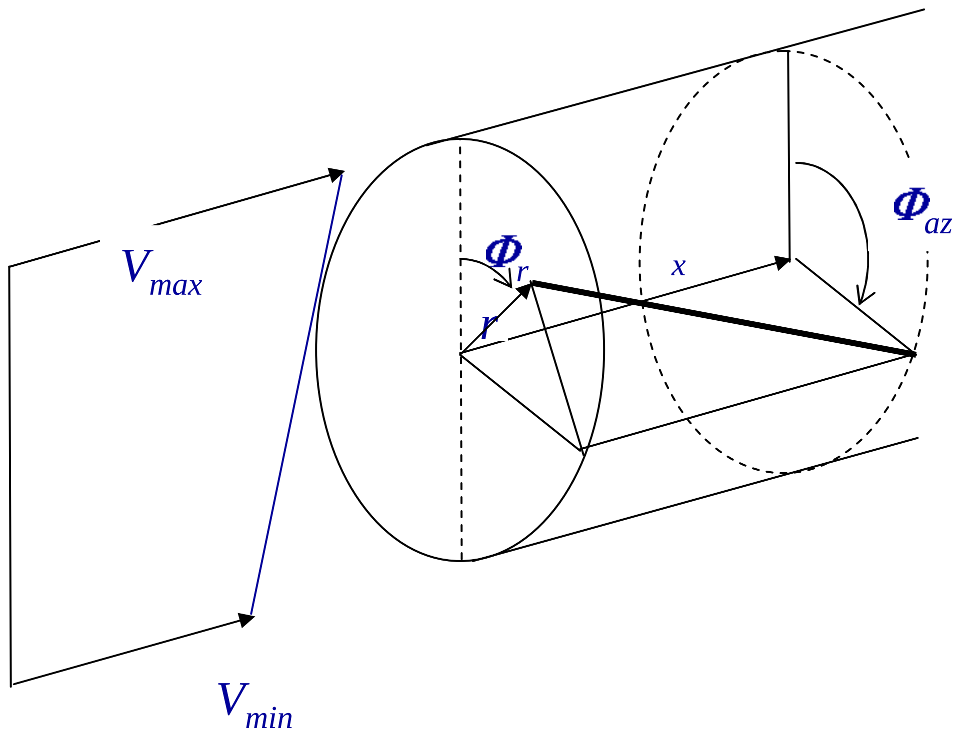
$$\gamma(\Phi) = \sum_{n=0}^{\infty} \gamma_n \cos n\Phi_{az}$$



Vorticity Distribution

This vorticity distribution is the result of:

- Varying transport velocity due to linear shear
- Harmonically varying bound vortex strength on blade



Inflow distribution

If the vorticity distribution were known, then inflow distribution follows from integration of Biot Savart:

$$u_i(r,\Phi_r)=\sum_{n=0}^{\infty}\int_{x=0}^{\infty}\int_{\Phi_{az}=0}^{2\pi}\frac{\gamma_n\cos n\Phi_{az}\left[R-r\cos(\Phi_{az}-\Phi_r)\right]}{4\pi\left[x^2+r^2+R^2-2rR\cos(\Phi_{az}-\Phi_r)\right]^{3/2}}d\Phi_{az}dx$$

the result of which (not trivial) is:

$$u_i(r,\Phi_r)=\frac{\gamma_0}{2}+\sum_{n=1}^{\infty}\frac{\gamma_n}{4}\left(\frac{r}{R}\right)^n\cos n\Phi_r$$

Relations for distribution strength

At any azimuthal position Φ_{az}, the blade bound vorticity $\Gamma_b(\Phi_{az})$ is trailed, and transported with a certain transport velocity $V_{tr}(\Phi_{az})$

In the cylindrical wake model, the trailed vorticity is distributed over a length L equal to the transportation length in the time between two blade passages:

$$L = V_{tr}(\Phi_{az})\frac{2\pi}{B\Omega} \quad \Longrightarrow \quad \gamma(\Phi_{az}) = \frac{\Gamma(\Phi_{az})}{V_{tr}(\Phi_{az})}\frac{B\Omega}{2\pi}$$

For the axisymmetric case, it can be shown that by taking the transport velocity equal to V_w-u_i, the BEM result is obtained.

Hence use

$$V_{tr} = V_0 + \frac{dV}{dz}R\cos\Phi_{az} - u_i(\Phi_{az})$$

First harmonic only

For simplicity the presentation will be limited to the first harmonic for the different quantities:

$$\gamma = \gamma_0 + \gamma_1 \cos\Phi_{az}$$

$$\Gamma = \Gamma_0 + \Gamma_1 \cos\Phi_{az}$$

$$V_{tr} = V_0 - \frac{\gamma_0}{2} + \left[\frac{dV}{dz}R - \frac{\gamma_1}{4}\right]\cos\Phi_{az}$$

Then

$$\gamma_0 + \gamma_1 \cos\Phi = \left(\frac{B\Omega}{2\pi}\right)\frac{\Gamma_0 + \Gamma_1 \cos\Phi}{V_0 - \frac{\gamma_0}{2} + \left[\frac{dV}{dz}R - \frac{\gamma_1}{4}\right]\cos\Phi}$$

Results

Multiplying the left hand side by the denominator of the RHS, and identifying constant and cos(Φ) terms, two equations for in terms of the blade vortex strengths Γ_0 and Γ_1 are obtained

Two more relations are obtained by expressing Γ_0 and Γ_1 in terms of the inflow geometry, containing γ_0 and γ_1. These equations can be solved for the induction distribution over the rotor plan.

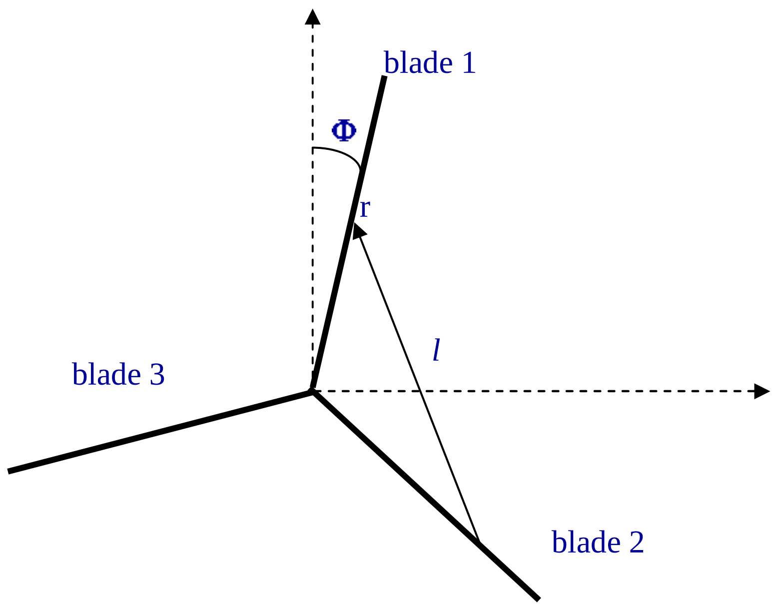
Note that Γ_1 does not contribute to the total rotor force, since the summation over the three blades always gives zero. However, it contributes to the 1P blade loads.

Mutual influence between blades

An additional effect of non-symmetry is the induction at a certain blade due to the bound vorticity on the other blades. For instance, blade 2 and 3 on blade 1

In symmetric conditions, these cancel, but not so for non-symmetry.

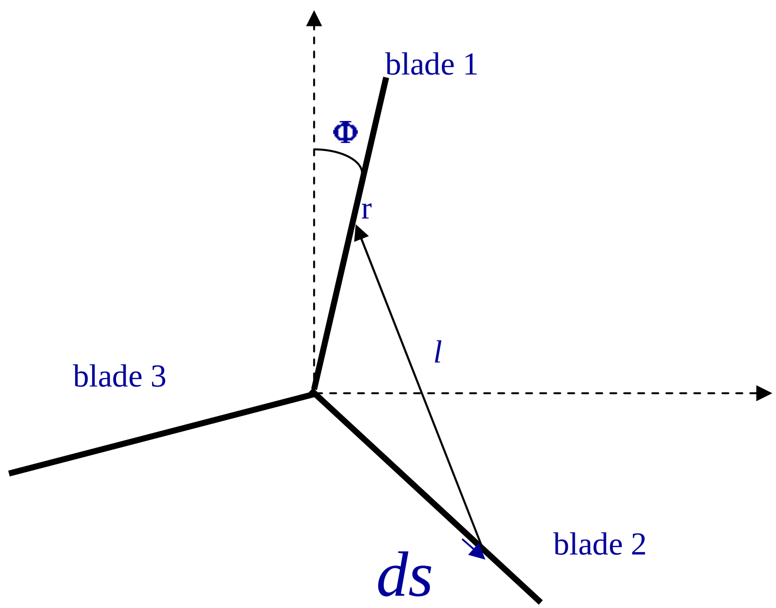
This applies generally to all non-symmetry conditions, e.g. shear, yawed flow, general non-uniform wind speed distribution. It is usually not included in BEM, but should be!



Induction expression

Induction on blade 1 due to blades 2 and 3, Biot Savart:

$$\Delta u_{i,1} = \sum_{b=2}^{3} \int_{sroot}^{R} \frac{\Gamma_b(\Phi) d\vec{s} \times \vec{l}}{4\pi |l|^3}$$



Result:

$$\Delta u_{i,1} = \frac{\Gamma(\Phi + 4\pi/3) - \Gamma(\Phi + 2\pi/3)}{4\pi} \left(\frac{r\sqrt{3}}{2} \right) \int_{sroot}^{R} \frac{ds}{\left[r^2 + s^2 + rs \right]^{3/2}}$$

Results

We can estimate the values for the induction working out the expressions:

Let
$$\Delta\Gamma = \Gamma\left(\Phi + \frac{4\pi}{3}\right) - \Gamma\left(\Phi + \frac{2\pi}{3}\right),\ x = \frac{s}{R},\ r = \frac{r}{R}$$

Then, after non-dimensionalizing and working out the integral:

$$\Delta u_{i,1} = \frac{\Delta\Gamma\sqrt{3}}{8\pi R}\left[\frac{2(r+2x)}{3r\sqrt{x^2+r^2+rx}}\right]_{x=xroot}^{x=1}$$

Next
$$\frac{\Delta u_{i,1}}{V_w} \approx \frac{\Delta\Gamma}{V_w R}\frac{\sqrt{3}}{8\pi}$$ with $$\frac{\Gamma}{V_w R} \approx \frac{1}{\lambda}$$

For large values of $\Delta\Gamma$, this can be approximately 5% of the average induction, near the root

Result

For cosine distribution as e.g. in shear, maximum result is for $\Phi = \pi/2$:

$$\frac{u_{ind}}{V_w} \approx \frac{1.5}{8\pi} \frac{\Gamma_1}{V_w R}$$

near the root

If Γ_1 is the first harmonic amplitude of the Γ expansion seen before.

Possibilities of validation

Shear:

1. Difficult from field measurements, but look for cases with strong shear in EWTW database
2. Not covered in wind tunnel experiments and difficult to cover
3. Using CFD solutions, e.g. Zahle, Soerensen and Johansen: Rotor aerodynamics in atmospheric shear flow. EWEC 2008, but also Free Vortex wake models as AWSM

Yawed flow:

1. From wind tunnel experiments (NREL and Mexico). For yawed flow without shear, the induction and bound vortex should be a sine distribution instead of a cosine, but rest the same.
2. From CFD solutions, including free vortex wake models like AWSM

Summary and statements

- Possibilities for BEM upgrades were presented, as 'work in progress', regarding the treatment of flow conditions which are not axi-symmetric.

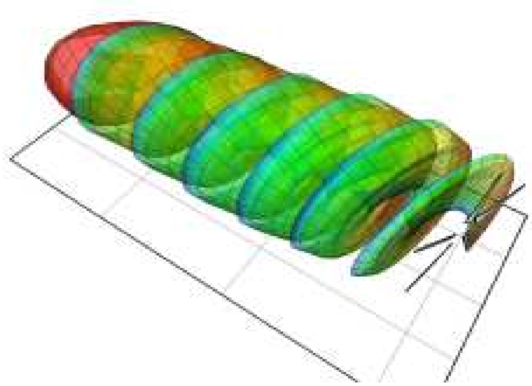
STATEMENTS

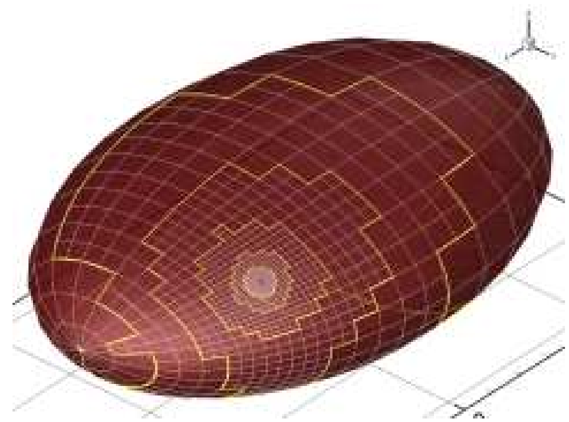
- BEM improvements are still much needed, notwithstanding the progress of CFD based codes
- BEM improvements should be based as much as possible on the understanding of the global flow situation and physics
- Modelling for BEM improvements is fun

Dutch Wind Workshops, October 2008

Wind Turbine Aerodynamics RotorFlow I and II

Arne van Garrel, ECN
Hüseyin Özdemir, ECN
Henny Bijleveld, RUG





TU Delft

DUWIND

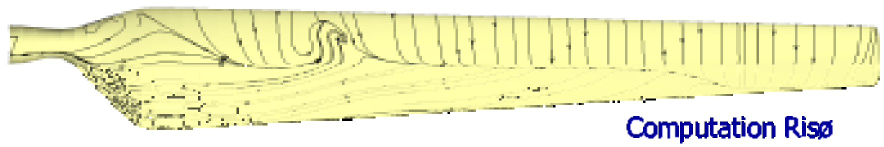
SenterNovem

ECN
Energy research Centre of the Netherlands

Knowledge Centre WMC

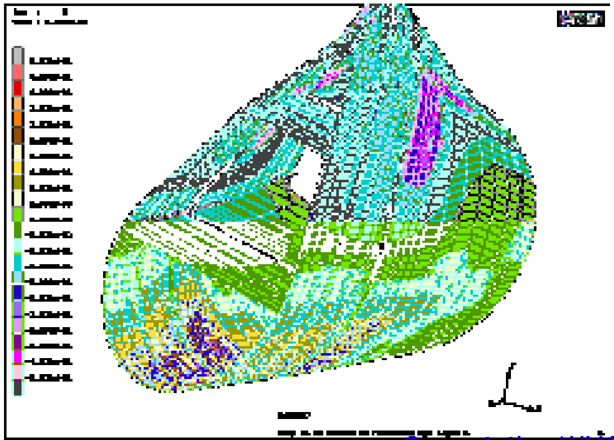
Aerodynamics of flow field

- Detailed wind turbine dynamics simulation



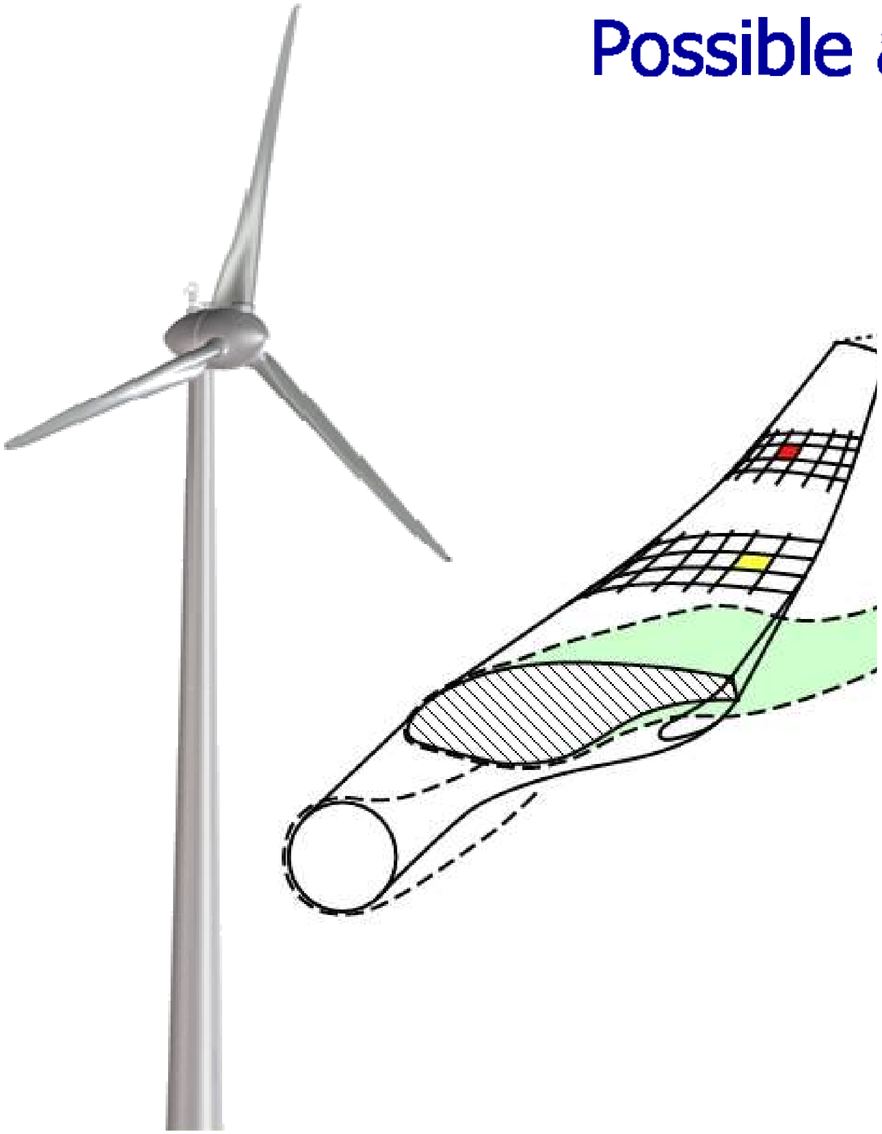
Computation Risø

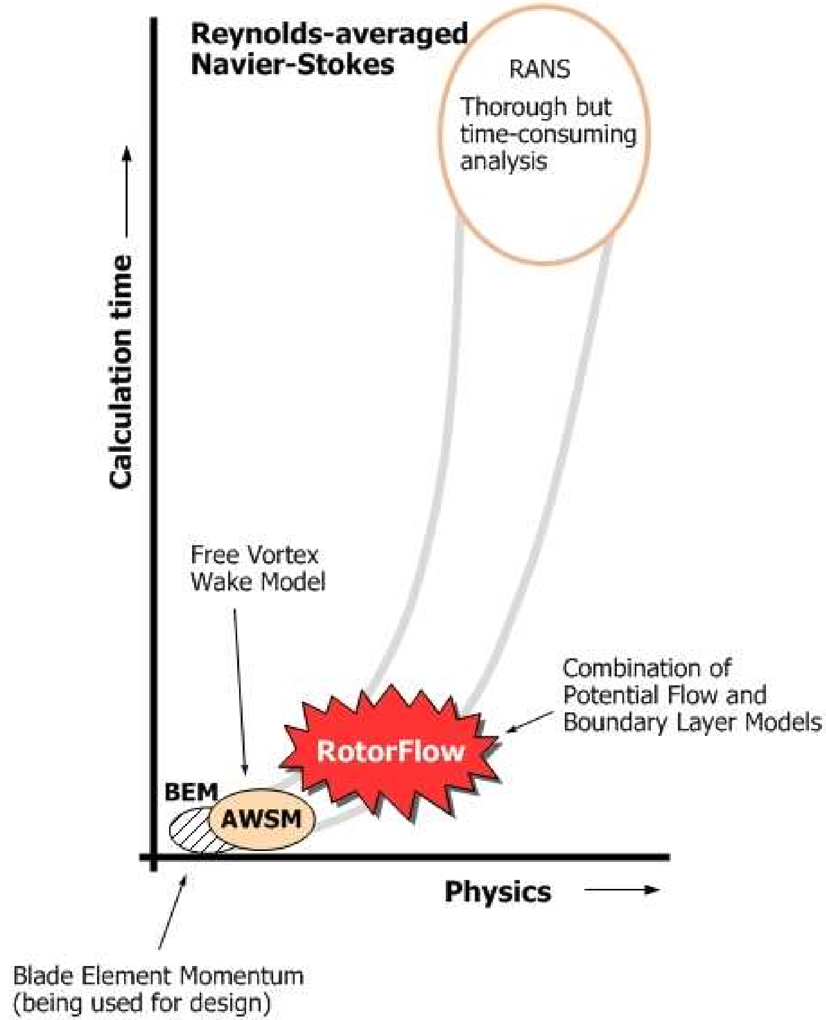
- Local aerodynamic forces, structural stresses and deformations



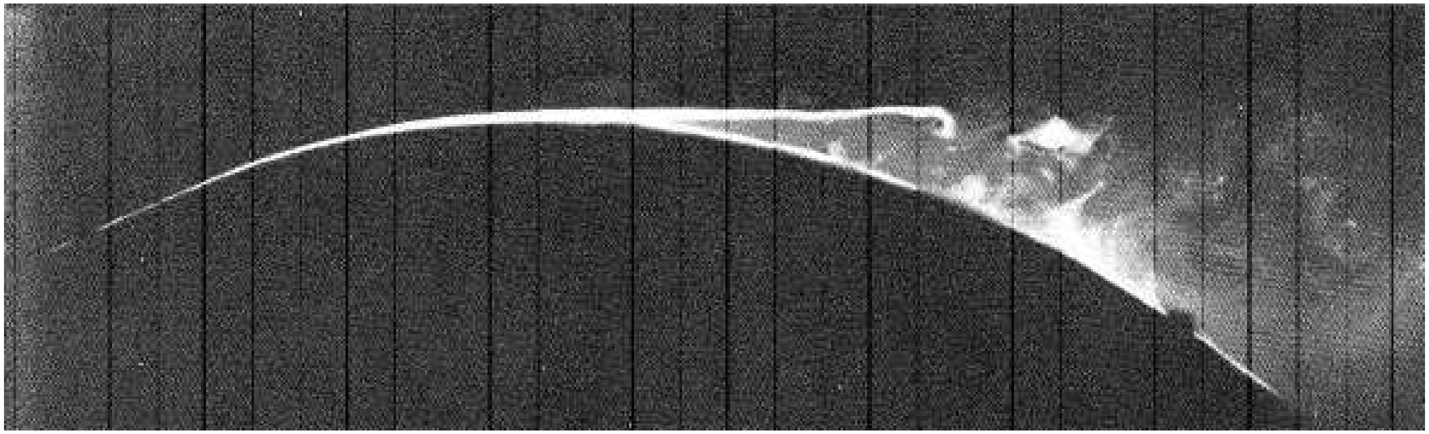
Computation WMC

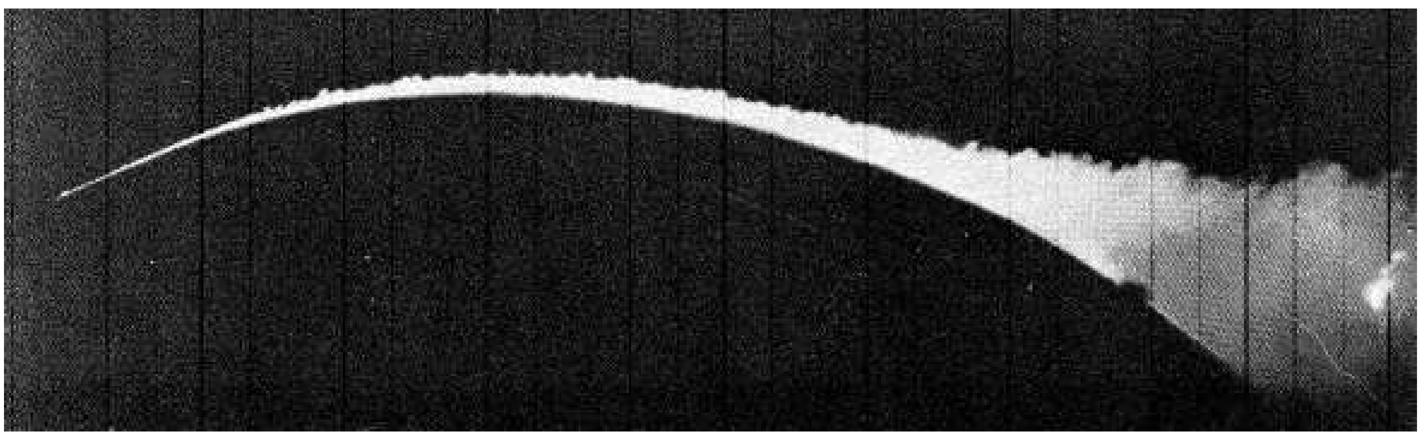
Possible approaches



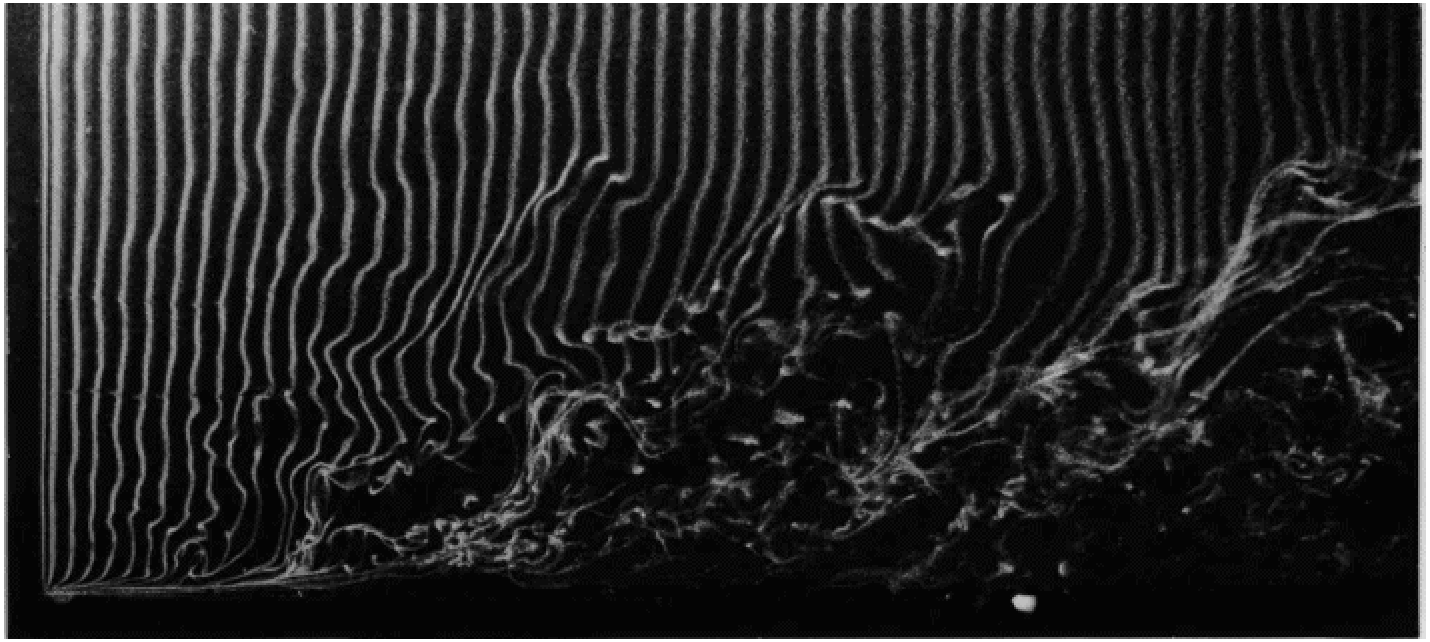


RotorFlow: Approach





RotorFlow: Approach



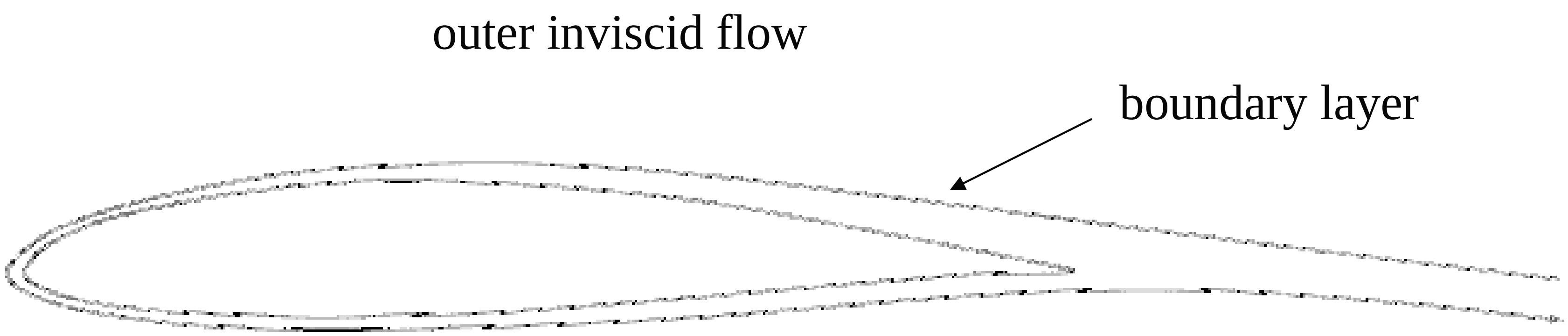
Boundary Layer + Potential Flow + Interaction Scheme

RotorFlow: Boundary Layer + Potential Flow + Interaction Scheme

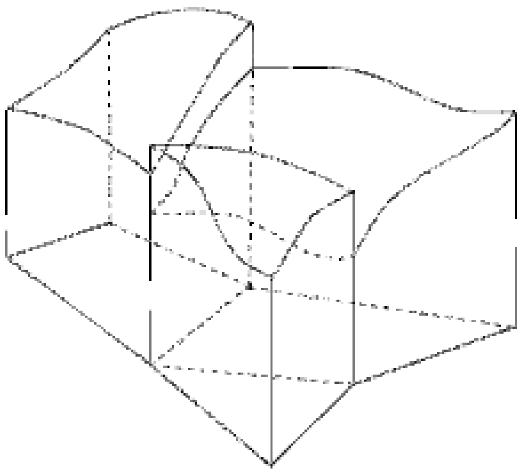
- Boundary Layer:
  - Field method
  - **Integral boundary layer method**
- Potential outer layer:
  - Field method
  - **Panel method**
- **Viscous – Inviscid interaction scheme**

RotorFlow II: Integral boundary layer method

- Unsteady problem
- We do not need to resolve the flow field in detail
- We need the *global* quantities: δ^*, θ_{ij}, etc.

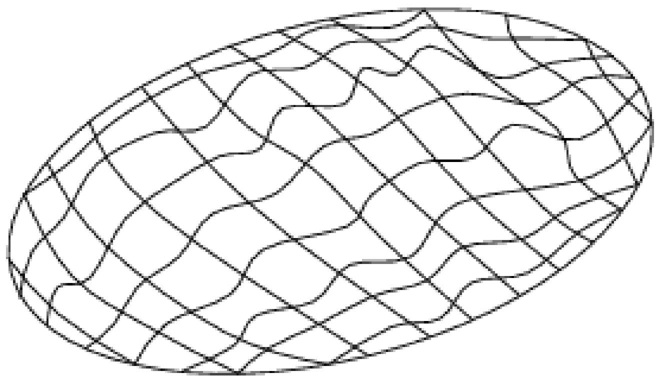


RotorFlow II: Discontinuous Galerkin method

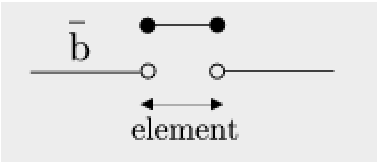


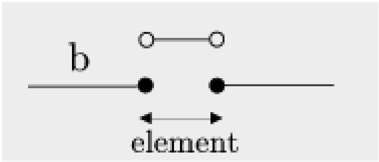
- Finite element method with discontinuous basis functions
- Highly compact method: basis functions are restricted to individual elements
- Higher-order method can be developed easily
- Highly parallelizable
- Implementation of boundary conditions is relatively simple
- Can be applied to a large variety of flow types: *steady, unsteady, linear, nonlinear, incompressible, compressible*.
- Can be applied to a large variety of problem types: **elliptic, parabolic, hyperbolic** *i.e. aeroacoustics, shock capturing, turbulent flows, elasticity, chemical flows, etc*.

RotorFlow II: Discontinuous Galerkin method

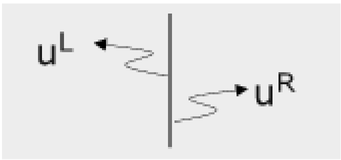


- Divide the solution domain into non-overlapping elements
- Write the weak formulation
- Use discontinuous basis functions within each element



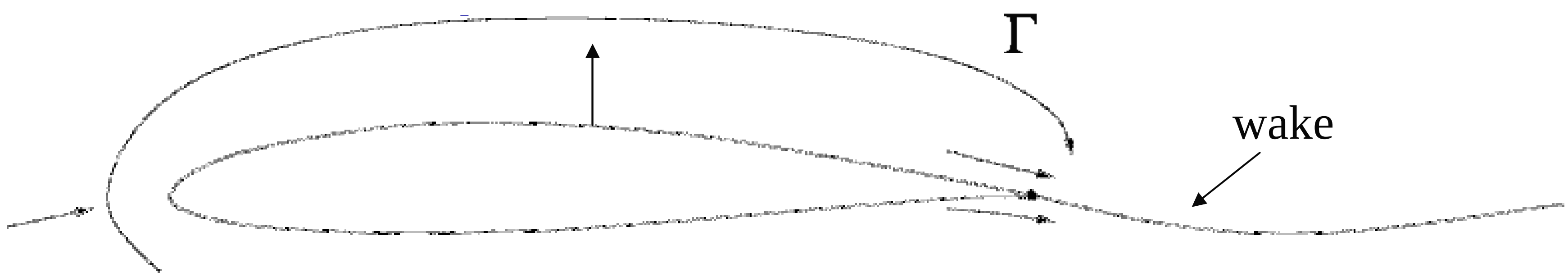


- Obtain the integral equation
- Solve the Riemann problem at element interfaces



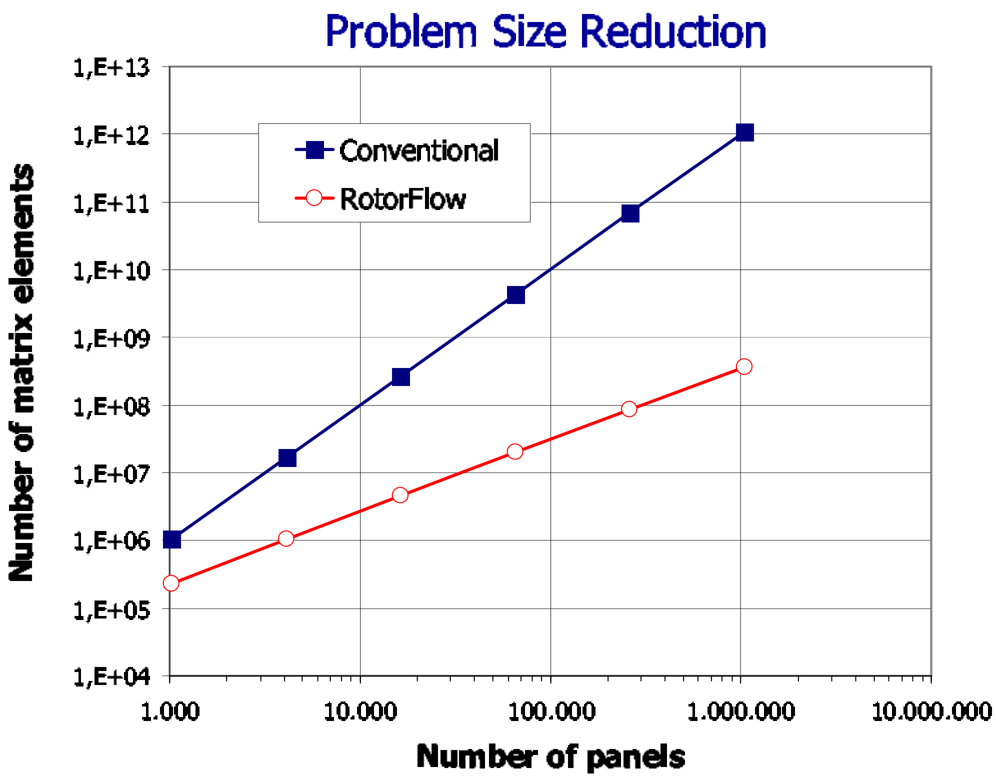
RotorFlow I: Potential Flow Model

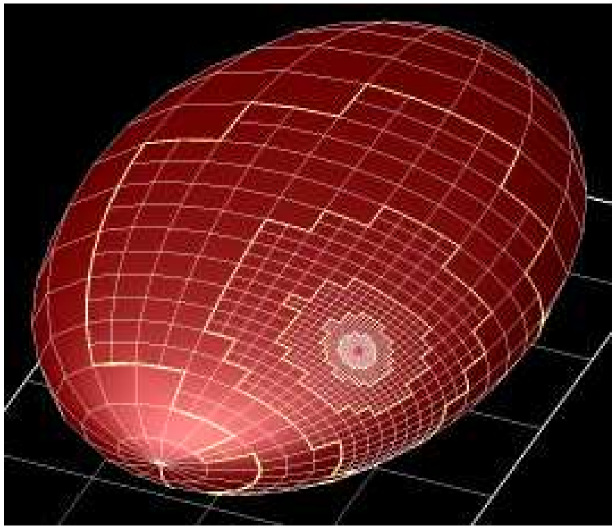
- Mass conservation
- Transport equation for vorticity
- Kutta condition to fix circulation/separation at trailing edge
- Prescribed normal velocity



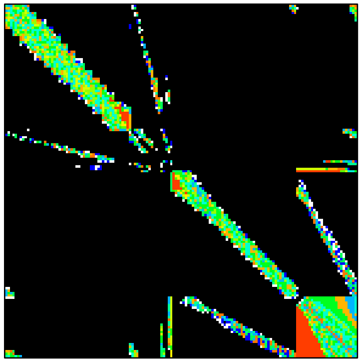
- 1st Order multilevel panel method
- Internal perturbation potential boundary conditions
- Highly parallelizable method

RotorFlow I: Multilevel Panel Method





Nested Grid



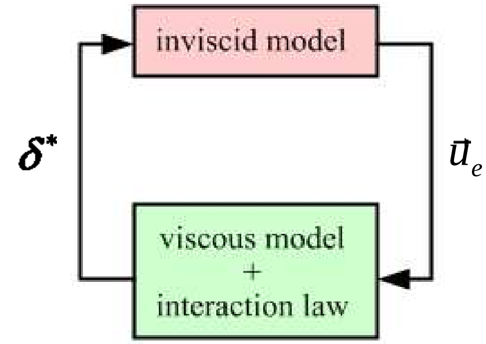
Sparse Matrix

RotorFlow: Viscous-Inviscid Interaction

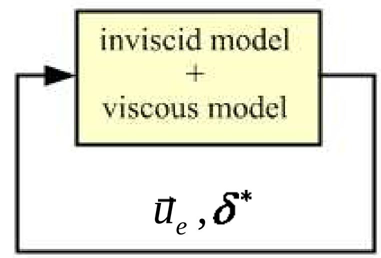
- Quasi-Simultaneous Interaction:
  - Independent viscous and inviscid flow codes
  - Simple and robust

- δ^*: boundary layer displacement thickness
- $\vec{u}_e$: inviscid edge velocity

- Simultaneous Interaction:
  - Interwoven viscous and inviscid flow codes
  - Robust, but implementation laborious

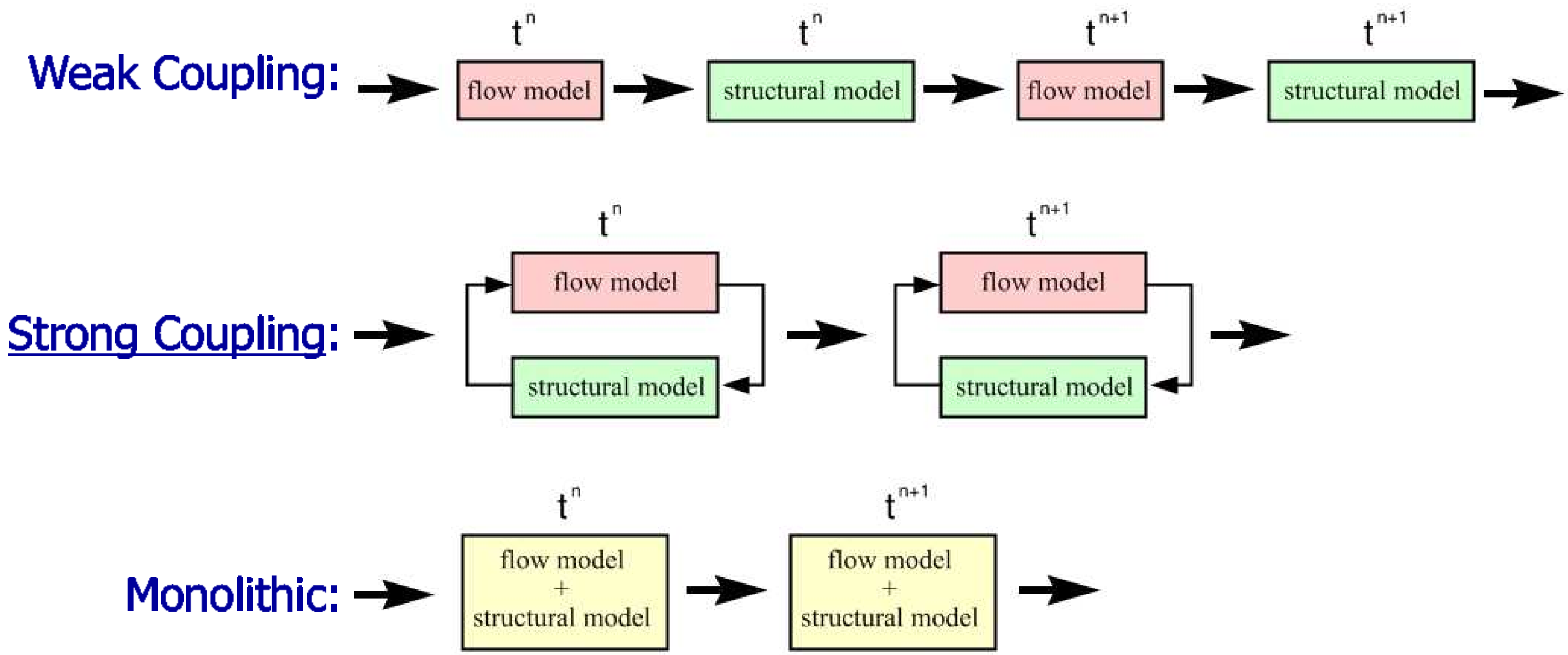


Quasi-Simultaneous



Simultaneous

RotorFlow: Fluid-Structure Interaction



The Mexico project and IEA Wind Task 'MexNex(t)'

Gerard Schepers

EU project Mexico [1])

Model EXperiments In COntrolled conditions

- 2001-2006
- Measurements in German Dutch Wind tunnel, DNW
  - North East Polder at NLR premises
  - Open test section: 9.5 x 9.5 m^2
  - Diameter of rotor: 4.5 m
    - Pressure measurements along the blade
    - Particle Image Velocimetry (PIV): Quantitative flow visualisation

[1])**Acknowledgements**
Financial support by EC 5th Framework program and by National Agencies (e.g. SenterNOVEM)

Content

- Mexico project
  - Background
  - Sketch of the Mexico experiment
  - Results
- IEA Task MexNext
  - Goal, workplan participants

‘Common’ validation measurements

- Validation measurements of power and loads do show differences but they are too global to form a basis for improvement of aerodynamic models
  - Loads are integrated over blade
  - Structural dynamics
- Desired:
  - Local aerodynamic loads (pressure distribution)
  - Induced velocities and wake velocities
  - Constant, controlled conditions (→Windtunnel)

Measurements in NASA-Ames wind tunnel

- Carried out by NREL (National Renewable Energy Laboratory), USA
- Spring 2000
- 24m x 36m NASA-Ames wind tunnel.
- 10 m rotor
- Measurement of pressure distributions at 5 locations along rotor blade
- Analysed in IEA Task XX (Scott Schreck)

Comparison between NASA-Ames and Mexico experiment

NASA-Ames	Mexico
D=10 m	D=4.5 m
2 blades	3 blades
Emphasis on stall	Entire operational range
Pressure measurements at 5 radial positions	Pressure measurements at 5 radial positions and PIV measurements of inflow and wake velocities

Goal of Mexico project

- **Main objective**: create a database of detailed aerodynamic measurements on a realistic wind turbine model, in a large high quality wind tunnel. Complementary to the NREL NASA Ames measurements

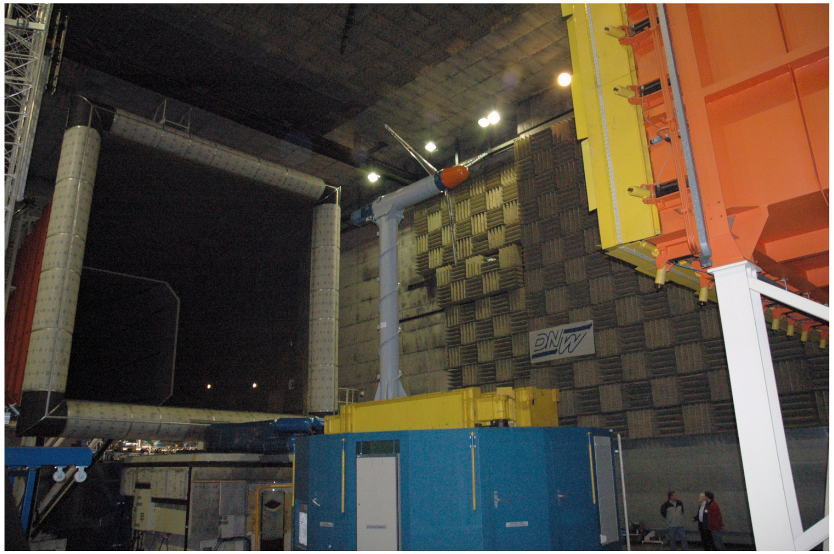
- The database is to be used for aerodynamic model evaluation, validation and improvement, from BEM to CFD **(i.e. Mexnext)**

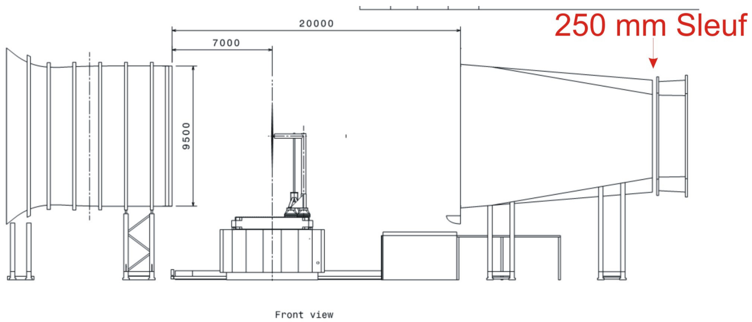
Mexico: Tasks/Participants

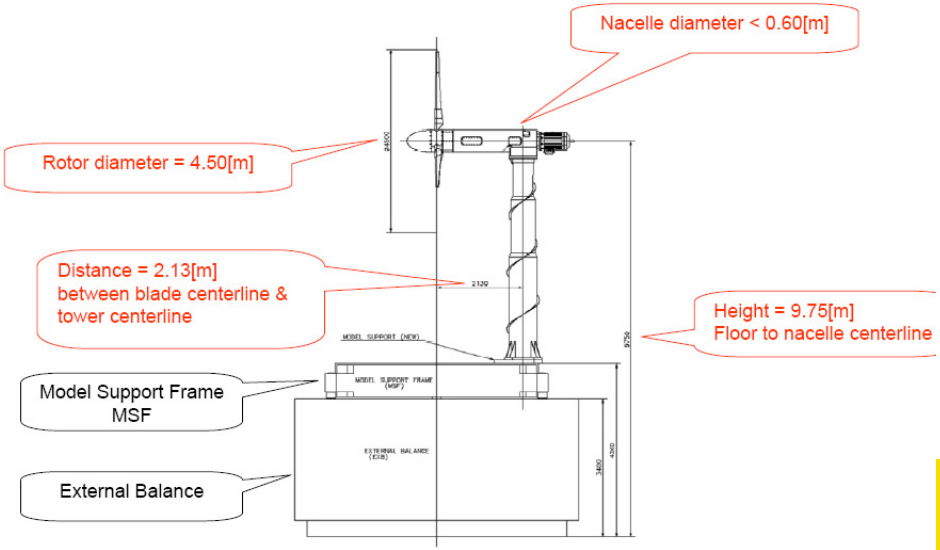
- Coordination (ECN)
- Design of model (ECN, Technion)
- Assembly of model incl. control (Technion)
- Instrumentation, DAQ (NLR, DUT)
- 2D wind tunnel measurements as a reference to the rotating measurements (DUT)
- Analysis of tunnel effects (ECN,NLR, RISO, DTU, NTUA,CRES)
- Development of test matrix (RISO,NLR,ECN,FFA,DNW)
- Measurements (NLR,ECN,Technion,DUT) (7 December-14 December 2006)
- (NREL brought in the NASA-Ames experiences)

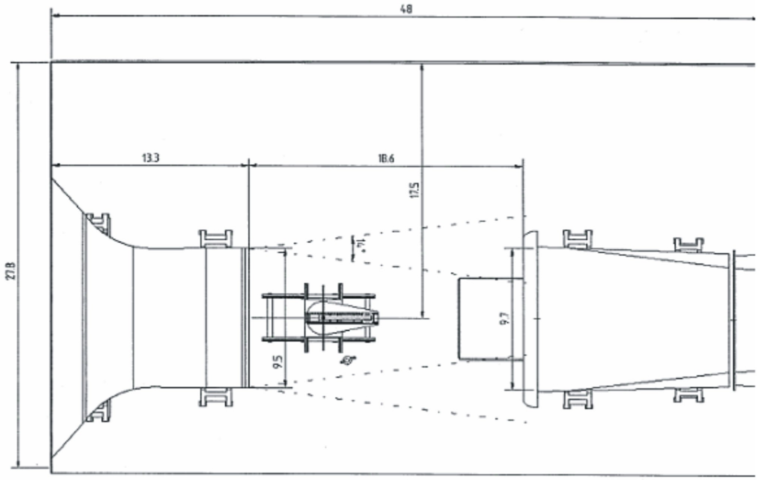
Global overview experiment

- 9.5 x 9.5 m^2 open test section at DNW
- Closed circuit
- Distance: Nozzle-collector: 20 m
  Distance: Nozzle-rotor: 7 m
- Slotted collector
- Rotor: 3-bladed, D= 4.5 m
- Electrical speed control
- Pitch control
- Tower on yawable DNW-balance:

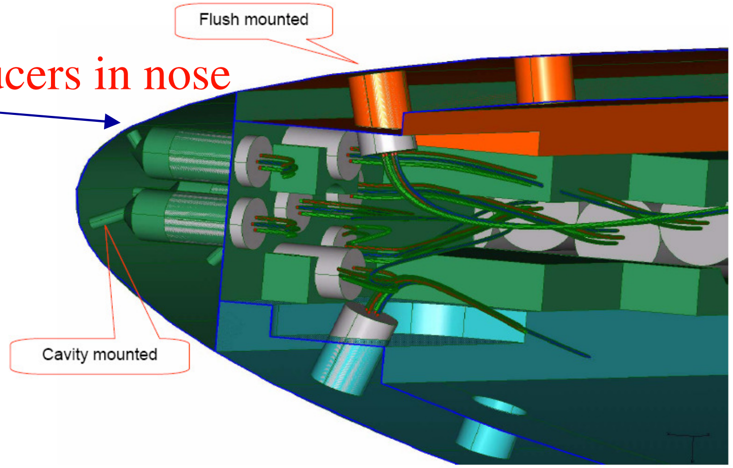




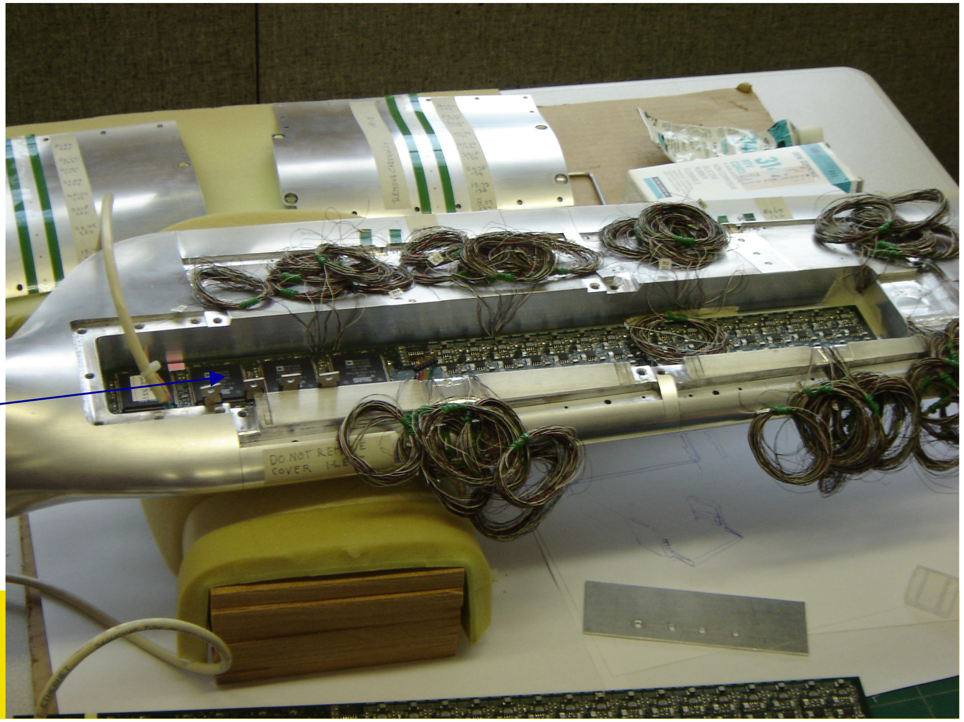




Global overview experiment, ctd



- Blades instrumented with
  Kulite pressure transducers at 5 sections
  - Blade 1: 25% and 35%
  - blade 2: 60%
  - blade 3: 82% and 92%
  - 25 to 28 Kulite pressure transducers per section
  - A few Kulites are placed on strategical positions to double with sections on one of the other blades to analyse differences in blade pressure distributions
  - Measurement of absolute pressures
    Maximum range: 5PSI (35 kPa)
    (could be heavily overloaded)
    Sampling frequency: 5.5 kHz
  - Connected to 5 PCB's
    (Printed Circuit Boards)
    in blade (root)



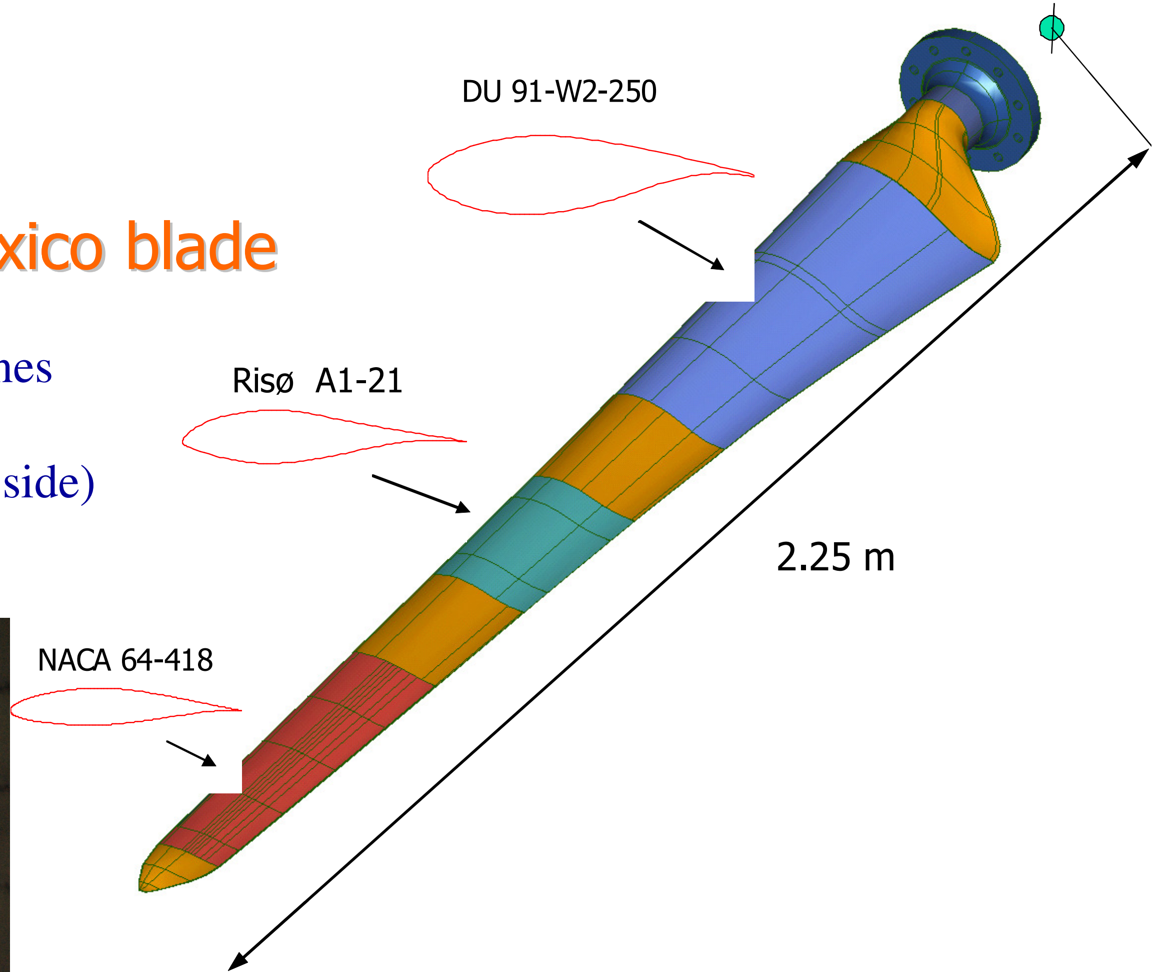
Global overview experiment, ctd

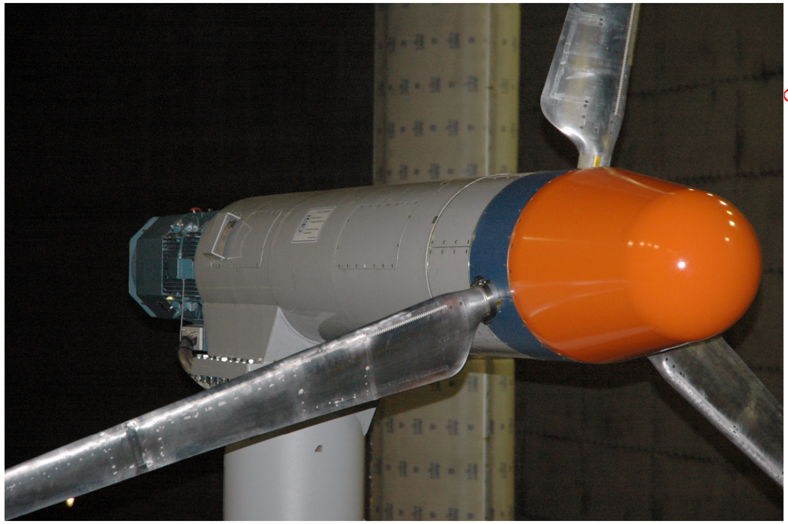
- Moments at blade root of all 3 blades
- PIV measurements:
  - Quantitative flow visualisation
  - Gives induced velocity in rotor plane and velocities in near wake

Representative aerodynamic profiles

The Mexico blade

3 Distinct airfoils with 2 transition zones
'Tripped' boundary layer
(0.05% c at both pressure and suction side)





The measurement matrix. A) pressures and loads

- Tunnel speeds: 10, 15, 20,25 and 30 m/s
- Rotor tip speeds: 100 and 76 m/s (424.5 rpm and 324.5 rpm, Re~800.000 and 600.000)
- Blade tip angles: 1.7, 0.7, -0.3, -1.3, -2.3, -4.3, -5.3 degrees

design angle for $\lambda = 6.7$

- Pitch ramps from -2.3 to 5 and back
- Rotor speed ramps from 100 to 76 m/s and back
- Yaw angles 0, 15, 30 and 45 degrees
- Rotor parked condition with blade angles varying from -2.3 to 90 degrees at V_{tunnel} = 30 m/s

For all except the dynamic ramp conditions: run duration of 5 seconds, sampled at 5.5 kHz (effectively)

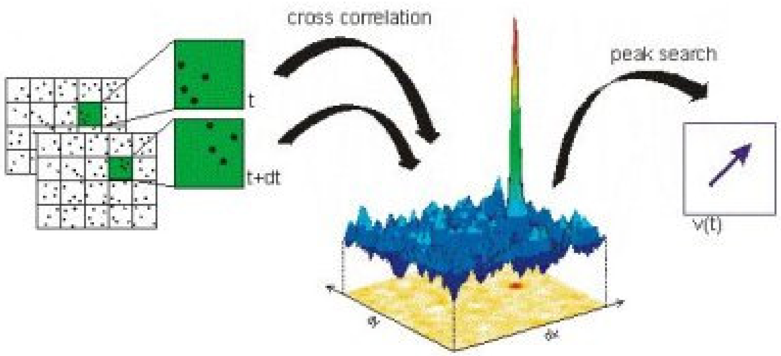
Measurement matrix B. Flow field measurements with stereo PIV, done by DNW

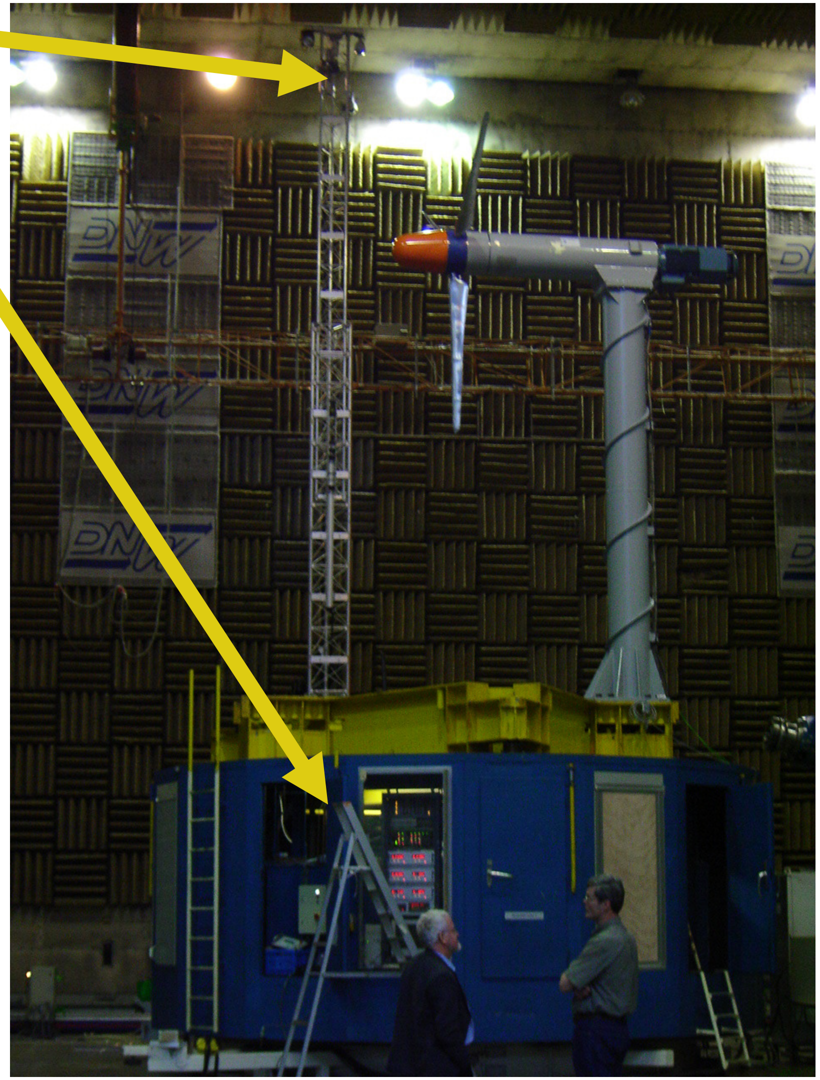
PIV traverse tower with two camera's, aimed at (horizontal) PIV sheet (35*42 cm) in symmetry plane of rotor ('9 o-clock').

Traversing in axial+radial direction

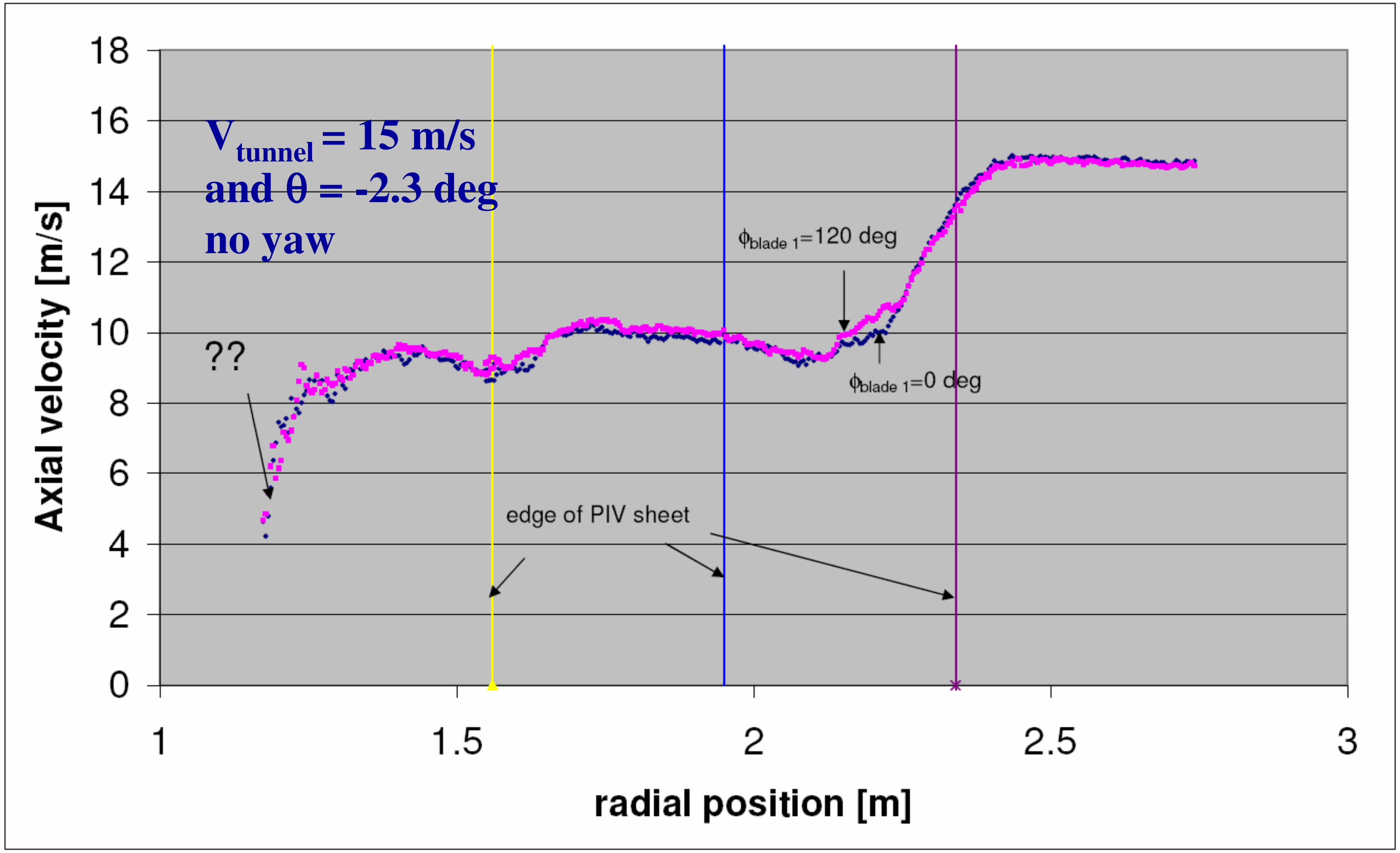
Seeding (tiny bubbles) are introduced in settling chamber, upstream of rotor.
PIV sheet is illuminated with laser flash, and two digital photographs are taken with a delay of 200 nanoseconds;

Sheet is subdivided into small 'interrogation windows' Velocity vector is the one resulting in maximum cross correlation between the two shots.





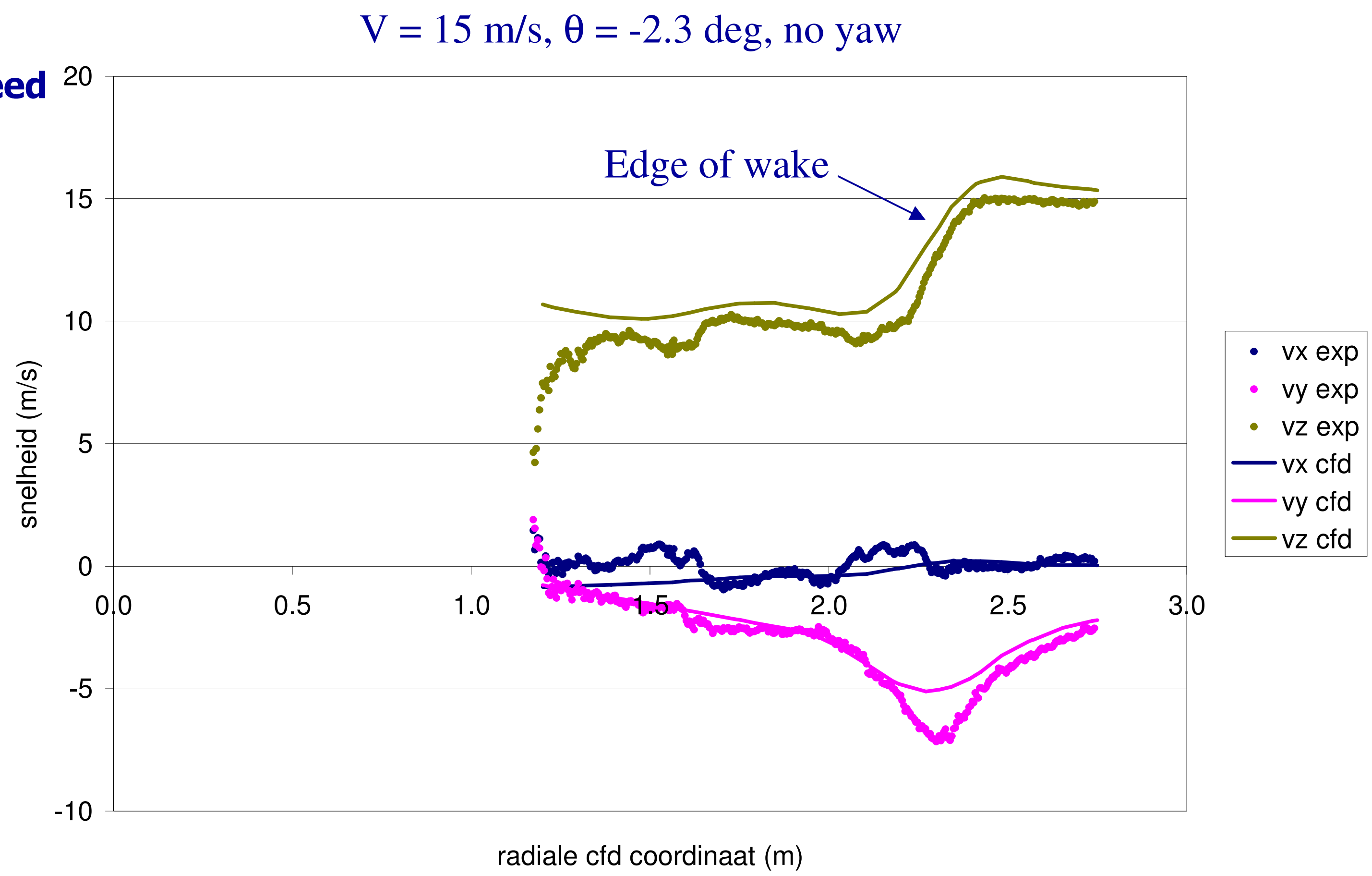
Similarity between PIV measured axial velocity as f(radial position) at x =0.3 m downstream of the rotorplane at ϕ_{blade1} = 0 degrees and ϕ_{blade1} = 120 degrees



PIV measured and Fluent calculated velocity as function of radius, 0.3 m downstream of rotor, 3 velocity components, calculations performed by NRG ϕ_{blade} =0 deg, i.e. vertically upward (in both meas and calculations!)

- **vx = vertical speed**
- **vy = tangential speed**
- **vz = axial speed**

V_{tunnel} = 15 m/s and θ = -2.3 deg no yaw



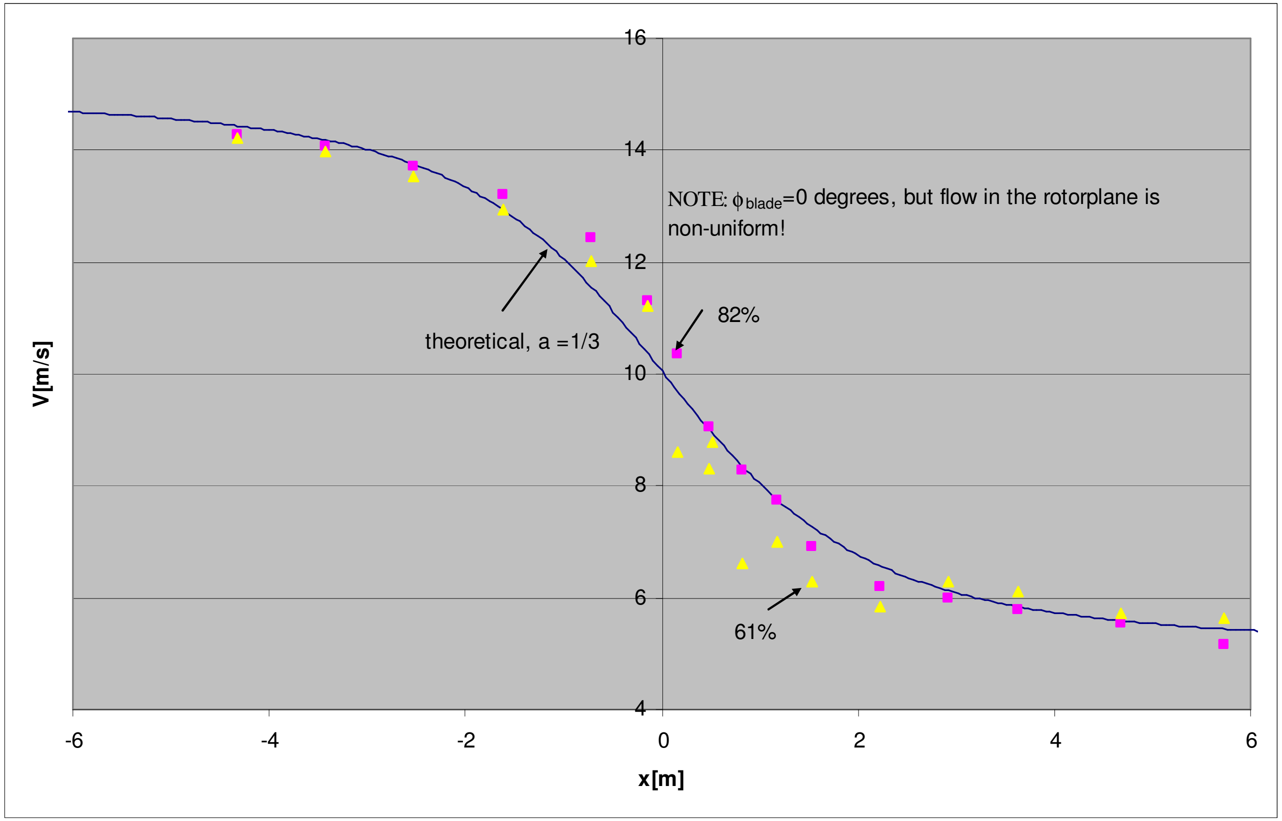
PIV measured and calculated speed decay as function of x at 61% and 82% span for V_{tunnel} = 15 m/s and θ = -2.3 degrees, no yaw

Calculations done with cylindrical vortex sheet model [1]) based on given C_{Dax} compatible to momentum theory

$C_{Dax} = 4a(1-a)$

$a_{\infty} = 2a_{rotor\ plane}$

Calculations for C_{Dax} =0.89 (a=1/3)



Measurements:

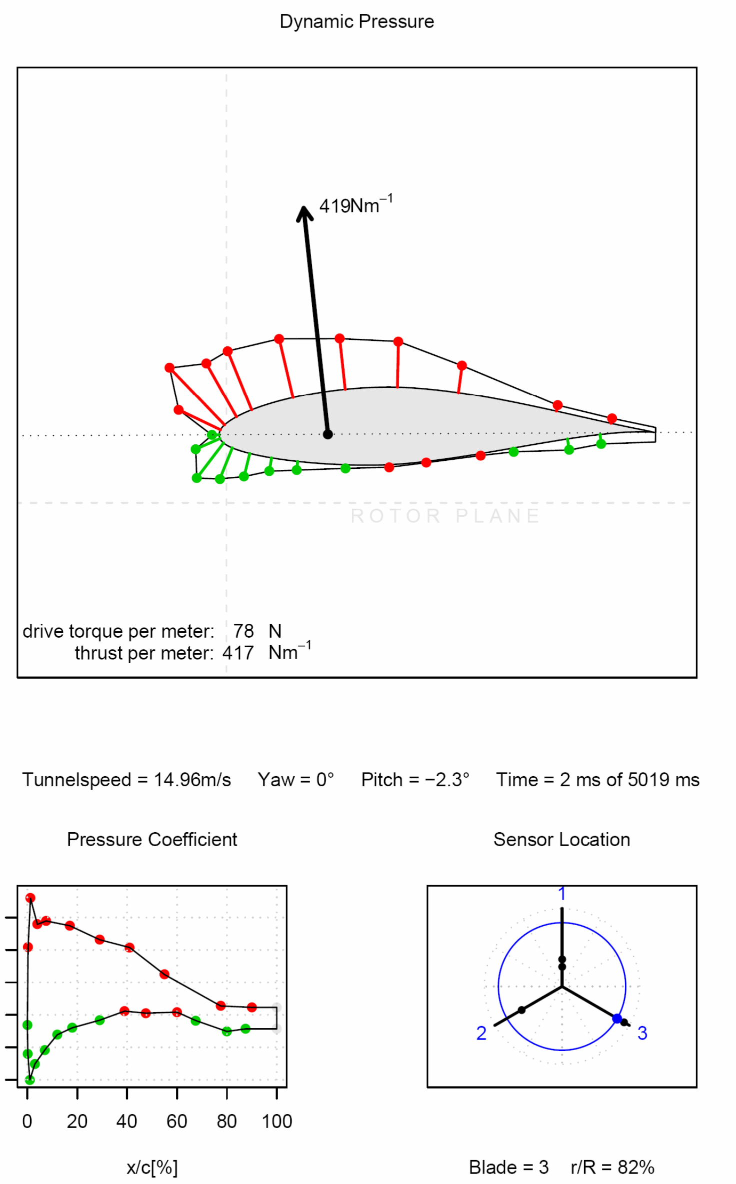
1) ϕ_{blade} =0, i.e. blade is vertically upward,

2) Measurements points averaged over the length of a PIV sheet

Strange behaviour at .61 R is the result of vortical structures shed from the blade at a slightly inboard position, For x>3m results get close to expectation again

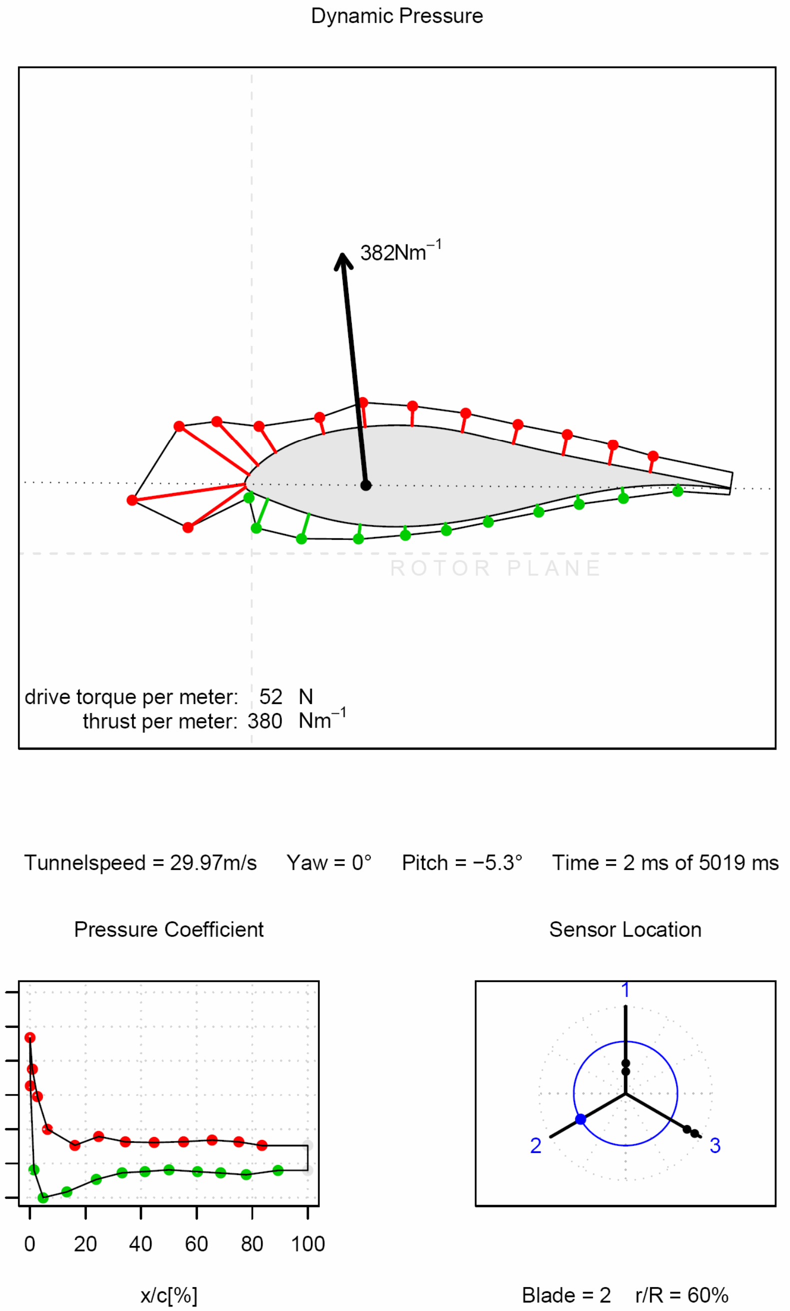
[1]) H. Snel and J.G. Schepers:
Joint Investigation of Dynamic Inflow Effects and Implementation of an Engineering Method, ECN-C-94-107, 1994

Animation of pressure distribution over 5 seconds sampled with 5.5 kHz;
Design conditions: V_{tun} = 15 m/s and θ = -2.3 degrees
Stable flow conditions around airfoil



Courtesy to S. Barth

Animation of pressure distribution over 5 seconds sampled with 5.5 kHz;
Stalled conditions: V_{tun} = 30 m/s
and θ = -5.3 degrees:
Unstable flow conditions around airfoil



Conclusions from Mexico project

- Very large, useful and consistent database with measurements to validate and/or improve design and analysis models
- Analysis of data should (obviously) be done but it needs years of work
- An IEA Wind Task 'MexNext' is urgently needed:
  - Activities should be 'task shared'
  - Forum for discussion, interpretation, explanation

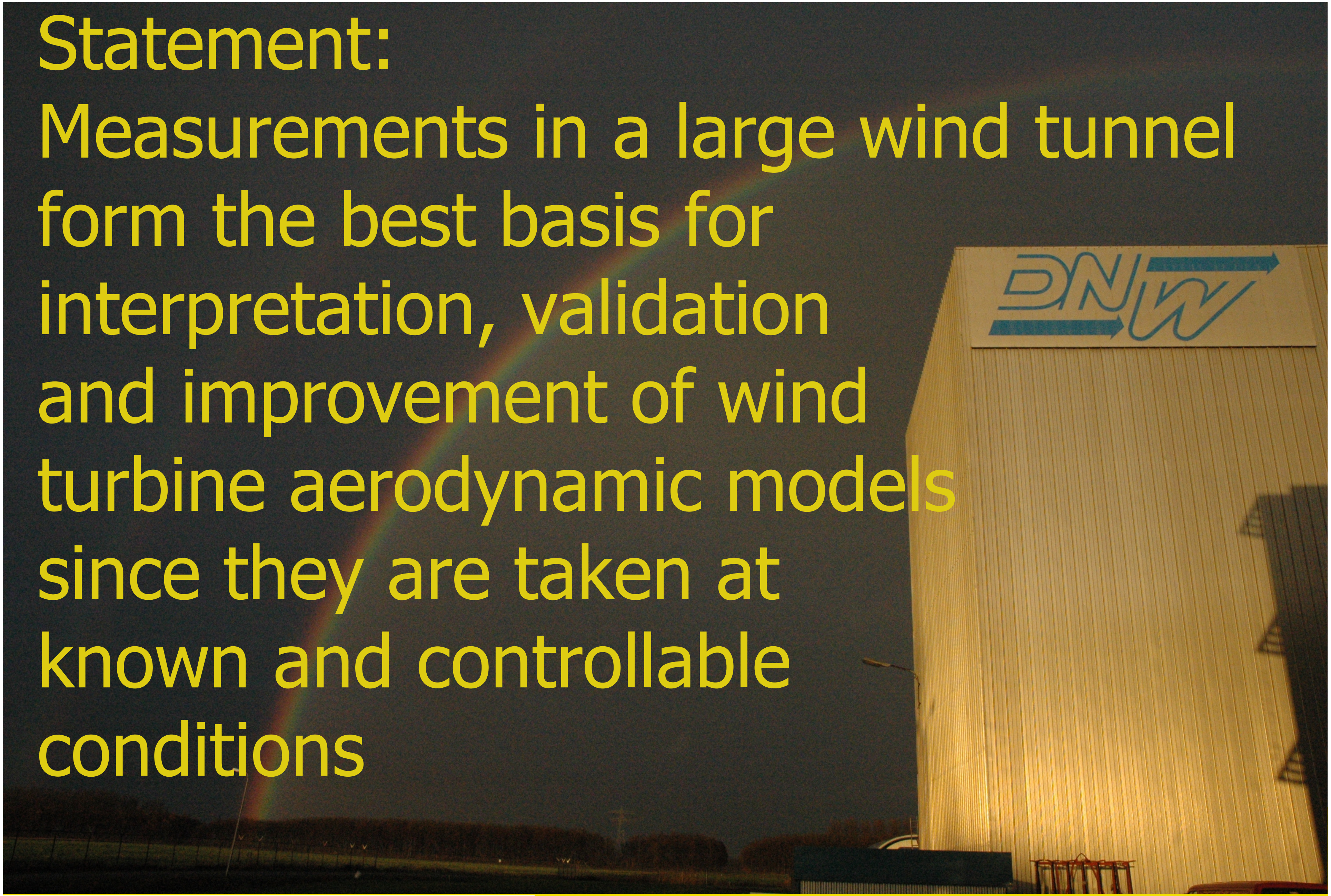
MexNext: Goal and Results

- Project Period: June 1, 2008-June 1, 2011
- Goal: A joint effort in which the Mexico measurements (together with the previously made NASA-Ames measurements) are evaluated.
- Validated and improved aerodynamic models:
    - General BEM modelling
    - Free vortex wake models
    - CFD blade flow and near wake flow
    - Yawed flow models
    - Dynamic Inflow models
    - Instationary airfoil aerodynamics
    - General inflow modelling (non-uniformity between blades)
    - 3D models (including tip effects)
- Results (i.e. the insights on accuracy of different models, and the recommendations/descriptions for model improvement) will be made public

MexNext: Potential participants

- Interest from the following research institutes from 12 different countries:
  - Canada (École de technologie supérieur, Montreal (ETS))
  - Denmark(RISØ-DTU and DTU(MEK))
  - Germany(University of Stuttgart (IAG), University of Applied Sciences, Kiel, ForWind)
  - Israel (Technion)
  - Japan (Mie University/National Institute of Advanced Industrial Science (AIST))
  - Korea((Korea Institute of Energy Research (Kier))
  - Netherlands(ECN, University of Delft (TUDelft))
  - Norway (Institute for Energy Technology/Norwegian University of Science and Technology (IFE/NTNU))
  - Spain(CENER, together with the (UK!) University of Liverpool)
  - Sweden(Royal Institute of Technology/University of Gotland (KTH,HGO))
  - Switzerland ((Swiss Federal Technical University Zurich (ETH))
  - USA (NREL)
- Industrial interest from LM-Glassfibre (Dk) and AE-Rotortechniek (NL, part of Suzlon)

BUT many participants still need to secure funding


Statement:
Measurements in a large wind tunnel form the best basis for interpretation, validation and improvement of wind turbine aerodynamic models since they are taken at known and controllable conditions
DNW

TUDelft

DUWIND

SenterNovem

ECN
Energy research Centre of the Netherlands

Knowledge Centre WMC

Extreme load extrapolation

J. M. Peeringa

Content

1. Extreme loads in IEC 61400-1 edition 3
2. We@Sea project on extreme loads
3. Preliminary results
4. Conclusions
5. Discussion

Statistical model

The long-term response distribution is the integration of the short-term response distribution, conditional on the wind speed (and turbulence), over all wind speeds.

$$F(L)_{long-term} = \iint_{V,T} \left(1 - F_{short-term}(L \mid V,T)\right) f(V,T)\,\mathrm{d}V\mathrm{d}T$$

$$\mathrm{f}(v,t)_{env} = \mathrm{f}(v)_{wind} * \mathrm{f}(t \mid v)_{turb}$$

Practice IEC 61400-1 edition 3 Annex F

- Long-term wind speed distribution is Weibull
- For every wind bin ΔVj a number of simulations are performed
- For every wind bin a short-term distribution is estimated using the maxima from the time series
- The longterm load distribution is the Weibull weighted summation of the short-term distributions found for every wind bin.
- Probability 50-year load is 3.8×10^{-7}

Summation long-term load distribution

$$P_e(F) = \sum_j \left(1 - \left(F_{\max}\left(F \middle| V_j\right)\right)^{n_j}\right)\left(e^{-\pi\left(\frac{V_j - \Delta V_j/2}{2V_{ave}}\right)^2} - e^{-\pi\left(\frac{V_j + \Delta V_j/2}{2V_{ave}}\right)^2}\right)$$

Empirical short-term distribution

wind [m/s]	Weibull
10.0	0.0728
11.0	0.0668
12.0	0.0596
13.0	0.0520
14.0	0.0443
15.0	0.0369
16.0	0.0300
17.0	0.0240
18.0	0.0187
19.0	0.0143
20.0	0.0107
21.0	0.0079
22.0	0.0057
23.0	0.0040
24.0	0.0028
25.0	0.0019

$$F(x(i)) = \Pr\{X \le x(i)\} = \frac{i}{n+1}$$

$$\Pr(X \ge x(i)) = 1 - F(x(i)) \approx 1.0e-6$$

We@Sea project

- Aim is validation of extreme value models by comparing extreme loads based on measurements and calculations.

Work packages

- WP 1 ECN Extreme value based on 10-minute simulation
- WP 2 TU-Delft Extreme value based on constrained simulation

How?

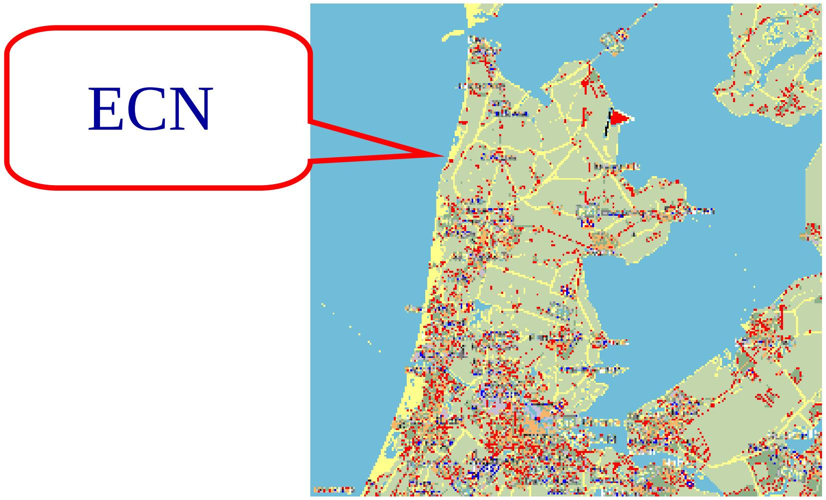
- Select three wind bins (below, near and above rated wind speed) for free stream, partial wake and wake conditions
- Aero-elastic (PHATAS) model of wind turbine
- Comparison short-term distribution

wake?	(Alle)

Aantal van t6_mbf1_load_avg	stdvV_bin						
Vbin	0.25	0.75	1.25	1.75	2.25	2.75	Eindtotaal
3	25	20	1				46
4	143	77	3				223
5	159	133	12	1			305
6	145	183	24	5	1		358
7	92	285	53	10	2		442
8	39	255	84	9	1		388
9	9	105	90	4	1	1	210
10		61	88	14	1		164
11		10	83	19			112
12		2	44	19	1		66
13		1	18	3			22
14			1				1
Eindtotaal	612	1132	501	84	7	1	2337

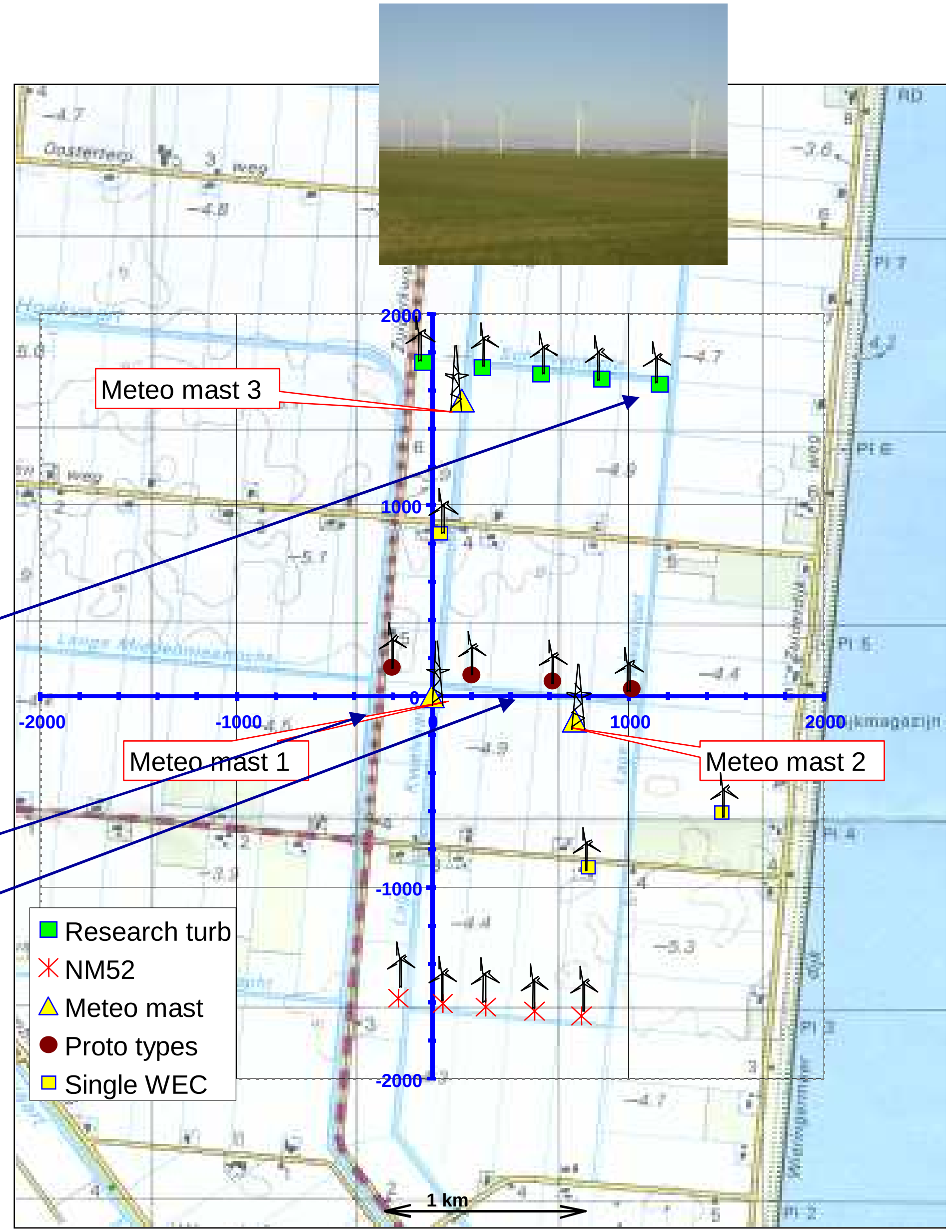
ECN approach

- Keep the existing software (Gumbel, 3-p Weibull and random process)
- Add Block Maxima
- Add L-moment estimate for Gumbel, 3-p Weibull, Log normal, GEV and GPD
- Add confidence limits (bootstrap)
- Prepare graphical plots for checking
- Goodness of fit test

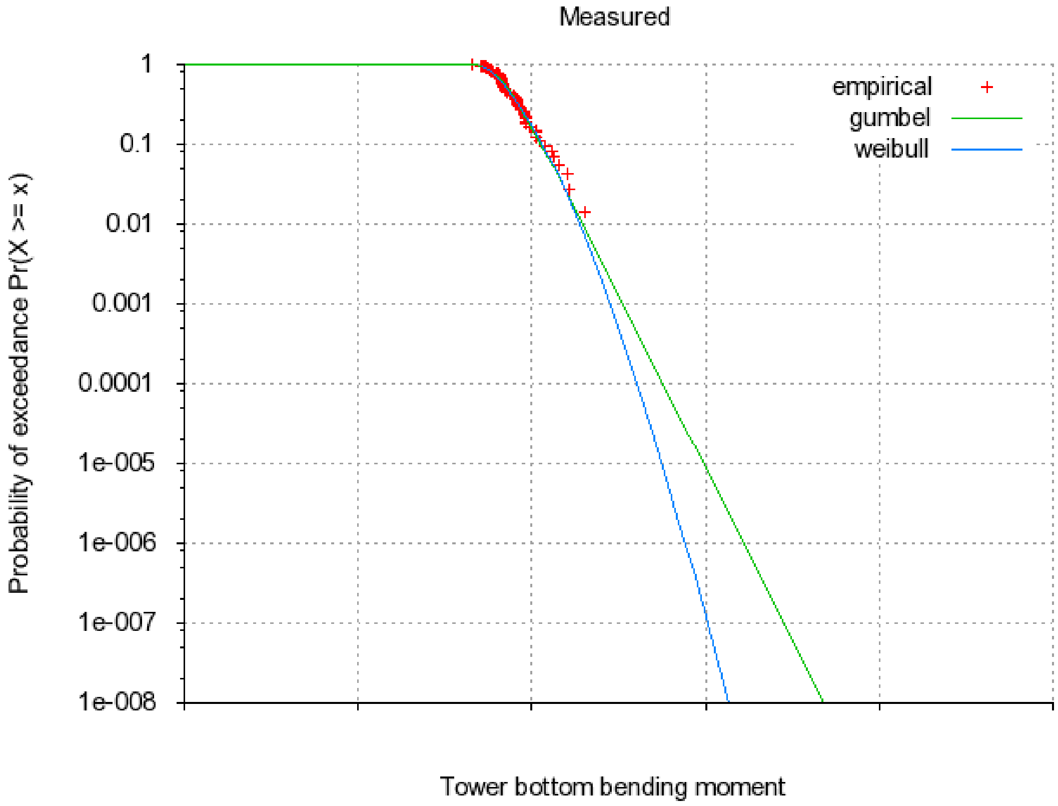


ECN Wind Turbine Test Farm Wieringermeer (EWTW)

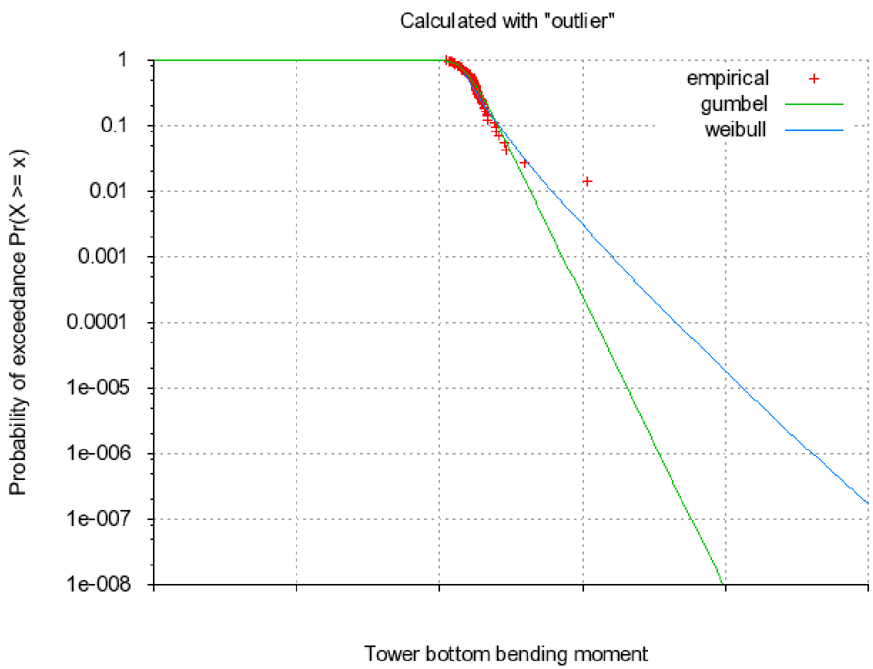
- Two rows:
  - Five **research** turbines with one 108m high meteorological mast (mm3)
  - Four **prototype** turbines with two 108m high meteorological masts (mm1 and mm2)
  - Scaled farm
- Measurement Infrastructure
- Measurement Pavilion

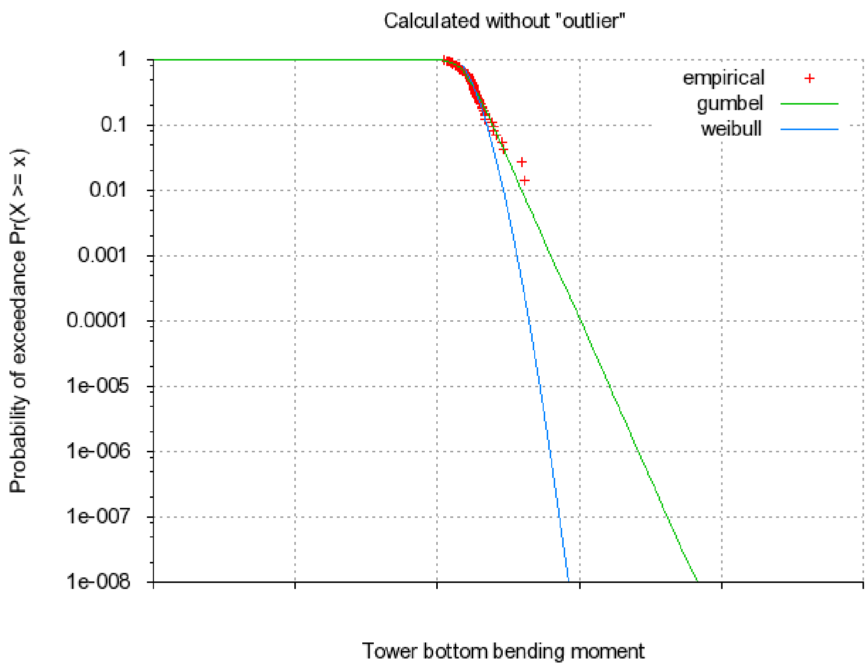


Measured short-term distributions

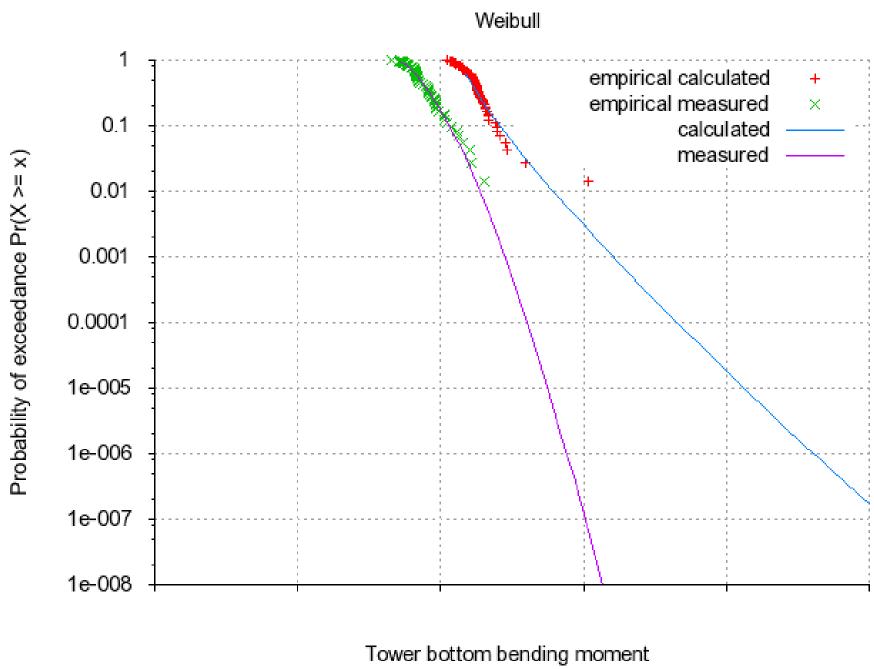


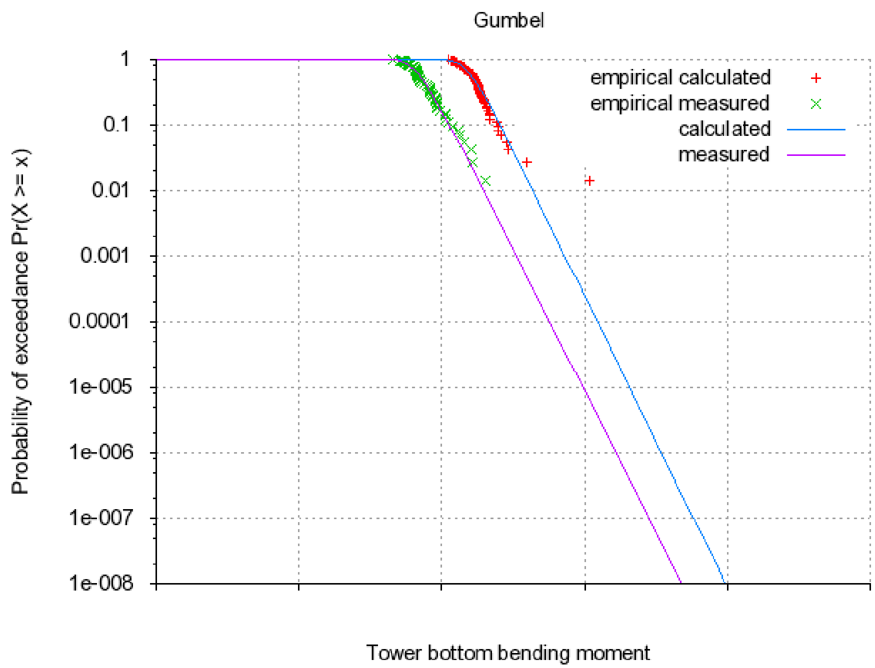
Calculated short-term distribution





Comparison of measurements and calculations





Conclusions

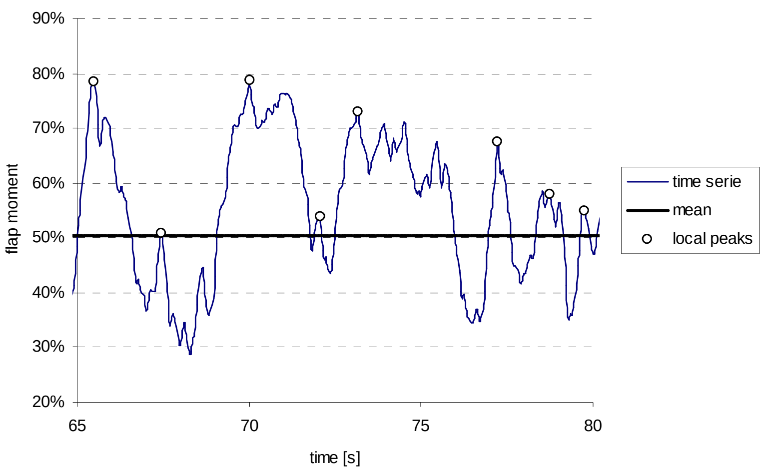
- The quality of the data used should be checked.
- Extreme value models are needed since the probability is beyond the probability observed in the empirical distributions.
- Tools like graphical plots, goodness of fit test or confidence intervals, are needed to identify the best extreme value model.

Question?

- Is there a physical explanation for using the Weibull distribution?

Short-term distributions should be defined in rules like the Rayleigh distribution for wind speed. For instance:

- Global data – Generalized Extreme Value
- Block maxima– Generalized Extreme Value
- Peak over threshold (POT) – Generalized Pareto



TUDelft

DUWIND

SenterNovem

ECN
Energy research Centre of the Netherlands

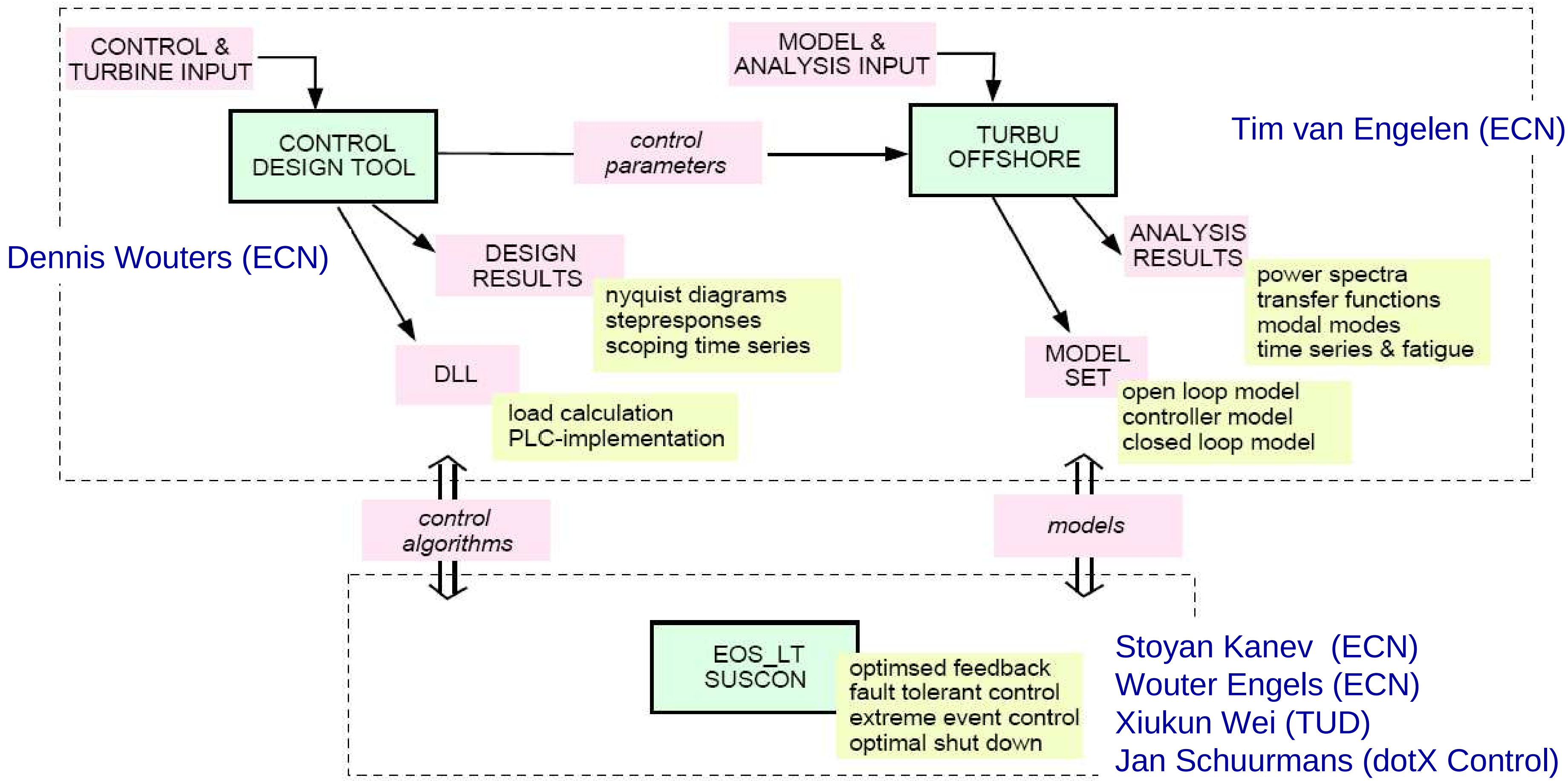
Knowledge Centre WMC

Tools for Wind Turbine Control

Tim van Engelen, Dennis Wouters

CONTENTS

SCOPE


CONTROL & TURBINE INPUT
MODEL & ANALYSIS INPUT
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control parameters
TURBU OFFSHORE
Tim van Engelen (ECN)
Dennis Wouters (ECN)
DESIGN RESULTS
nyquist diagrams
stepresponses
scoping time series
ANALYSIS RESULTS
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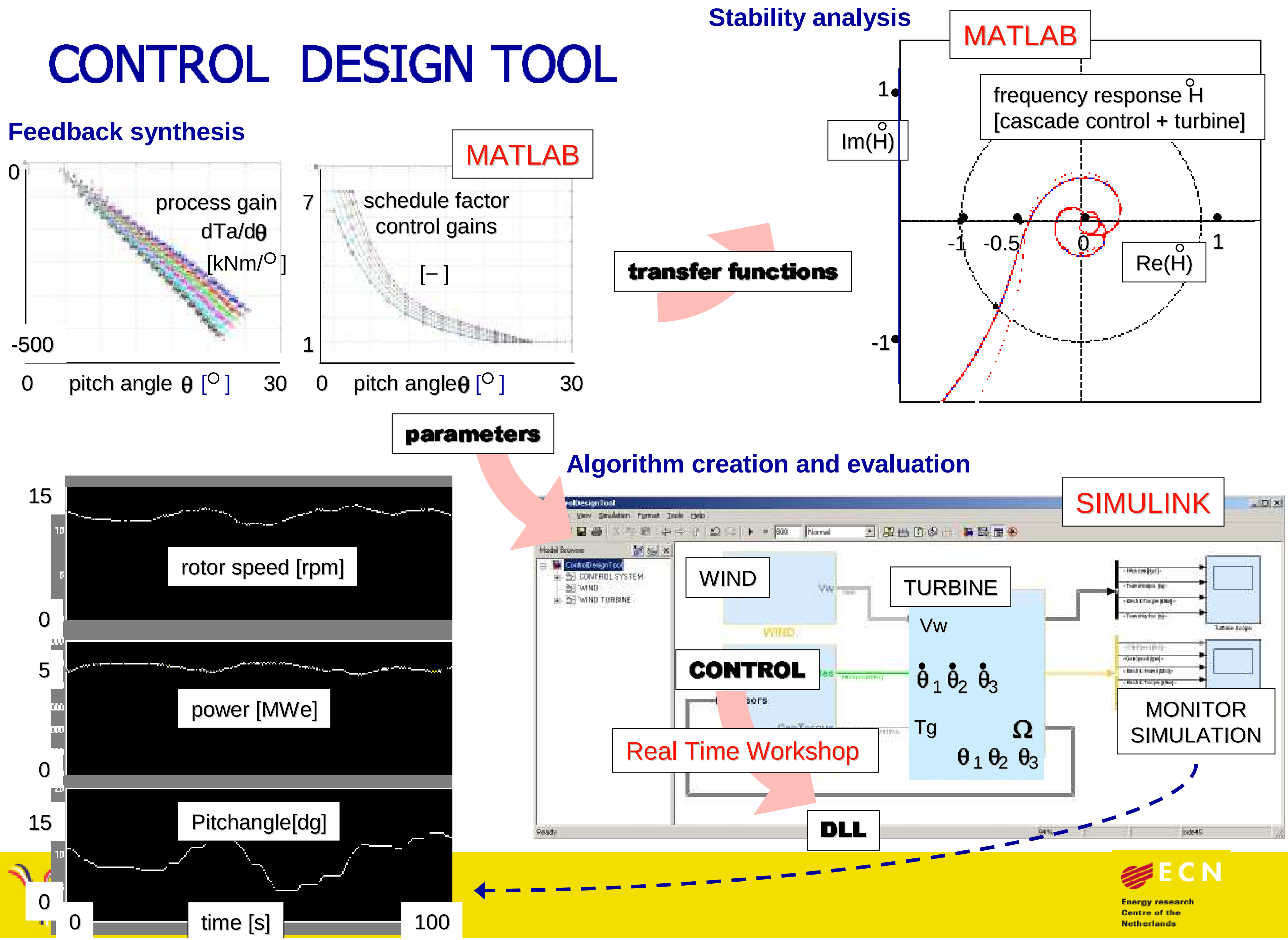
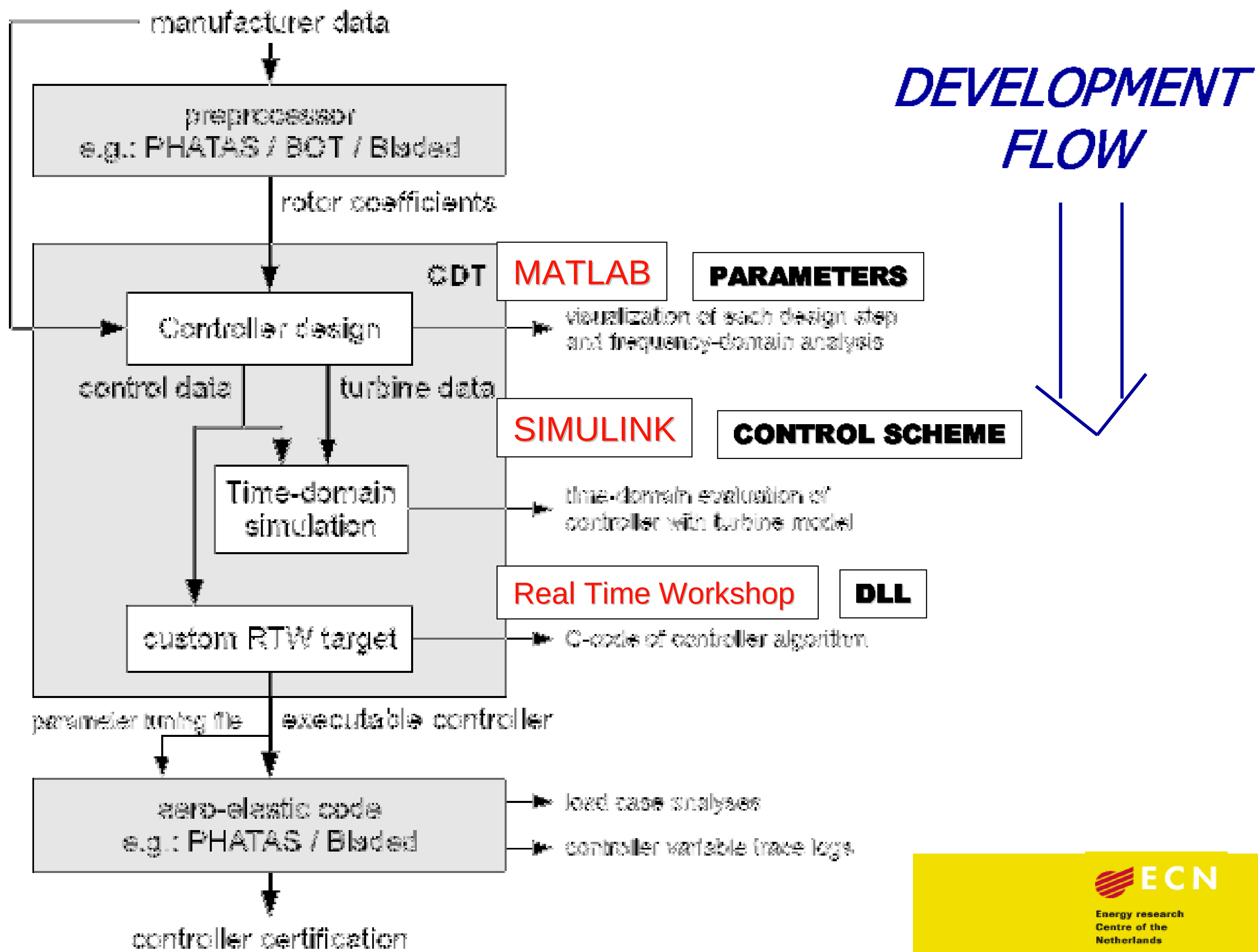
fault tolerant control
extreme event control
optimal shut down
Stoyan Kanev (ECN)
Wouter Engels (ECN)
Xiukun Wei (TUD)
Jan Schuurmans (dotX Control)

CONTROL DESIGN TOOL

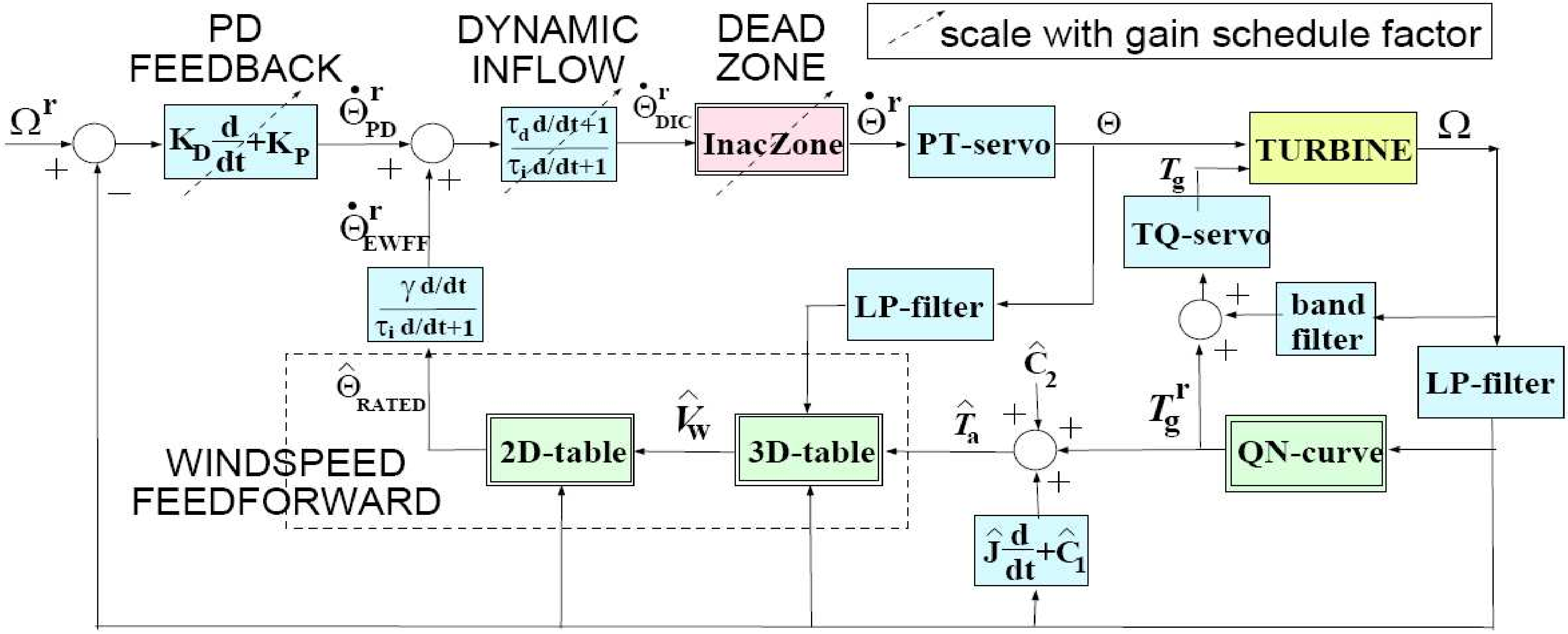


CONTROL DESIGN TOOL



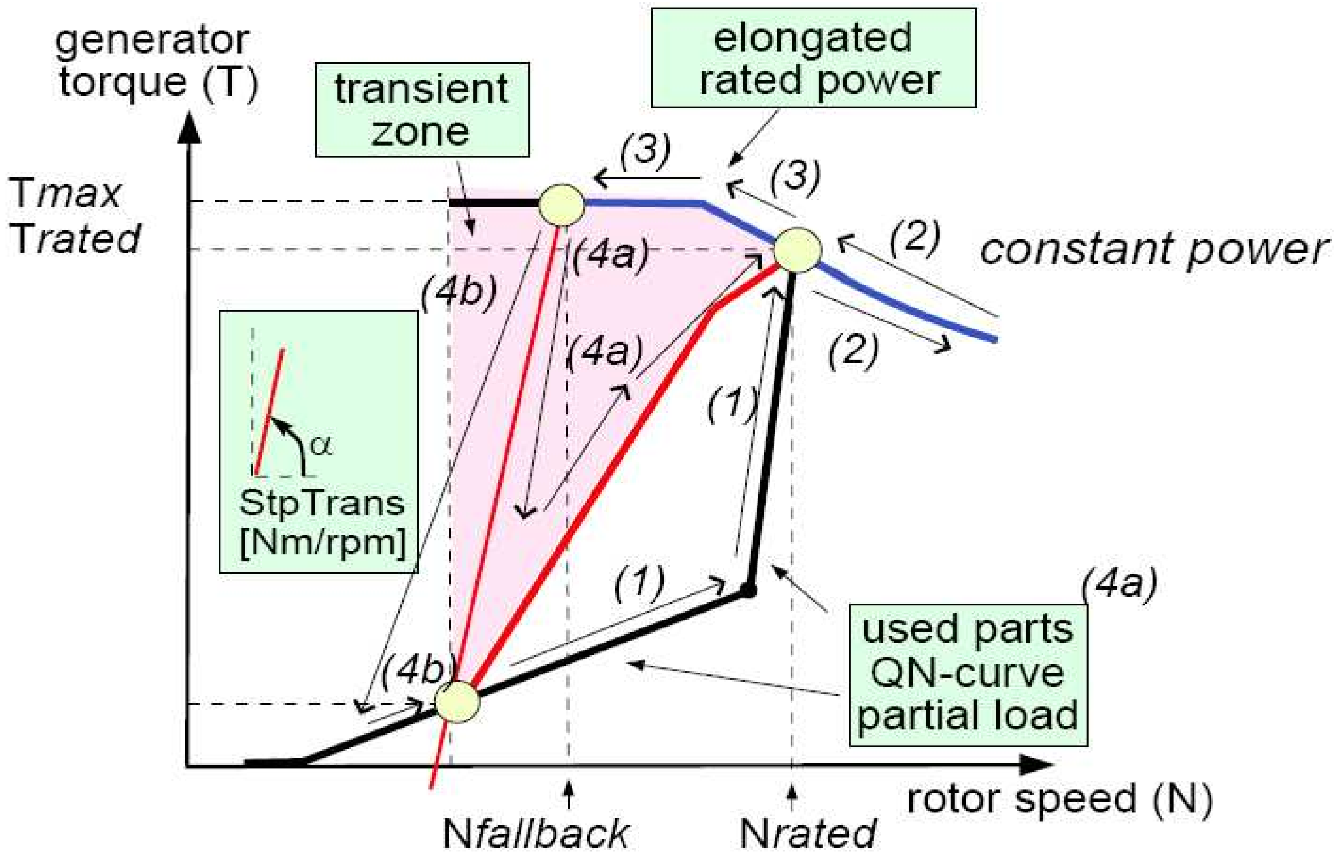
CONTROL DESIGN TOOL

Pitch Setting



CONTROL DESIGN TOOL

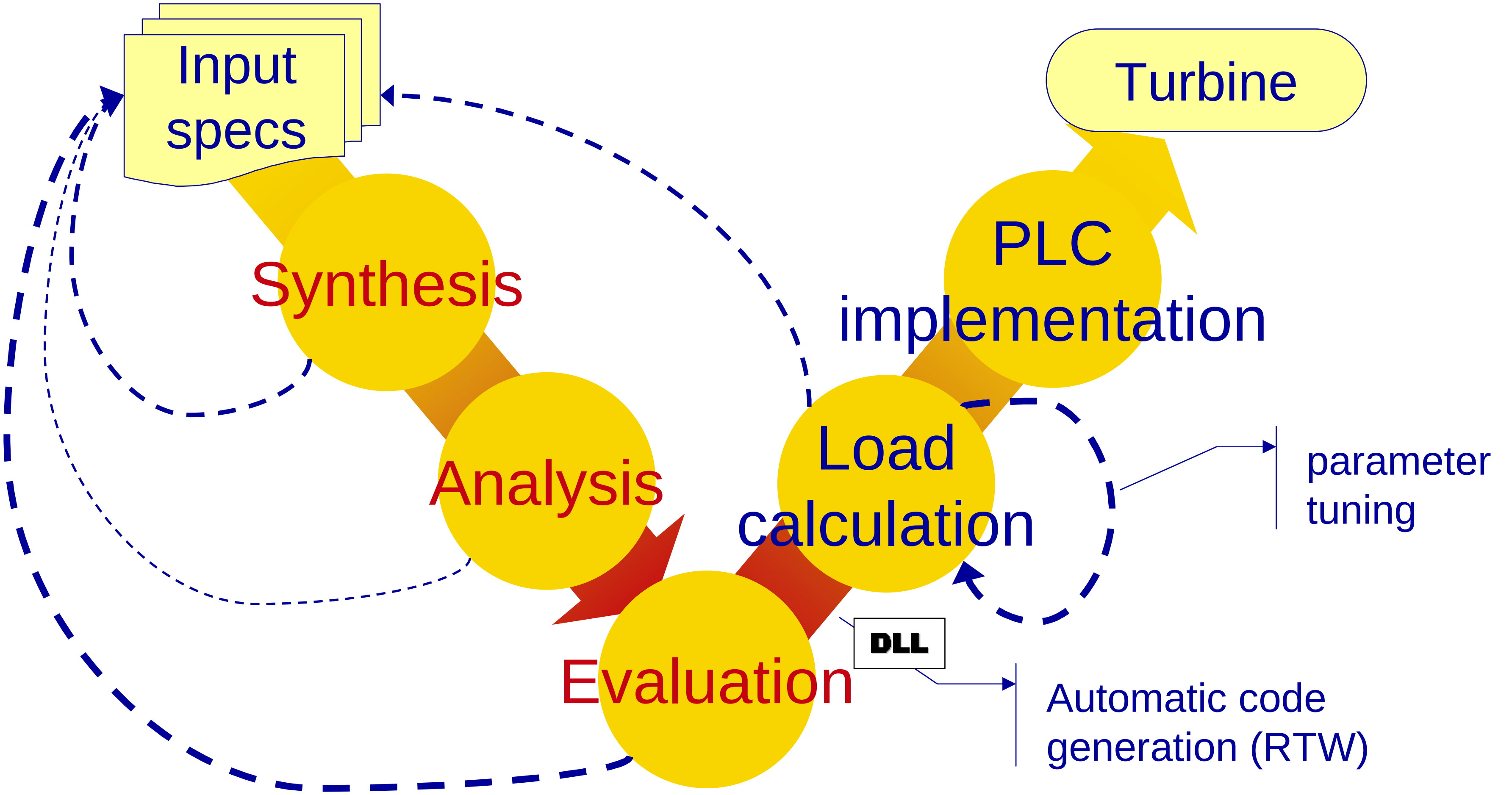
Torque Setting



CONTROL DESIGN TOOL

Design iteration

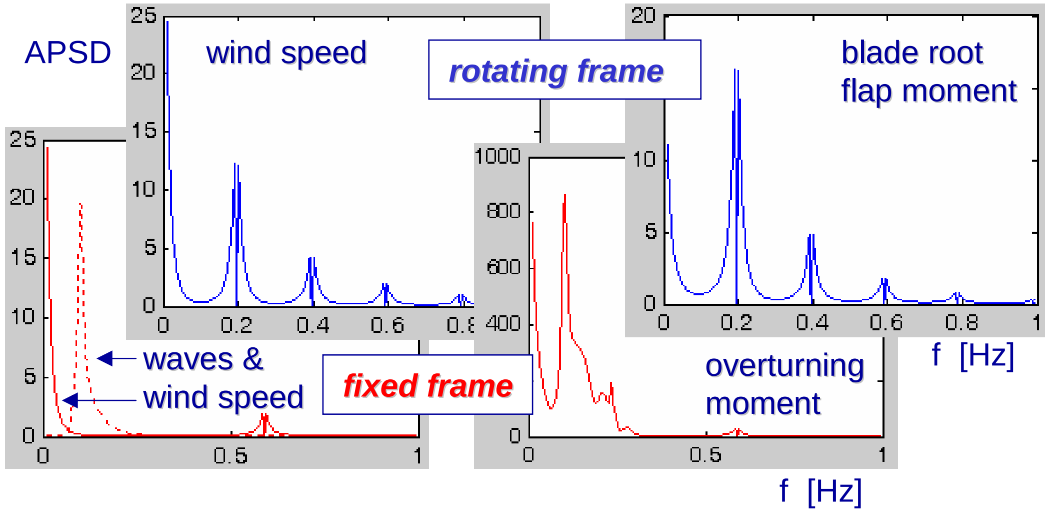
Early and fast iterations



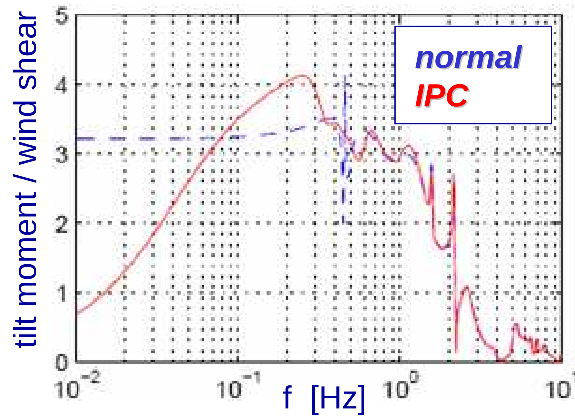
TURBU OFFSHORE

MATLAB

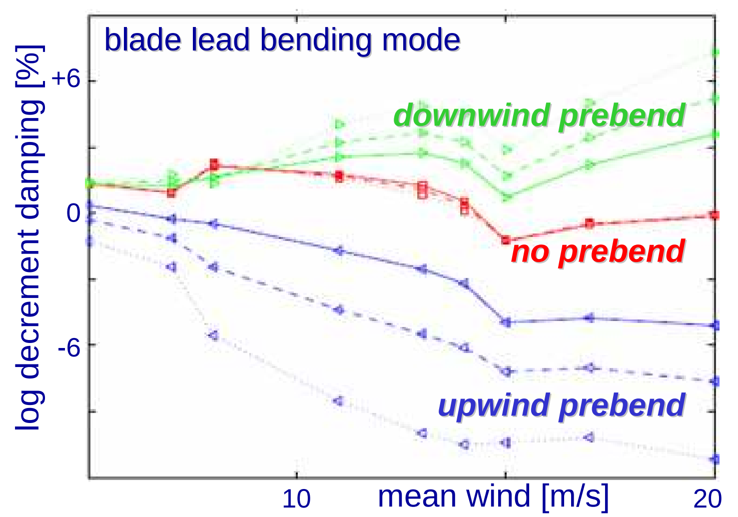
Frequency domain loads for foot-print and fatigue



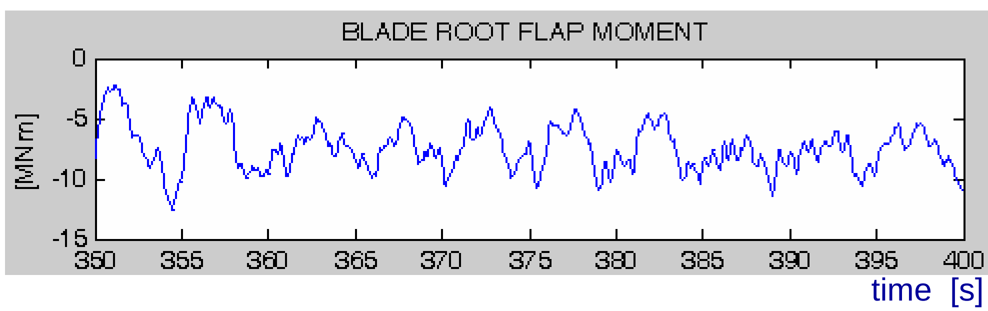
Transfer functions for control



Eigenvalue analysis for aeroelastic stability

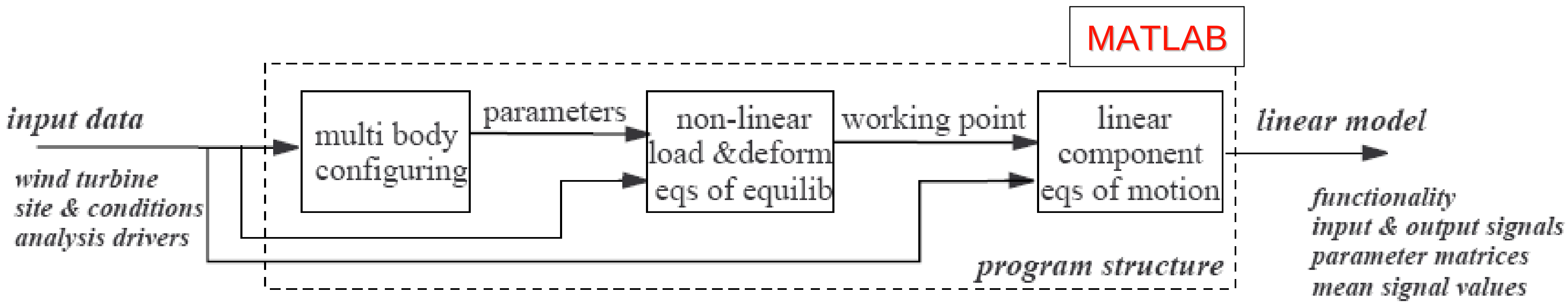


Structural linear co-simulation with advanced aerocode or linear full model



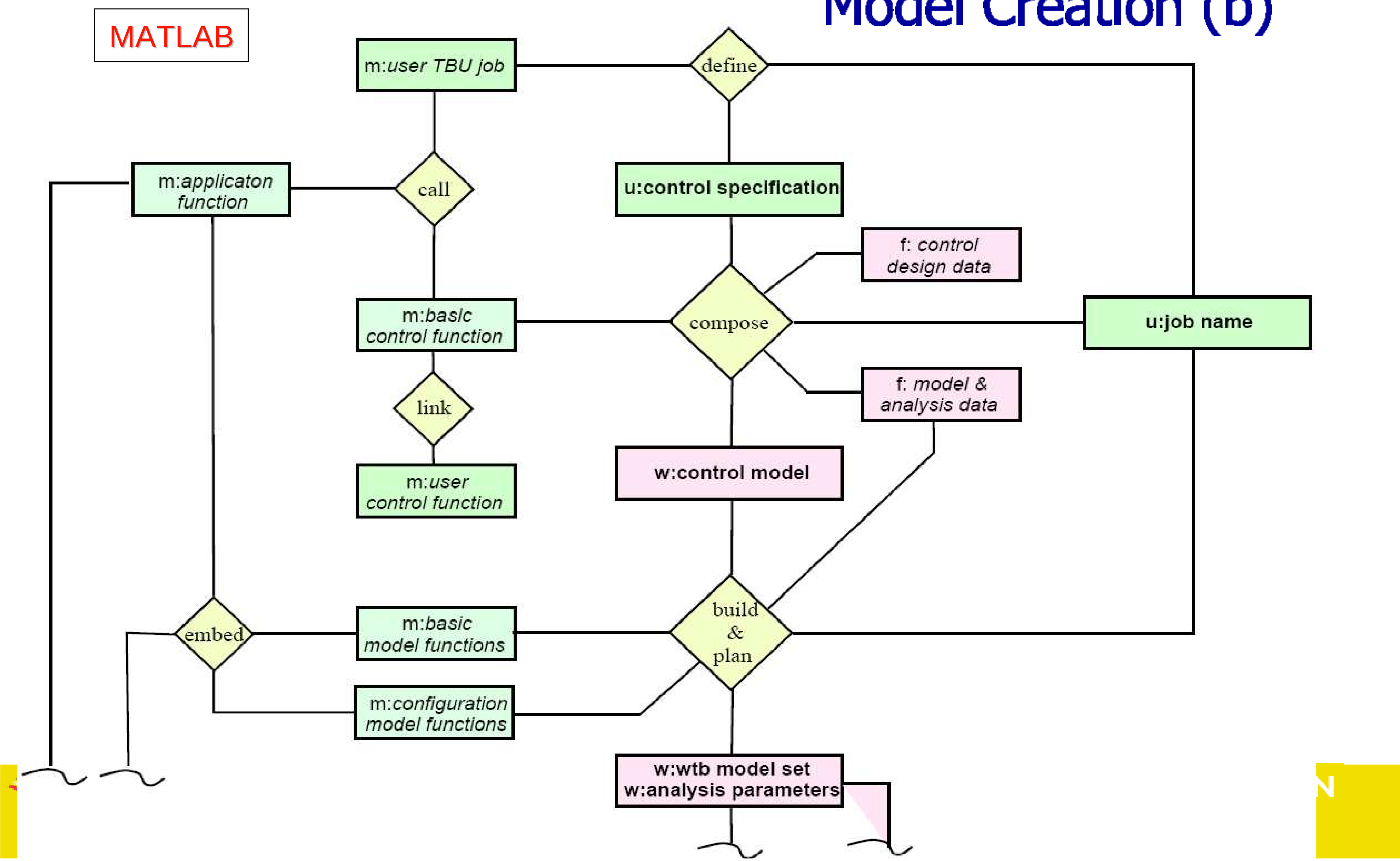
TURBU OFFSHORE

Model Creation (a)



TURBU OFFSHORE

Model Creation (b)



TURBU OFFSHORE

MATLAB

Model Properties

- Linear frequency and time domain analysis of 3-bladed HAWTs
- Time-invariant linear dynamic model (multi-body, Newton, Coleman)
- Full non-linear steady state model (multi-body average deformation)
- Wind and wave excitation (per element)
- Dynamic wake, unsteady aerodynamics
- Reduced order blade and tower models (Hurty [Craig-Bampton])

APPLICATION CLUSTER **FULL**

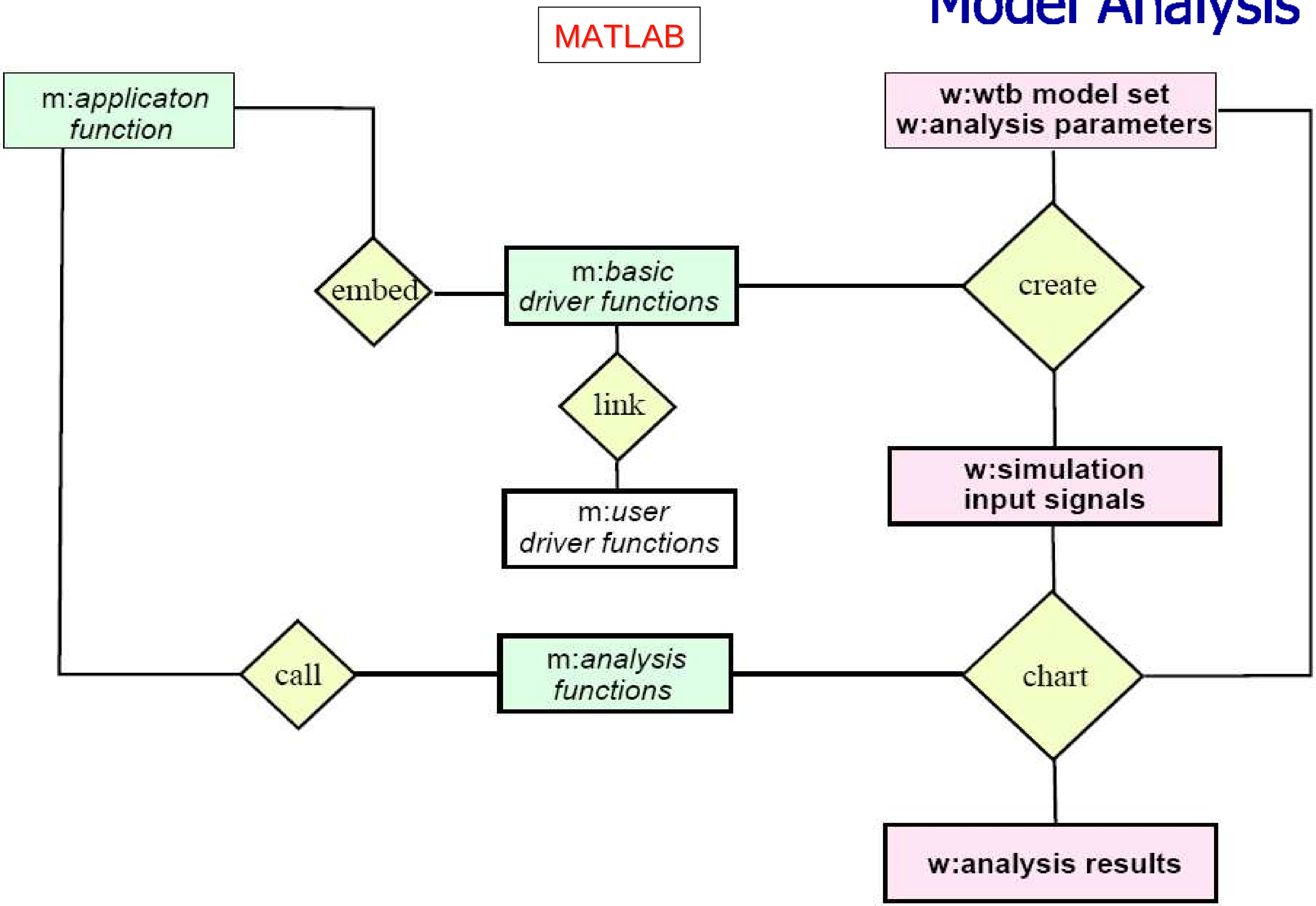
structural dynamics and
aero- & hydro-elastic interaction
for
control design & stability analysis,
(frequency domain load calculation)

APPLICATION CLUSTER **STRUC**

isolated
structural dynamics
for
co-simulation with aerodynamic code

TURBU OFFSHORE

Model Analysis



EOS-LT PROJECT SUSCON

Sustainable Control by

- Optimized Feedback Control
- Fault Tolerant Control
- Extreme Event Control
- Optimal Shutdown Control

Participants

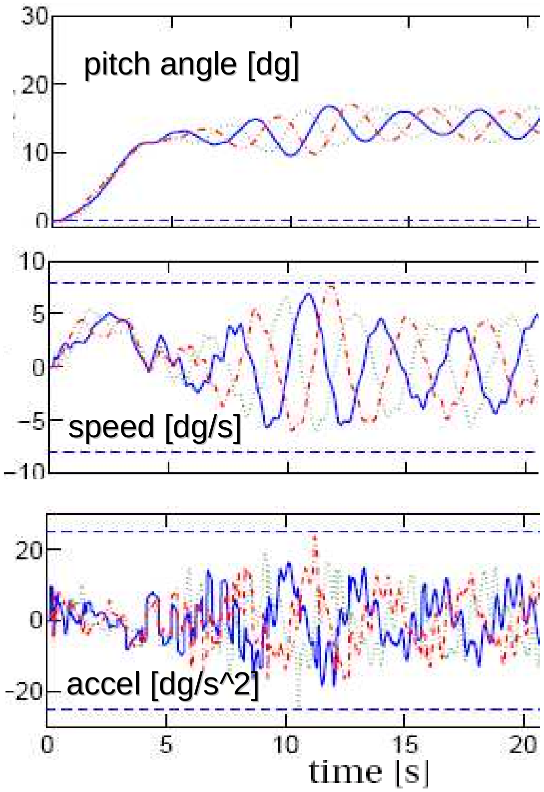
- ECN, TUD (research)
- Mitsubishi, Alstom Ecotecnia, Nordex (experiments)
- Garrad Hassan (steering, research)

SUSCON OPTIMIZED FEEDBACK CONTROL

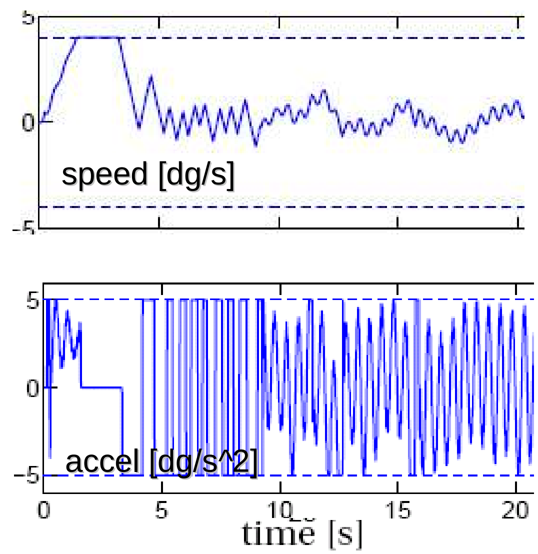
Individual pitch control & collective pitch

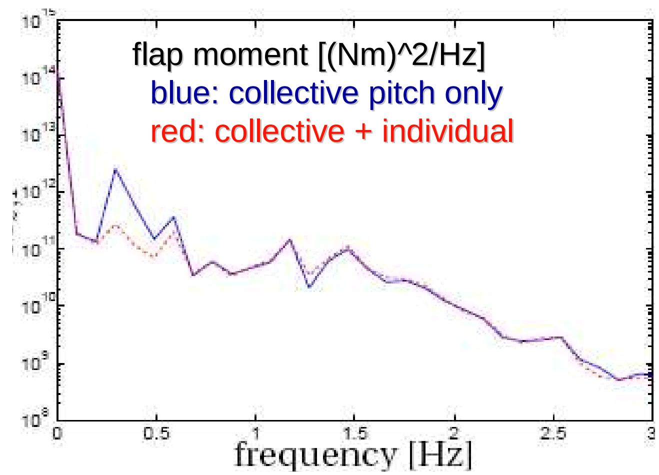
- specific limits collective, alltogether
- dynamic compensation rotor inbalance

collective + individual pitch actions



collective pitch fraction





courtesy Stoyan Kanev

ECN
Energy research Centre of the Netherlands

SUSCON FAULT TOLERANT CONTROL

jump error in flap moment sensor (2 x 3 sensors)

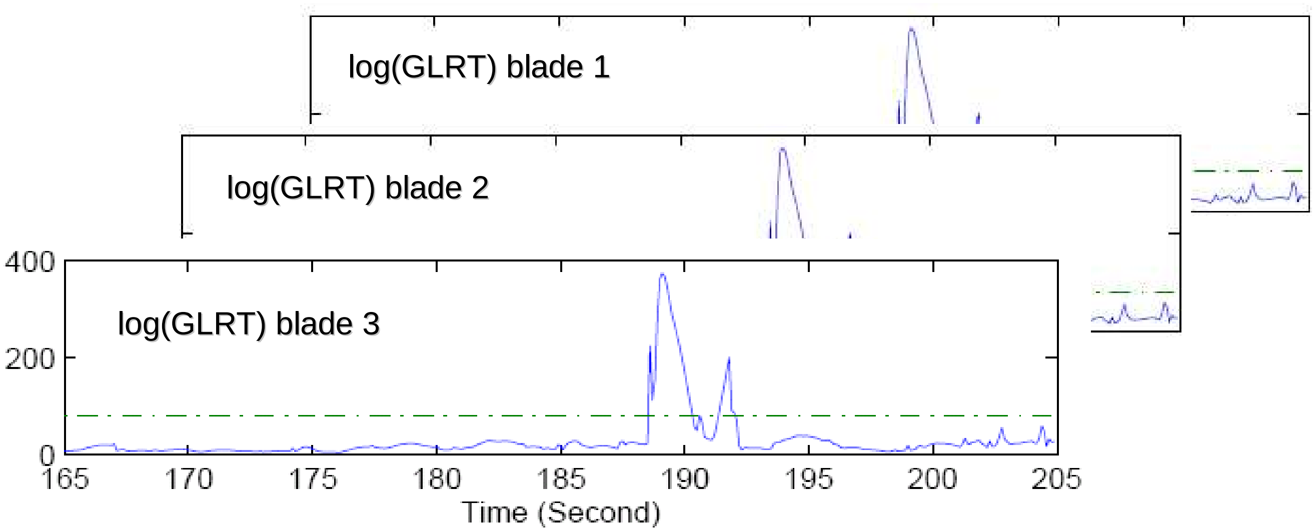
- detection by method of generalized likelihood ratio test (GLRT)

compute in each time point k the course over interval [k-L,k] of
upper limit of probability ratio yes/no
jump-error in flap moment sensor

GLRT-implementation uses
model in fixed-frame coordinates

Jump-error in ONE sensor detected in all 3 fixed-frame converted flap moment signals

isolation of specific sensor
by difference in sensor-pair



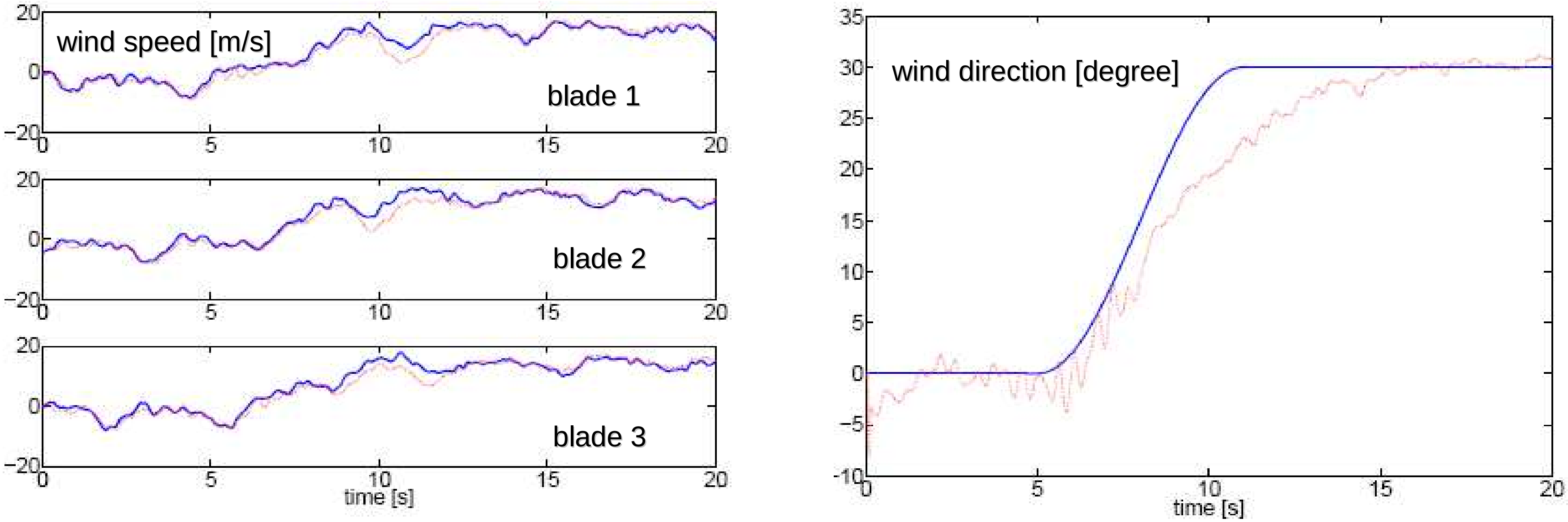
courtesy Xiukun Wei

SUSCON EXTREME EVENT CONTROL

blade effective wind speed and oblique inflow angle

•turbelence + gust on 3 blades, wind direction change EDC (IEC)

•estimation by extended Kalmanfilter



courtesy Stoyan Kanev

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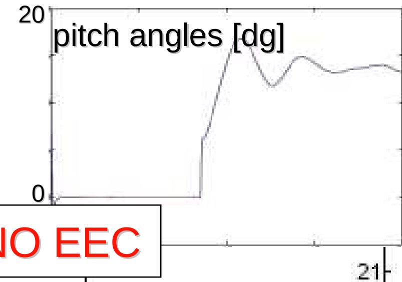
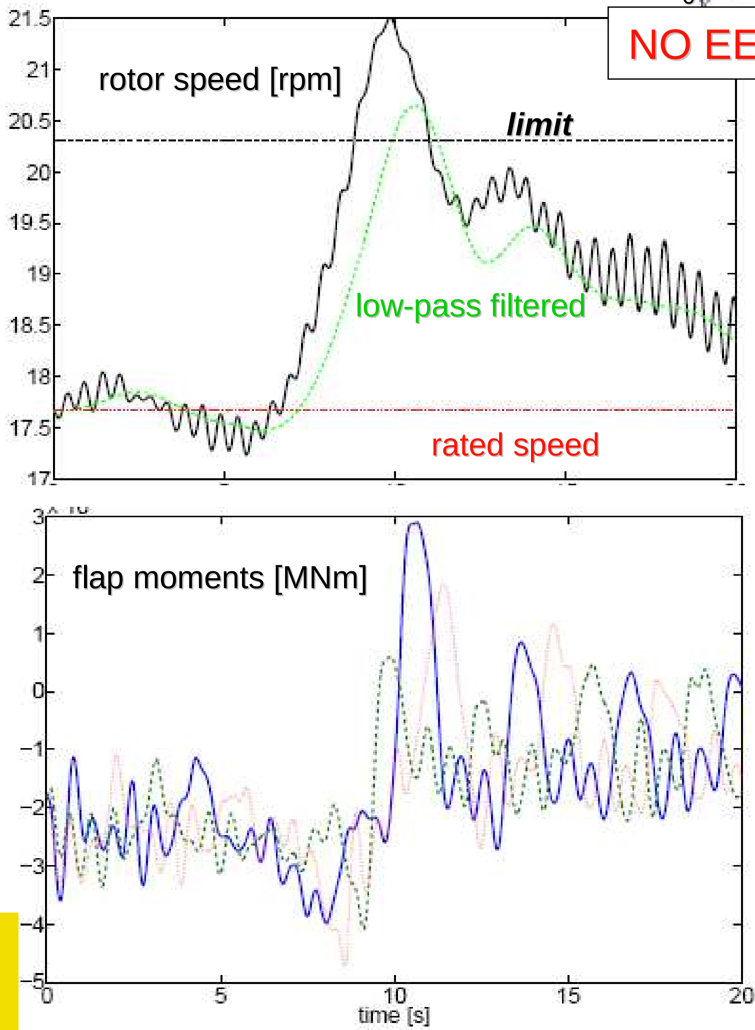
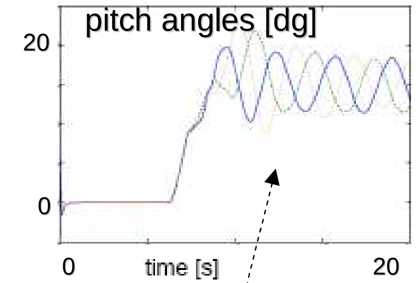
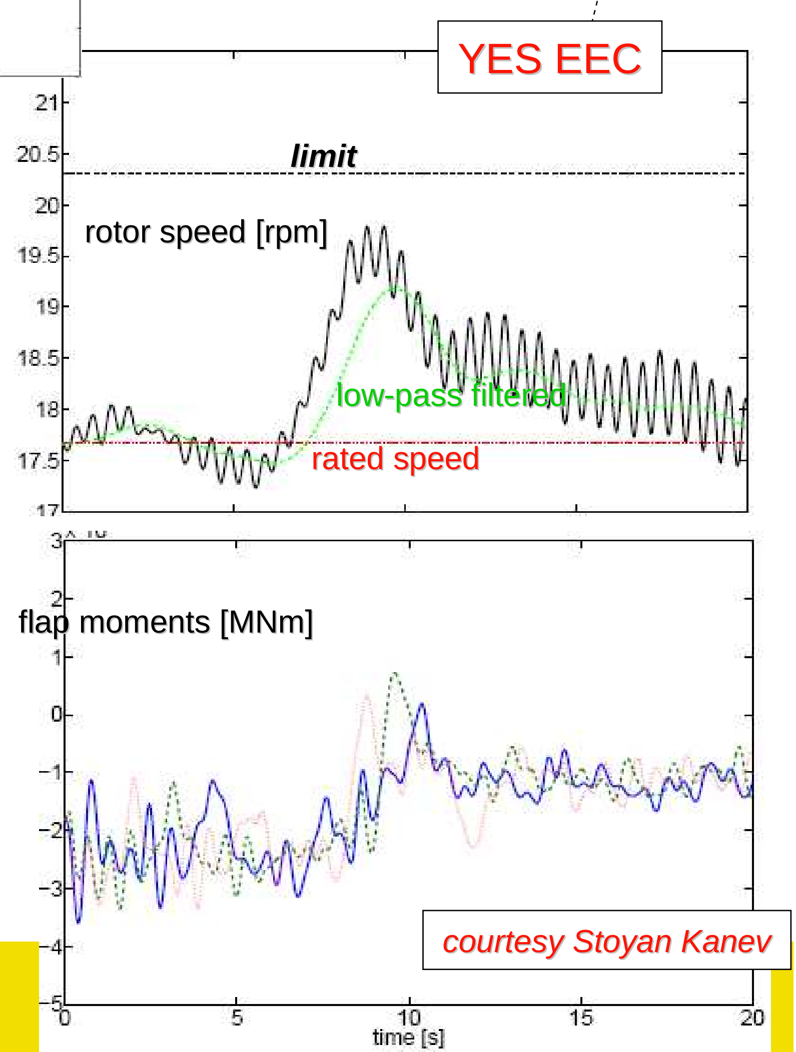
SUSCON EXTREME EVENT CONTROL

controlled behaviour



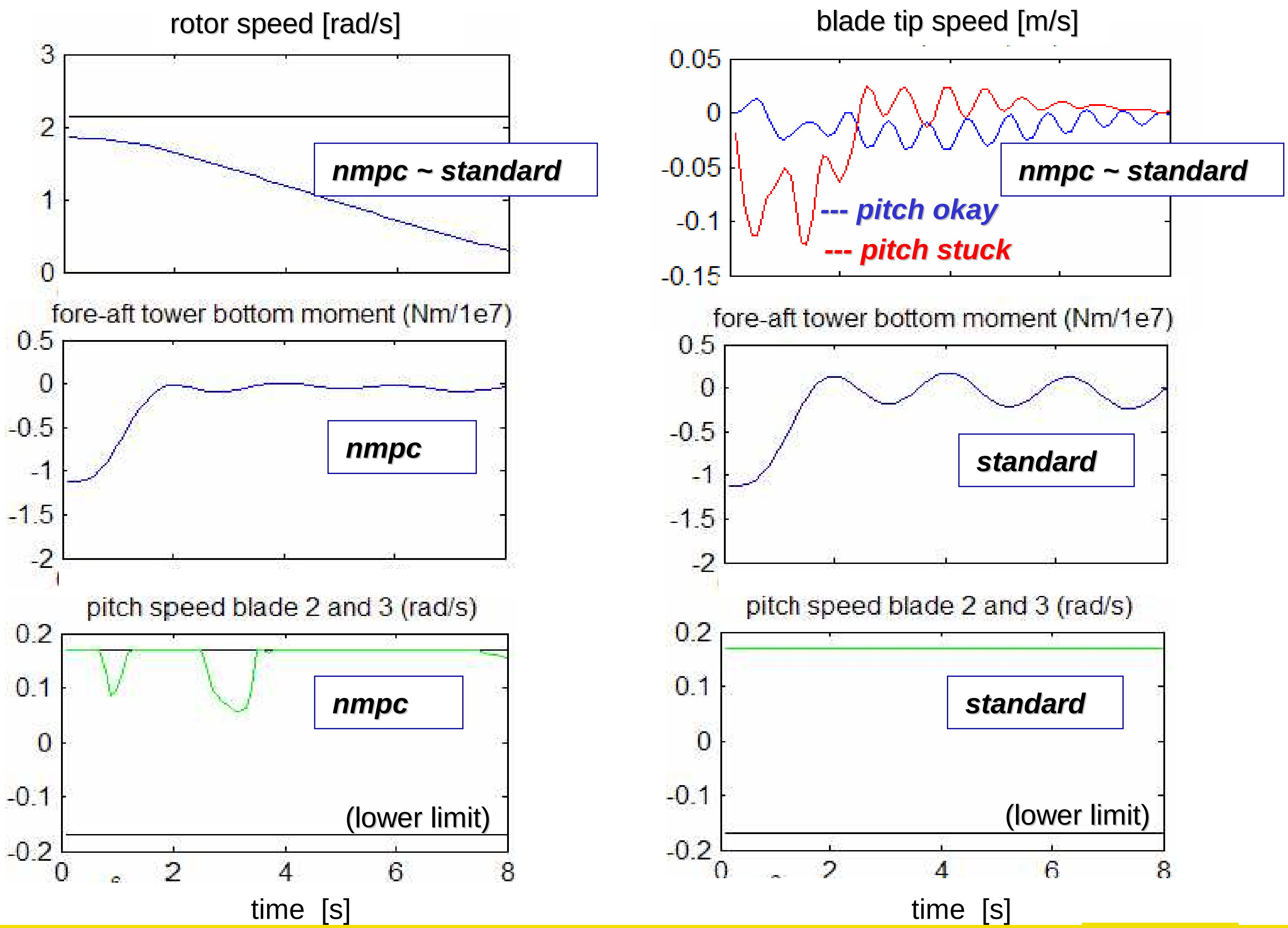






SUSCON OPTIMAL SHUT DOWN CONTROL

non-linear
model predictive
control
(nmpc)



courtesy Jan Schuurmans

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STATEMENTS

Control Design Tool gives an understanding of control & makes life easier

TURBU allows to do the control research you want

SUSUCON shows some promising new directions in control under realistic conditions

Aspiration

The ultimate challenge is to devise and control the 100 m diameter 100 MWth hydrogenoid generating grid-independent wind energy conversion plant (courtesy Santilli, Boyce, Bearden, Patterson, Schauberger)

TUDelft

DUWIND

SenterNovem

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Knowledge Centre WMC

EeFarm 2
A tool for Wind Farm electrical infrastructure optimization

J. Pierik

EeFarm 2:
what is it and what can it do?

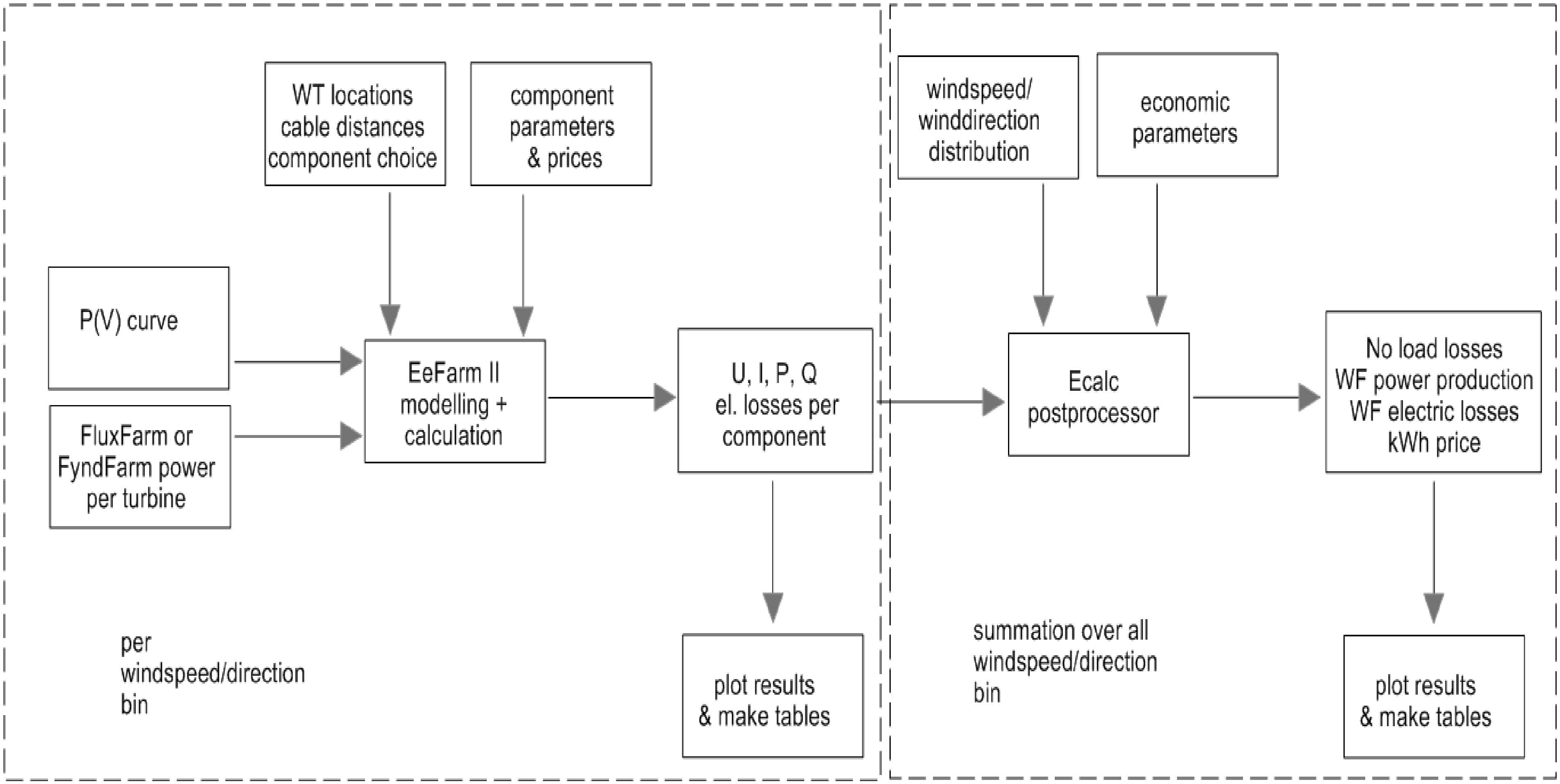
- easy to use program to calculate electrical infrastructure Offshore Wind Farms
- library of AC and DC component models
- database with component parameters and investment costs

- compare different electrical layouts
- determine best choice for a given wind farm area and distance to shore

EeFarm 2: method

- calculates voltage and current phasor
  for each component and
  each wind speed/direction bin
- calculates electrical losses, power production
- calculates effect of component non-availability
- calculates levelised production costs

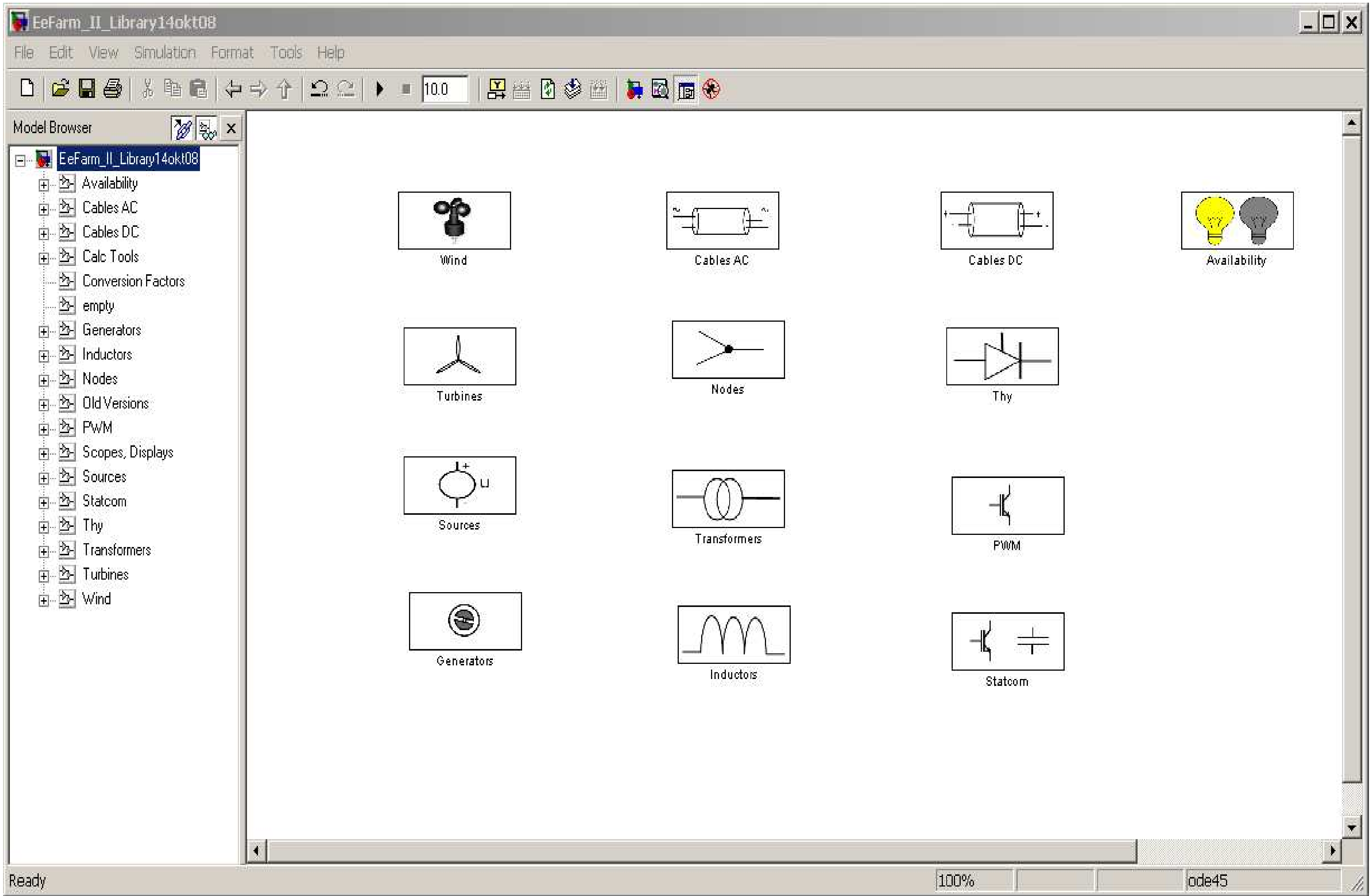
EeFarm 2 calculation steps



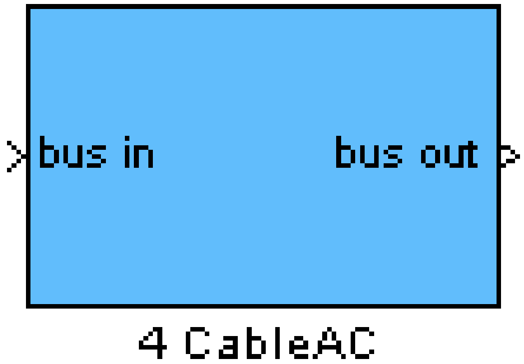
EeFarm 2 features

- reads standardised input from wind farm wake program, e.g. FluxFarm
  (power per wind speed/direction bin)
- AC or DC bus signal: connects components
  (makes connection almost fool-proof)
- parameter transfer by component mask
  different component types can use same model
- a single structure variable for all component parameters (only one call per component)
- standardized output processing
  m-files for plotting and tables

EeFarm 2 library

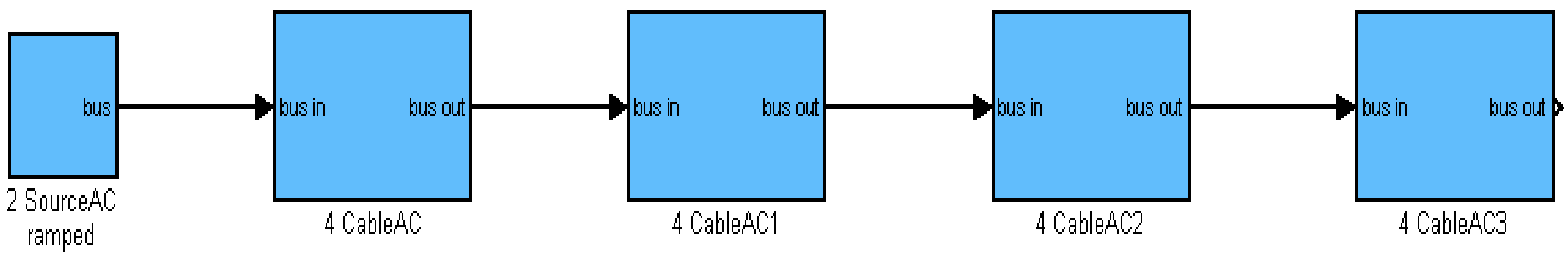


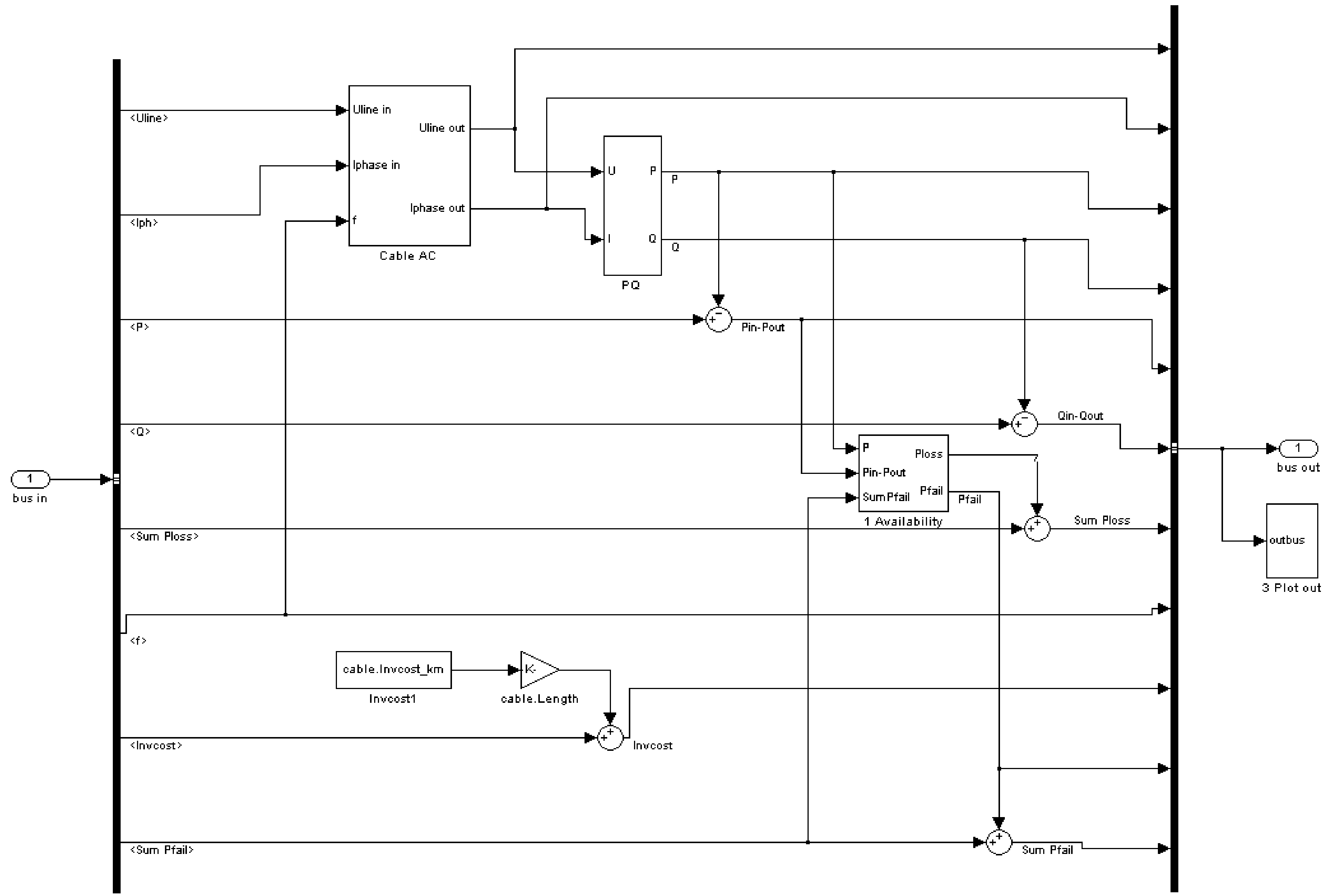
Component model



can only be connected in one way

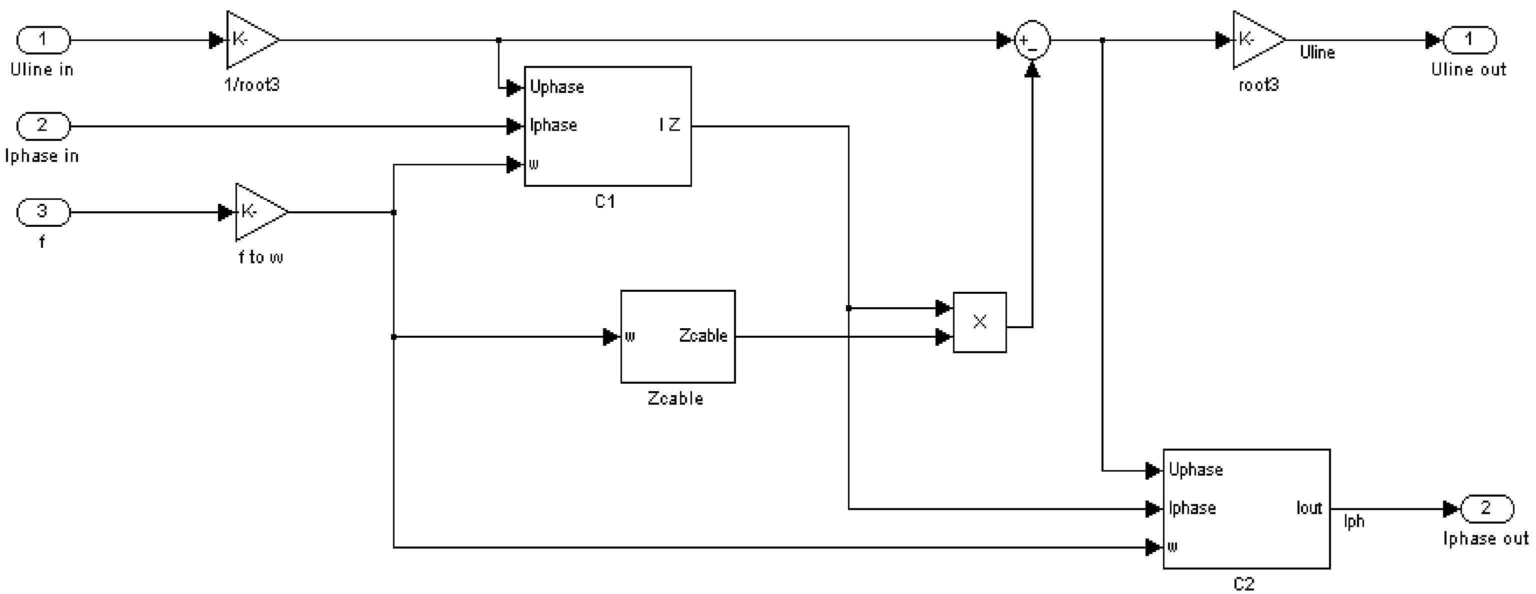
Connecting model blocks:




bus in
1
<Uline>
<Iph>
<P>
<Q>
<Sum Ploss>
<f>
<Invcost>
<Sum Pfail>
Uline in
Uline out
Iphase in
Iphase out
f
Cable AC
U
P
I
Q
PQ
P
Q
Pin-Pout
Qin-Qout
P
Ploss
Pin-Pout
Pfail
SumPfail
1 Availability
Pfail
Sum Ploss
cable.Invcost_km
Invcost1
K-
cable.Length
Invcost
Sum Pfail
1
bus out
outbus
3 Plot out

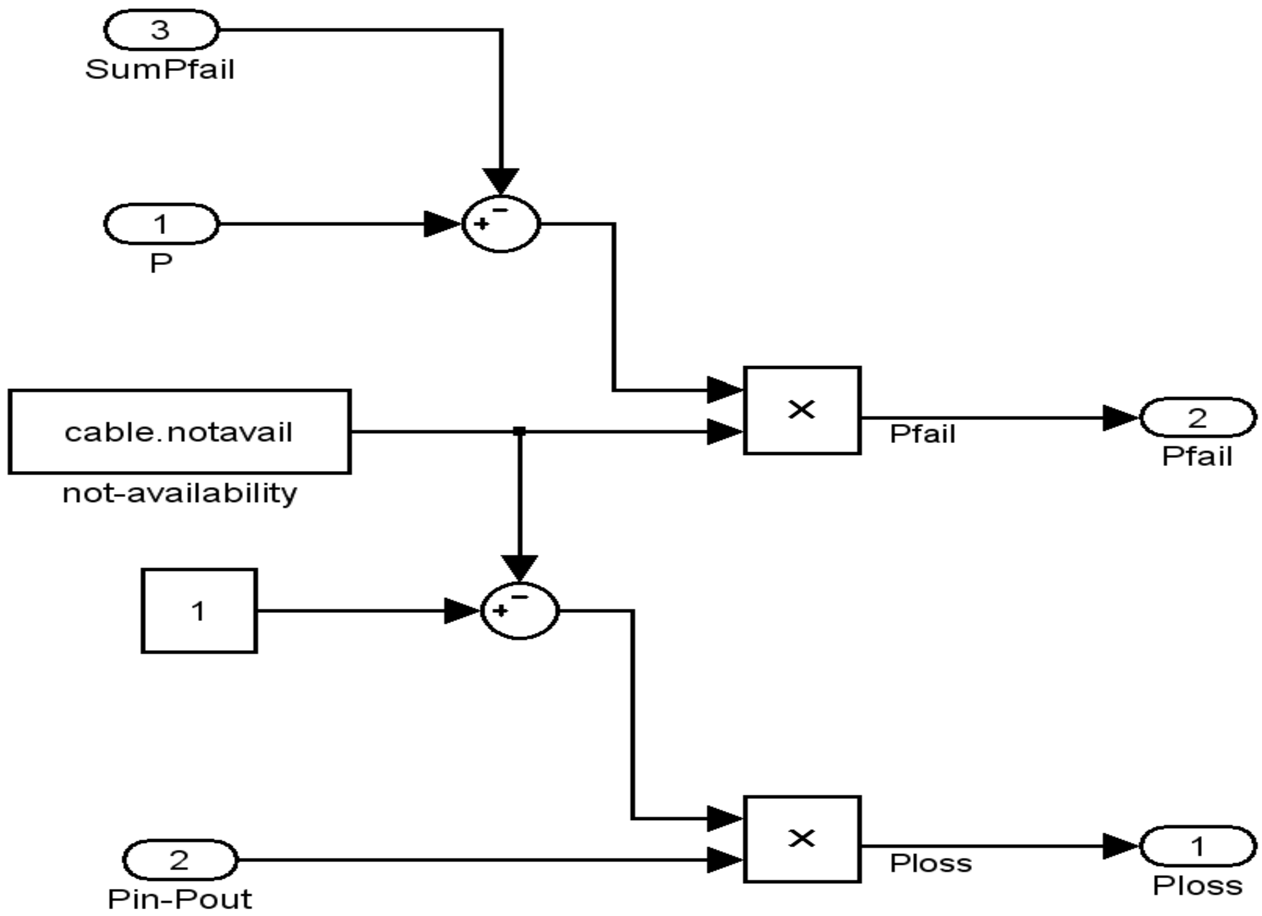
bus signals

Inside the AC cable model



standard pi-model (RLC)

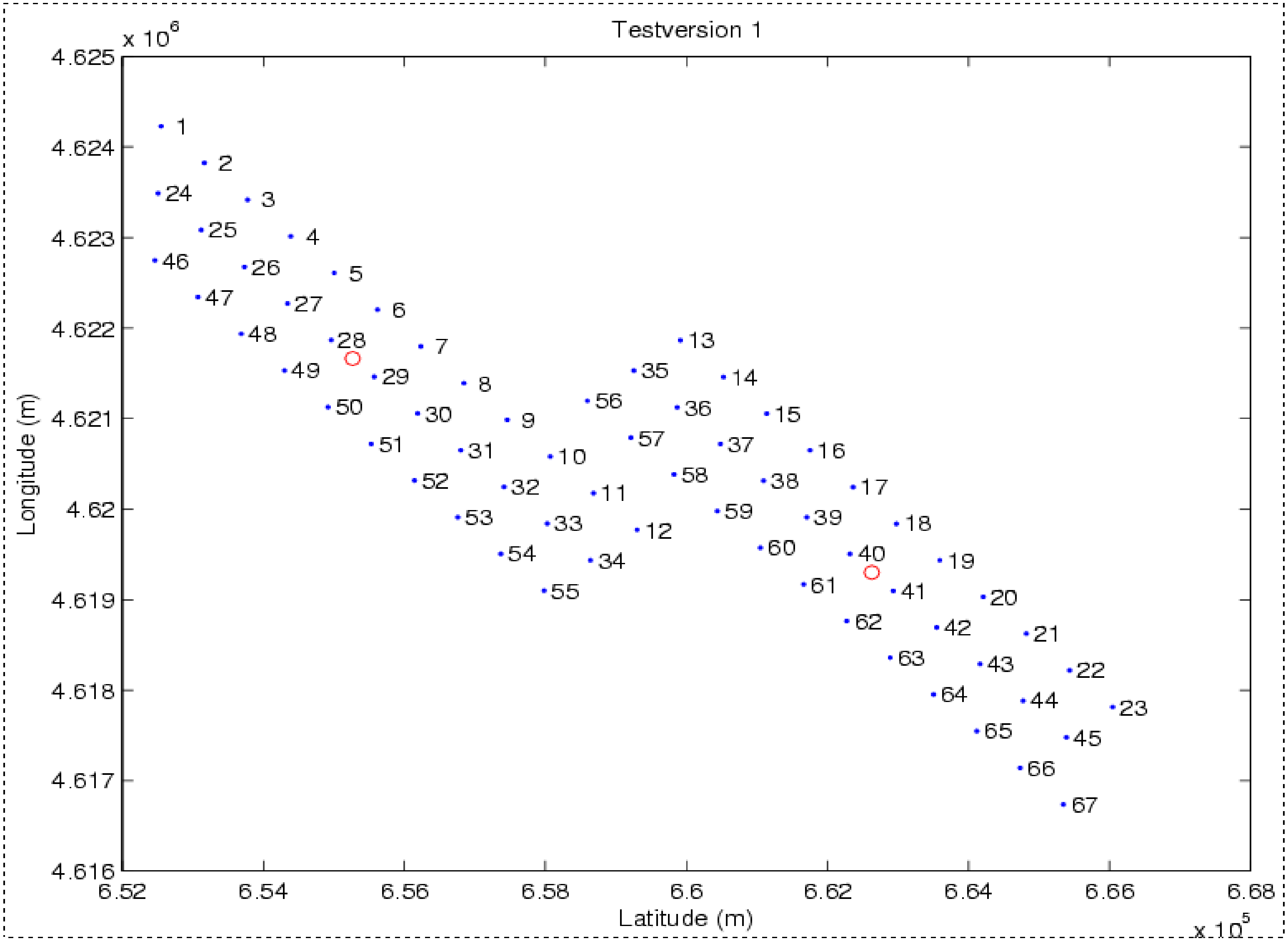
Component non-availability: effects upsteam power + power produced by component itself



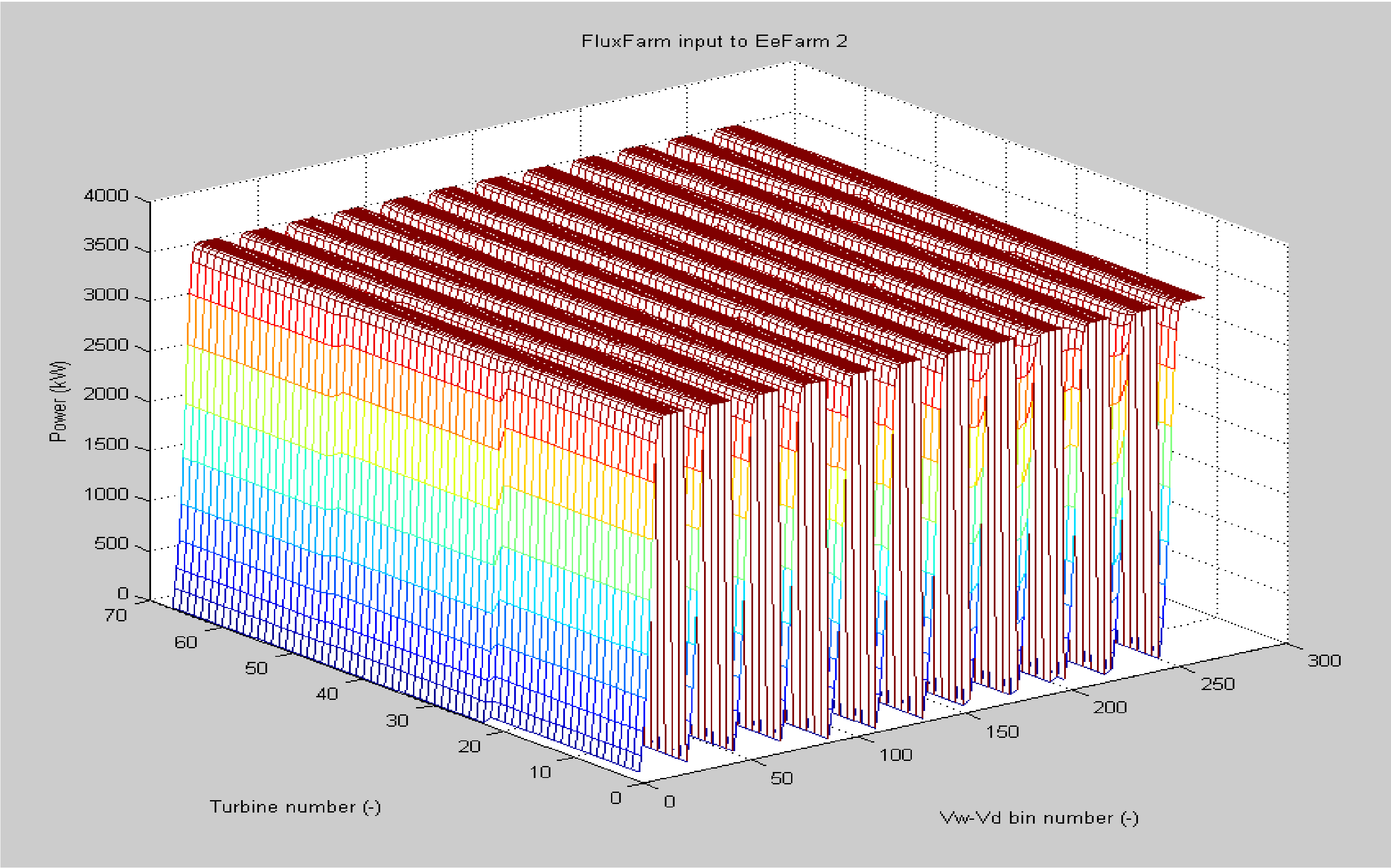
User actions:

- determine
  - turbine type(s) and coordinates (output FluxFarm)
  - cable types, transformer types and coordinates
  - converter types and coordinates
- prepare EeFarm simulation model
  (choose and connect component model blocks)
- specify turbine power input
  (output FluxFarm/Fyndfarm or P(V) curve)
- run EeFarm 2
  - preprocessor calculates cable lengths
- check component voltages and currents
- specify economic parameters (r, i, Lifetime)
- run postprocessor

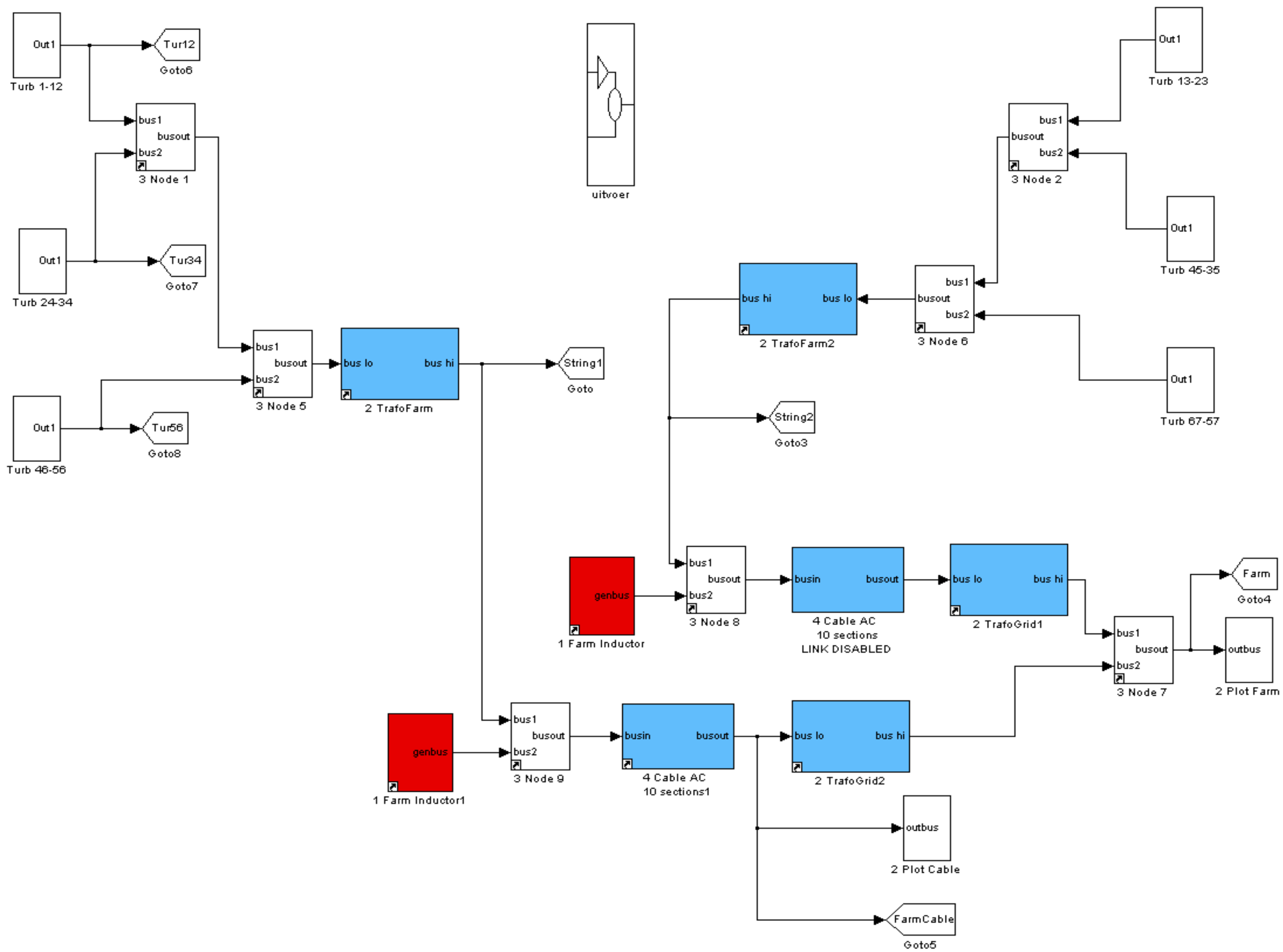
Calculation example: 67 turbines arranged in two blocks



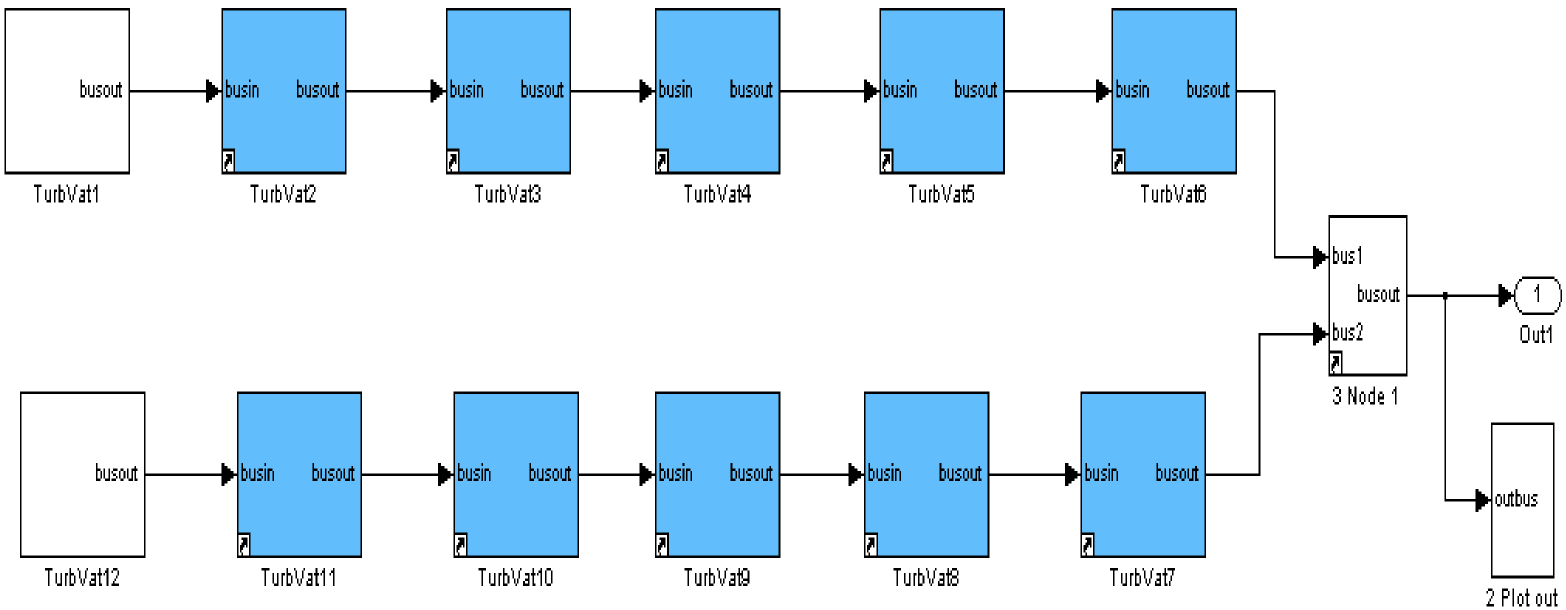
FluxFarm input to EeFarm 2



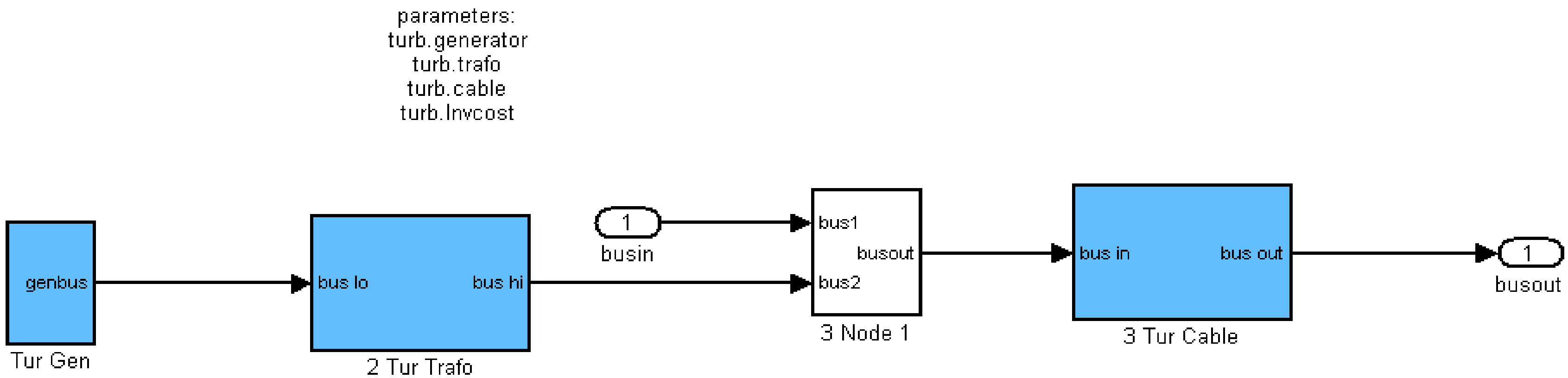
WF model in EeFarm 2

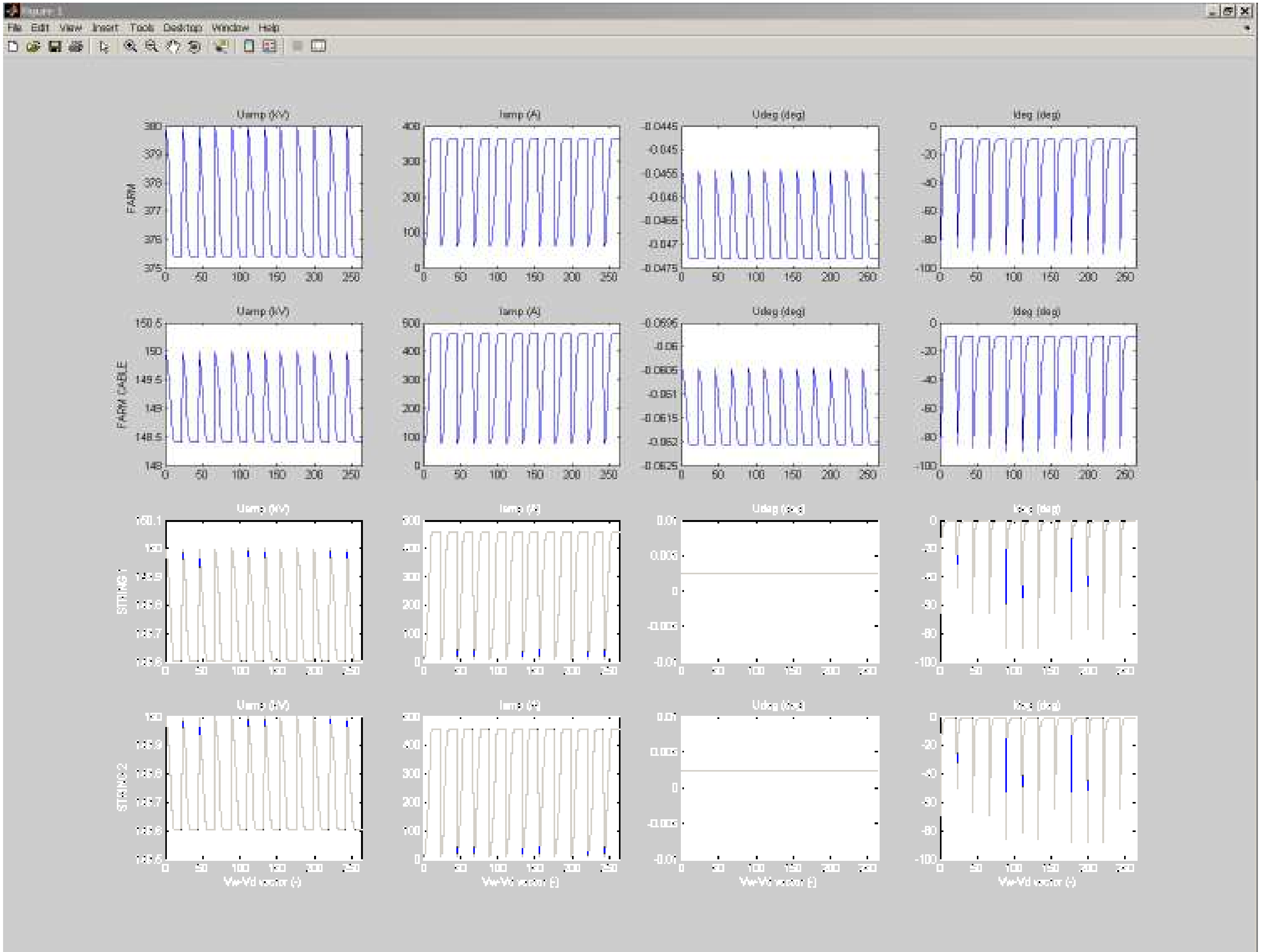


One string of turbines in WF



Turbine, turbine transformer, cable





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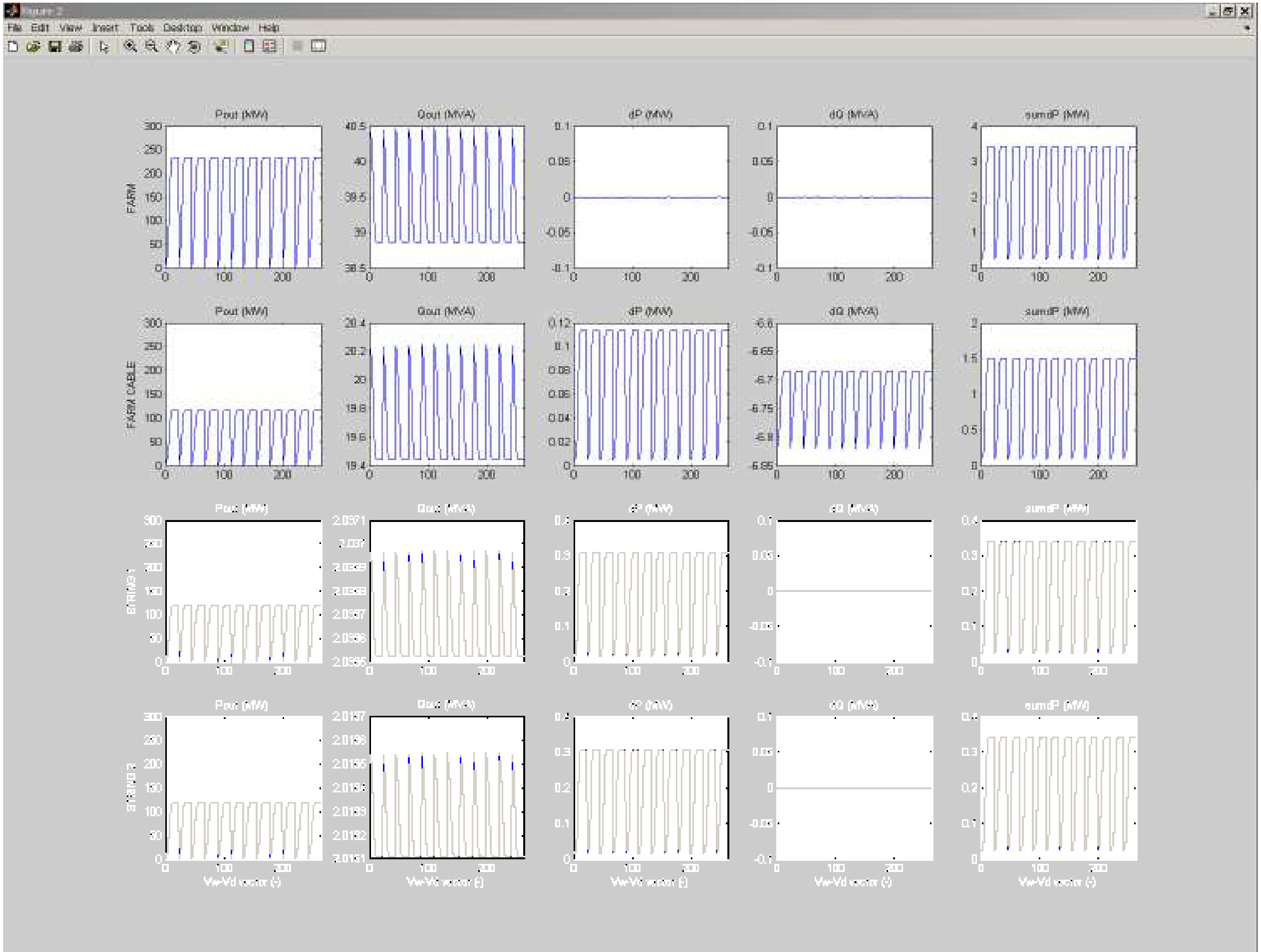

File Edit View Insert Tools Desktop Window Help
Pout (MW)
Qout (MVA)
dP (MW)
dQ (MVA)
sumdP (MW)
FARM
FARM CABLE
STRING 1
STRING 2
Vw-Vd vector (-)

E_{tot}	$E_{losstot1}$	$E_{noloadloss}$	$E_{losstot2}$	Elec-eff
(MWh/y)	(MWh/y)	(MWh/y)	(MWh/y)	(-)
1007003	13037	246	13283	0.9870

$E_{tot incl.avail}$	P_{av}	CF
(MWh/y)	(MW)	(-)
906081	103.4	0.4288

Investment cables, trafos	Investment turbines, platform, chokes	Investment total	Specific investment total
(MEuro)	(MEuro)	(MEuro)	(MEuro/MW)
65.0	503.0	567.9	2.3547

Life time (y)	Nominal interest (percent)	LPC (Euro/kWh)
12.0	7.0	0.1024
13.0	7.0	0.0984
14.0	7.0	0.0950
15.0	7.0	0.0921
16.0	7.0	0.0896
17.0	7.0	0.0874
18.0	7.0	0.0854
19.0	7.0	0.0837
20.0	7.0	0.0821

Wind farm optimization:

- location of turbines (aerodynamic opt. with FluxFarm)
- cable choice and cable routing inside wind farm
- number and location of wind farm transformers
- location, type and size of reactive power compensation
- effect of redundant transformers and cables
- AC versus DC energy transport
- number and type of AC-DC converters (Thy vs. PWM)
- new electrical system concepts (for example cluster control)

EeFarm 2

- Advantages:
  - easy to use (copy-paste)
  - very easy to change system layout
  - includes database with parameters and prices
  - simulation is fast, also for very large wind farms
  - pre-programmed output generation (plots, LaTeX tables)
- Disadvantages:
  - Matlab-Simulink required

To do
(in collaboration with Vattenfall Sweden)

- complete the DC models (Statcom, Chopper)
- update database (Vattenfall)
- model verification (Vattenfall)
- re-evaluation of systems of Erao-1 study (compares 13 AC and DC systems)

EeFarm 2 will be available June 2009

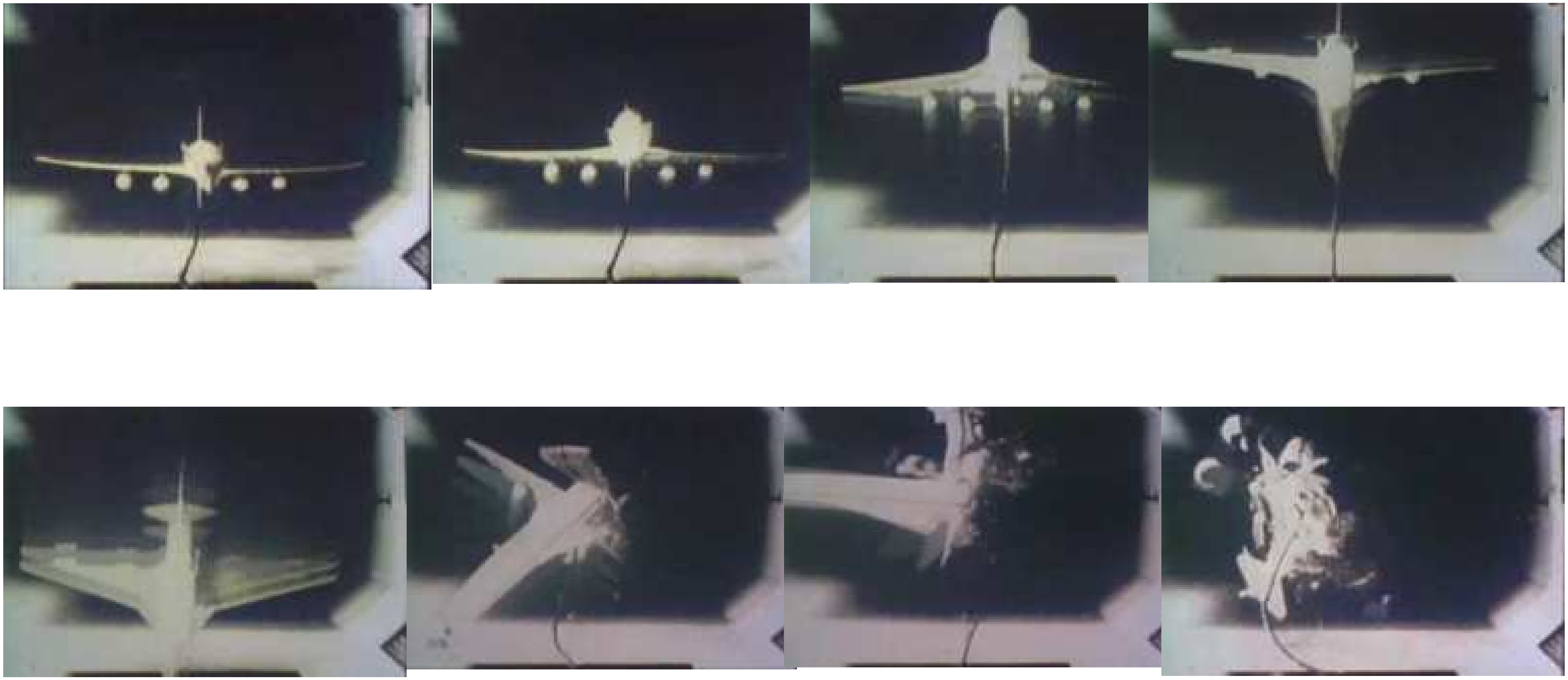
Aeroelastic Stability Analysis

Jessica Holierhoek

Set-up

- Importance Aeroelastic Analysis
- Bladmode
- Turbu
- Future
- Proposition

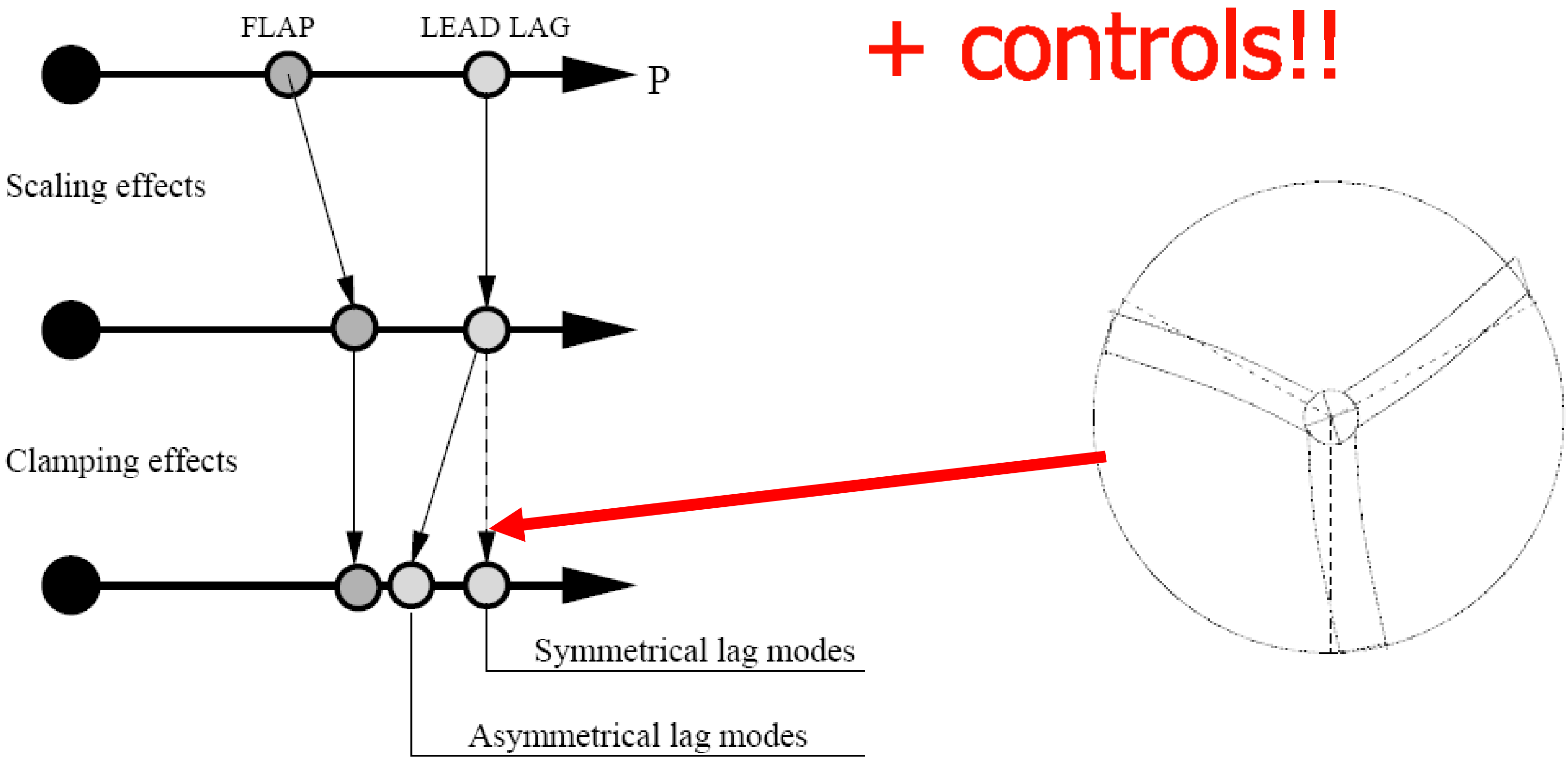
Importance Aeroelastic Analysis



Importance Aeroelastic Analysis

Importance Aeroelastic Analysis

Changes over the years:



Importance Aeroelastic Analysis

Suggested approach:

- During design: Bladmode
- Testing design: Turbu

Bladmode

- During design phase
- Quick and simple
- Detailed blade model, takes into account:
  - Location elastic axis (along radius)
  - Location shear centre (along radius)
  - Cross coupling stiffness (along radius)
  - Bending torsion coupling (along radius)
  - Choose BEM or vortex wake model
  - Torsion

Structural Pitch Angle

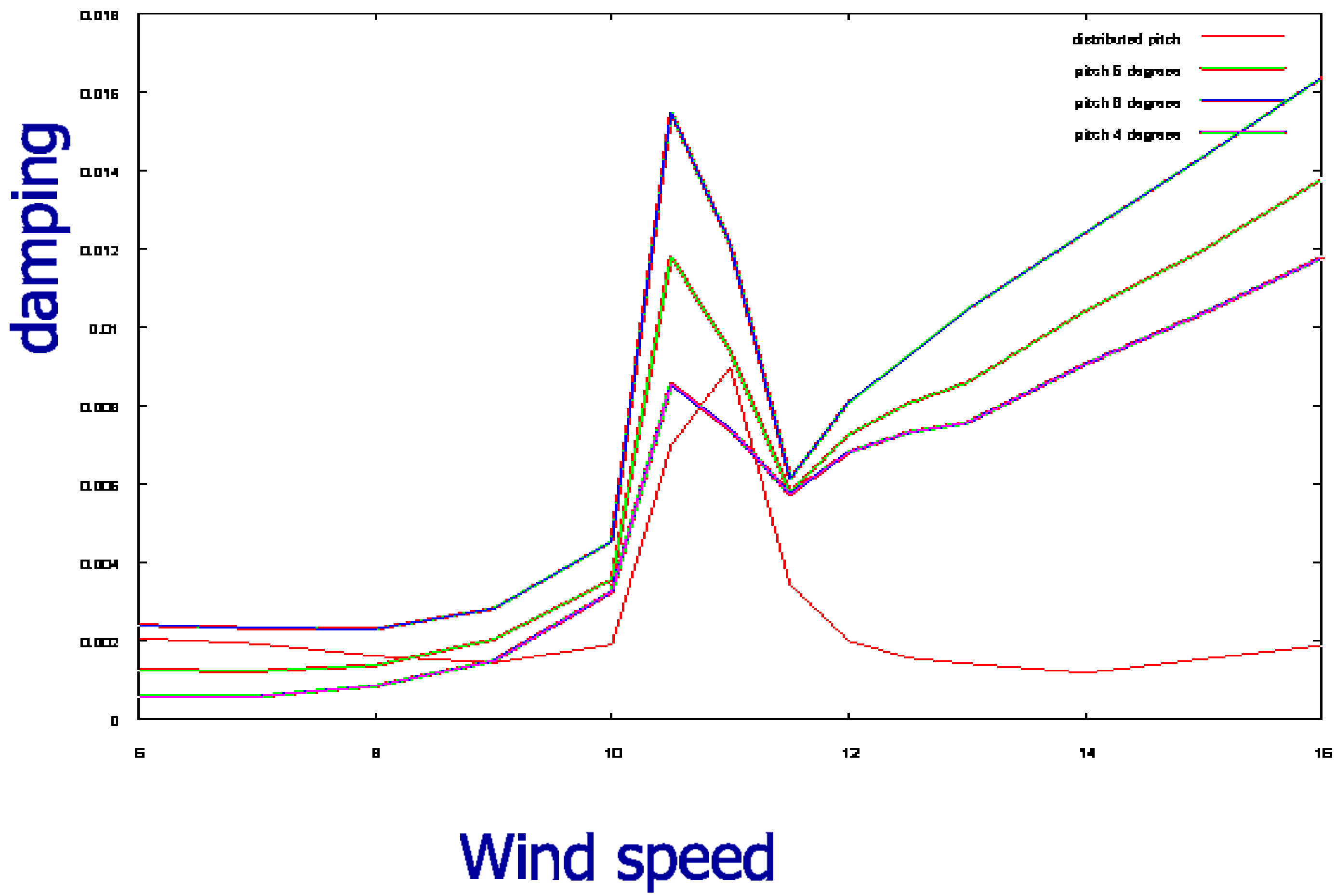
- Angle defining the most flexible and stiffest directions of the blade
- Varies along the blade
- Important effect on stability (gives stability to edgewise mode, reduces damping flatwise mode)
- Several tools give possibility of defining one value for entire blade
- Custom is to use 5 degrees

Structural Pitch Angle

Structural Pitch Angle

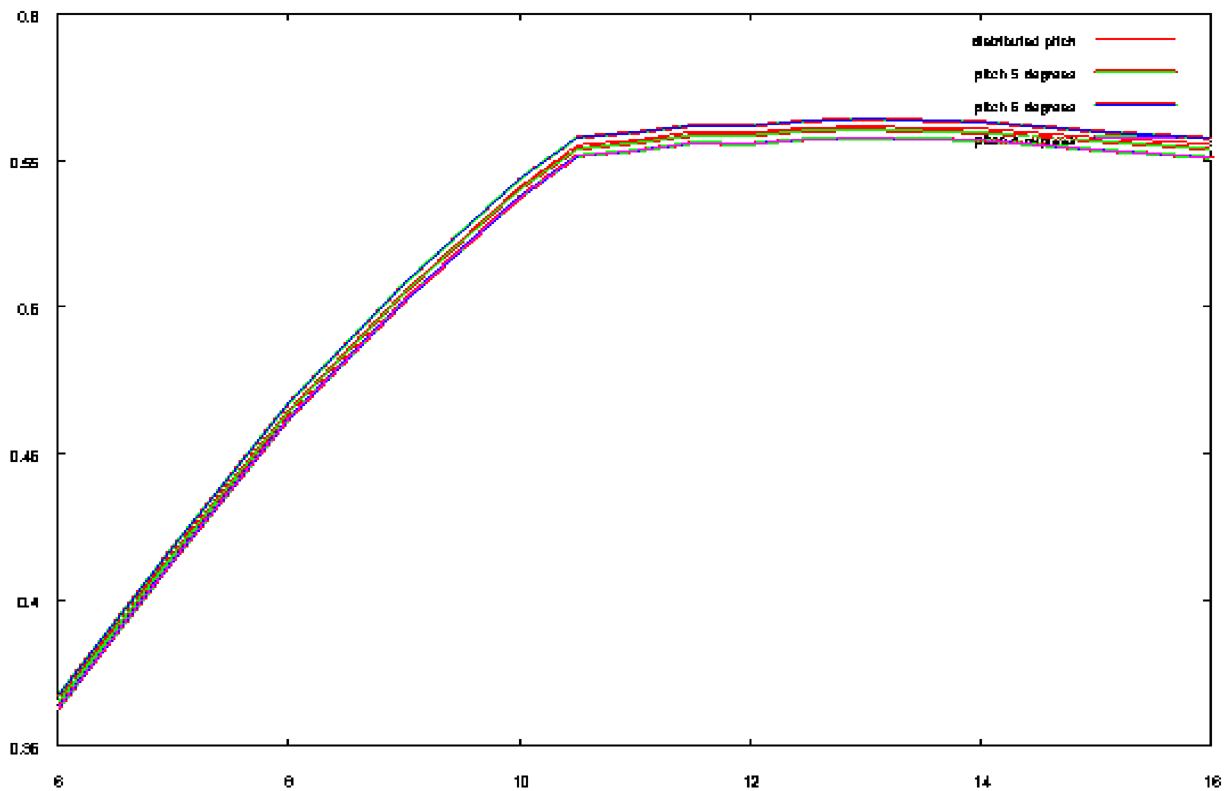
- For modern large blades, this custom is not good enough!
- The distribution of the structural pitch has significant influence on the stability

Structural Pitch Angle



1st coll. edgewise mode

Structural Pitch Angle

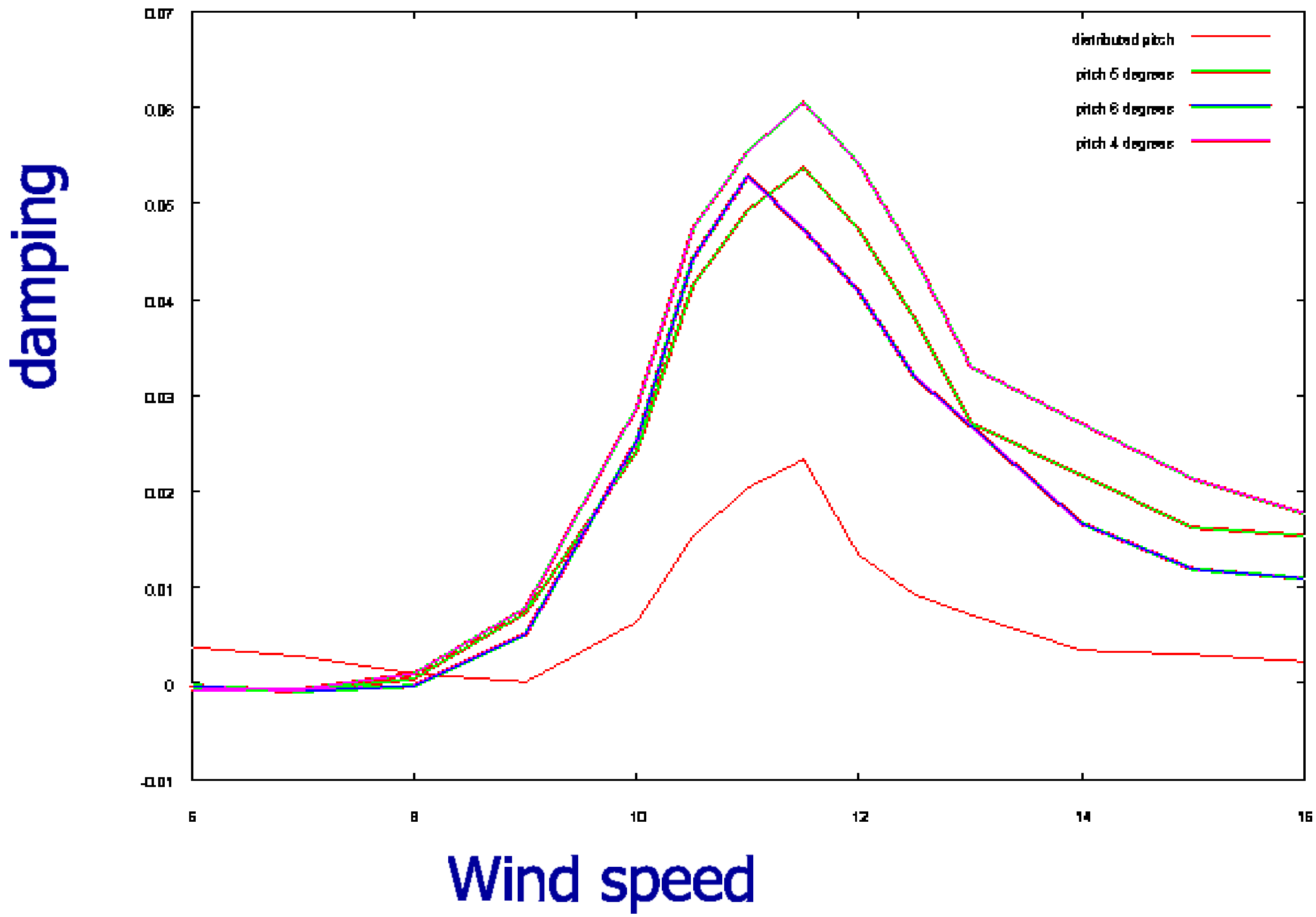


damping

Wind speed

1st coll. flatwise mode

Structural Pitch Angle



1st reaction-less edgewise mode

Structural Pitch Angle

Analysis has shown:

1. Better representation using distributed structural pitch angle
2. When using one single angle, the direction of vibration at 75% radius looks representative

Turbu

- Matlab code
- Validated during STABCON

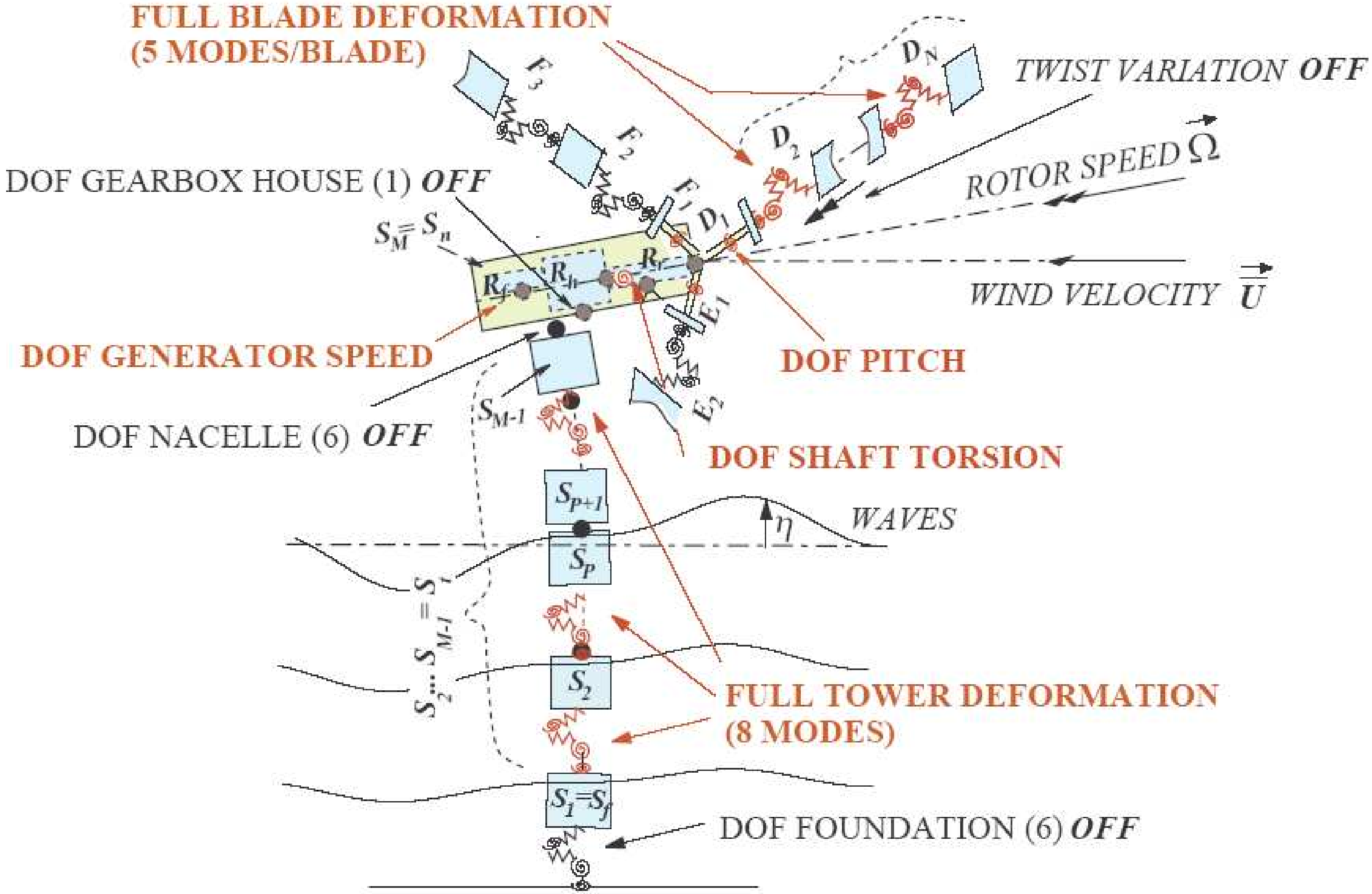
Useful for:

- aeroelastic analysis
- controls

Turbu

- Linear frequency and time domain analysis of 3-bladed HAWTs
- Time-invariant linear dynamic model (multi-body, Newton, Coleman)
- Full non-linear steady state model (multi-body average deformation)
- Wind and water excitation (definable wave, current, wind direction)
- Dynamic wake, unsteady aerodynamics
- Reduced order blade and tower models (Hurty [Craig-Bampton])

Turbu



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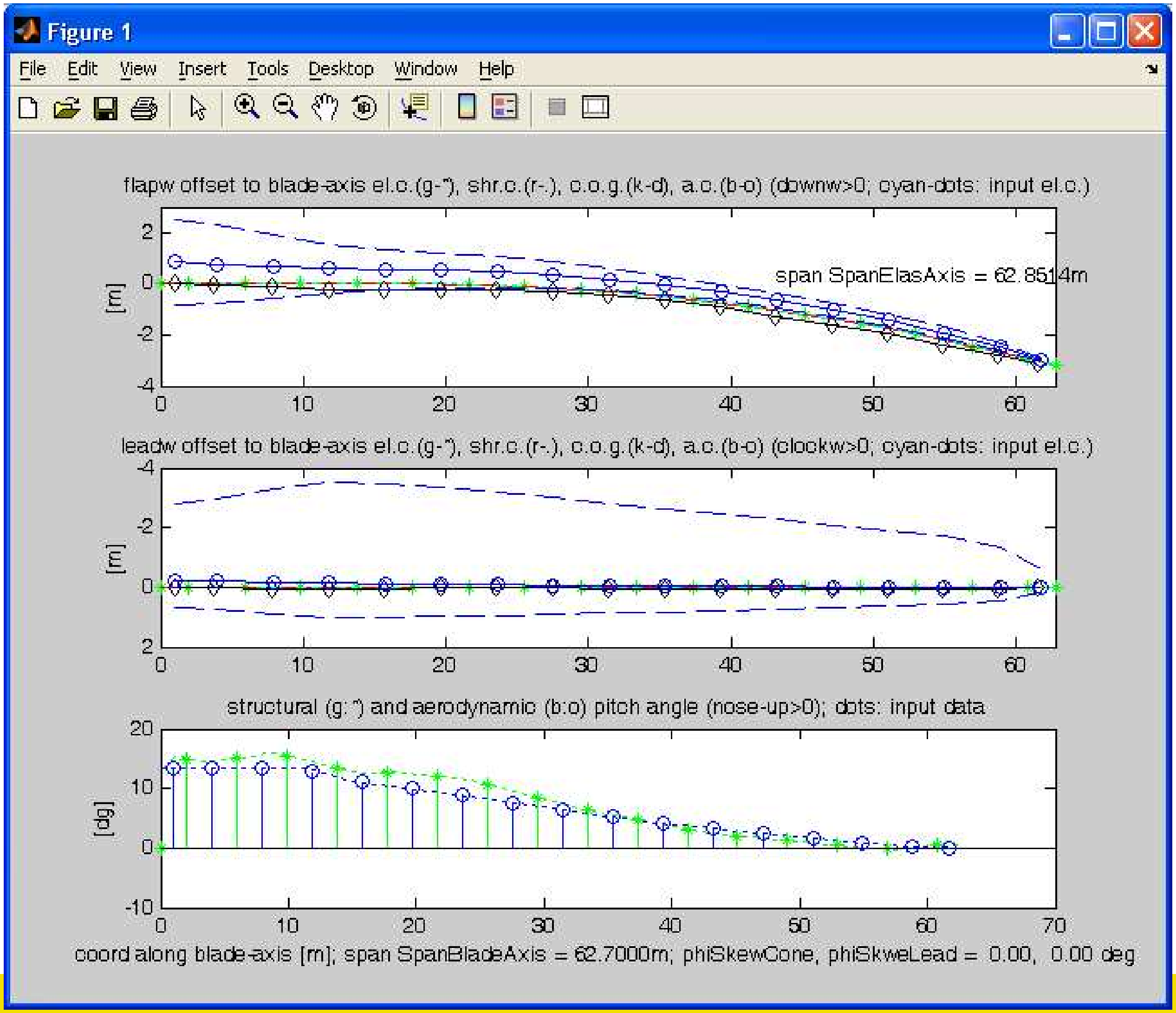
Turbu

Reference model is reduced high-order multi-body:

- 13-element tower model with torsion and bending deformation
- 13-element blade models with torsion and bending deformation
- 8 tower modes retained; 5 modes per blade retained
- pitch servo actuation with blade-pitch-motion included

Turbu



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Turbu

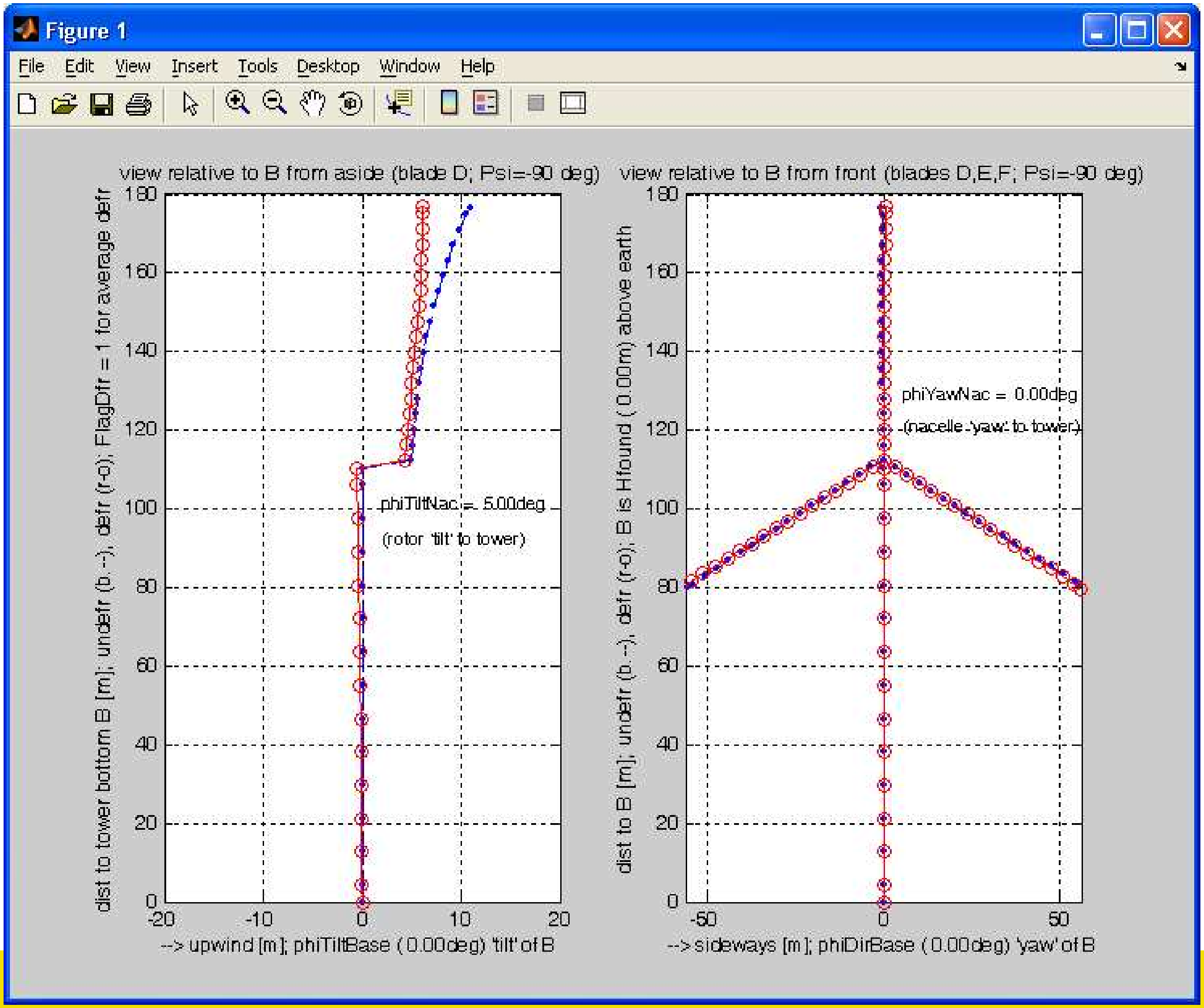


Figure 1
File Edit View Insert Tools Desktop Window Help
view relative to B from aside (blade D; Psi=-90 deg)
view relative to B from front (blades D,E,F; Psi=-90 deg)
dist to tower bottom B [m]; undefr (b.-), defr (r-o); FlagDfr = 1 for average defr
phiTiltNac = 5.00deg
(rotor 'tilt' to tower)
--> upwind [m]; phiTiltBase (0.00deg) 'tilt' of B
dist to B [m]; undefr (b.-), defr (r-o); B is Hfound (0.00m) above earth
phiYawNac = 0.00deg
(nacelle 'yaw' to tower)
--> sideways [m]; phiDirBase (0.00deg) 'yaw' of B

Turbu

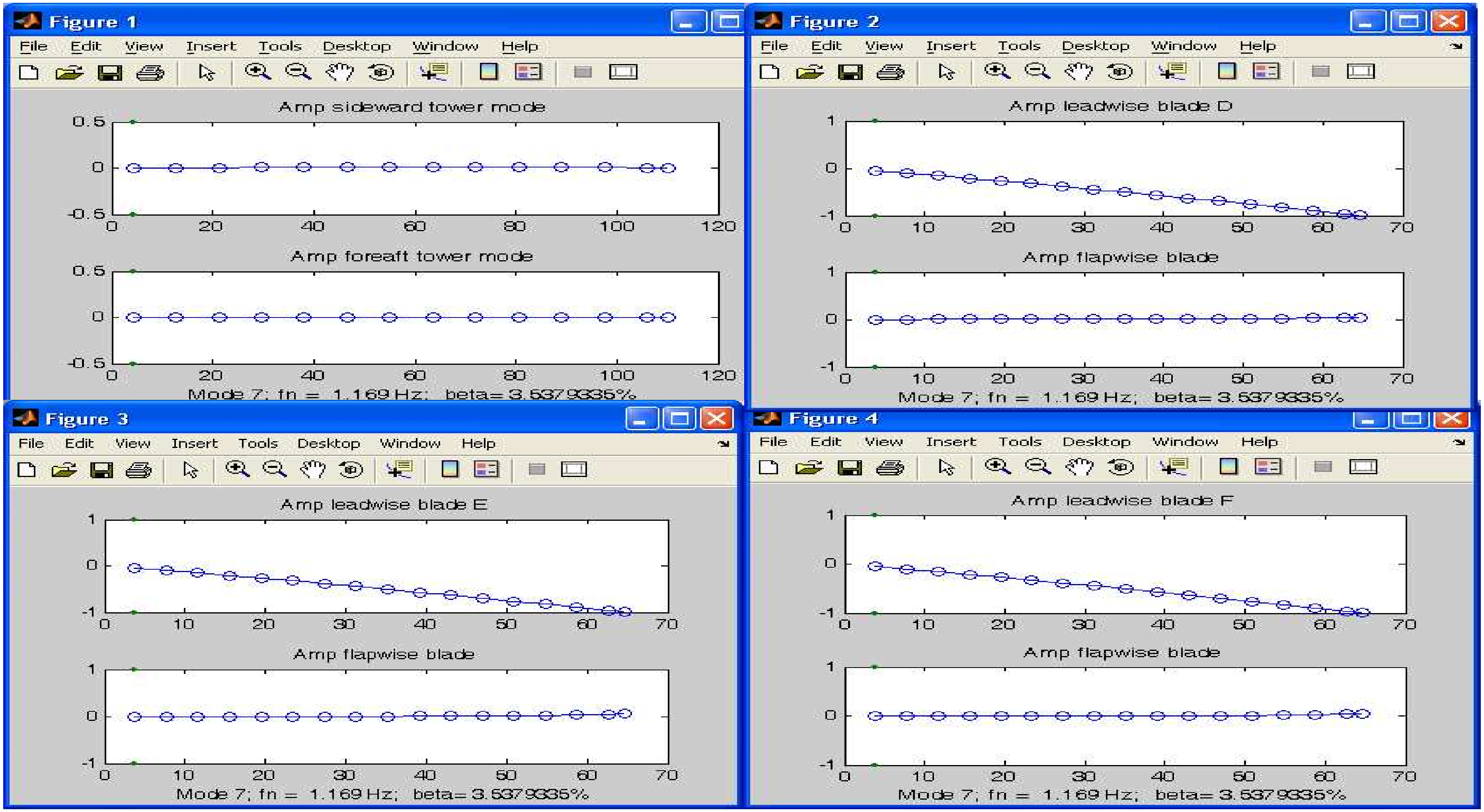


Figure 1
File Edit View Insert Tools Desktop Window Help
Amp sideward tower mode
0.5
0
-0.5
0 20 40 60 80 100 120
Amp foreaft tower mode
0.5
0
-0.5
0 20 40 60 80 100 120
Mode 7; fn = 1.169 Hz; beta= 3.5379335%
Figure 2
File Edit View Insert Tools Desktop Window Help
Amp leadwise blade D
1
0
-1
0 10 20 30 40 50 60 70
Amp flapwise blade
1
0
-1
0 10 20 30 40 50 60 70
Mode 7; fn = 1.169 Hz; beta= 3.5379335%
Figure 3
File Edit View Insert Tools Desktop Window Help
Amp leadwise blade E
1
0
-1
0 10 20 30 40 50 60 70
Amp flapwise blade
1
0
-1
0 10 20 30 40 50 60 70
Mode 7; fn = 1.169 Hz; beta= 3.5379335%
Figure 4
File Edit View Insert Tools Desktop Window Help
Amp leadwise blade F
1
0
-1
0 10 20 30 40 50 60 70
Amp flapwise blade
1
0
-1
0 10 20 30 40 50 60 70
Mode 7; fn = 1.169 Hz; beta= 3.5379335%

Turbu

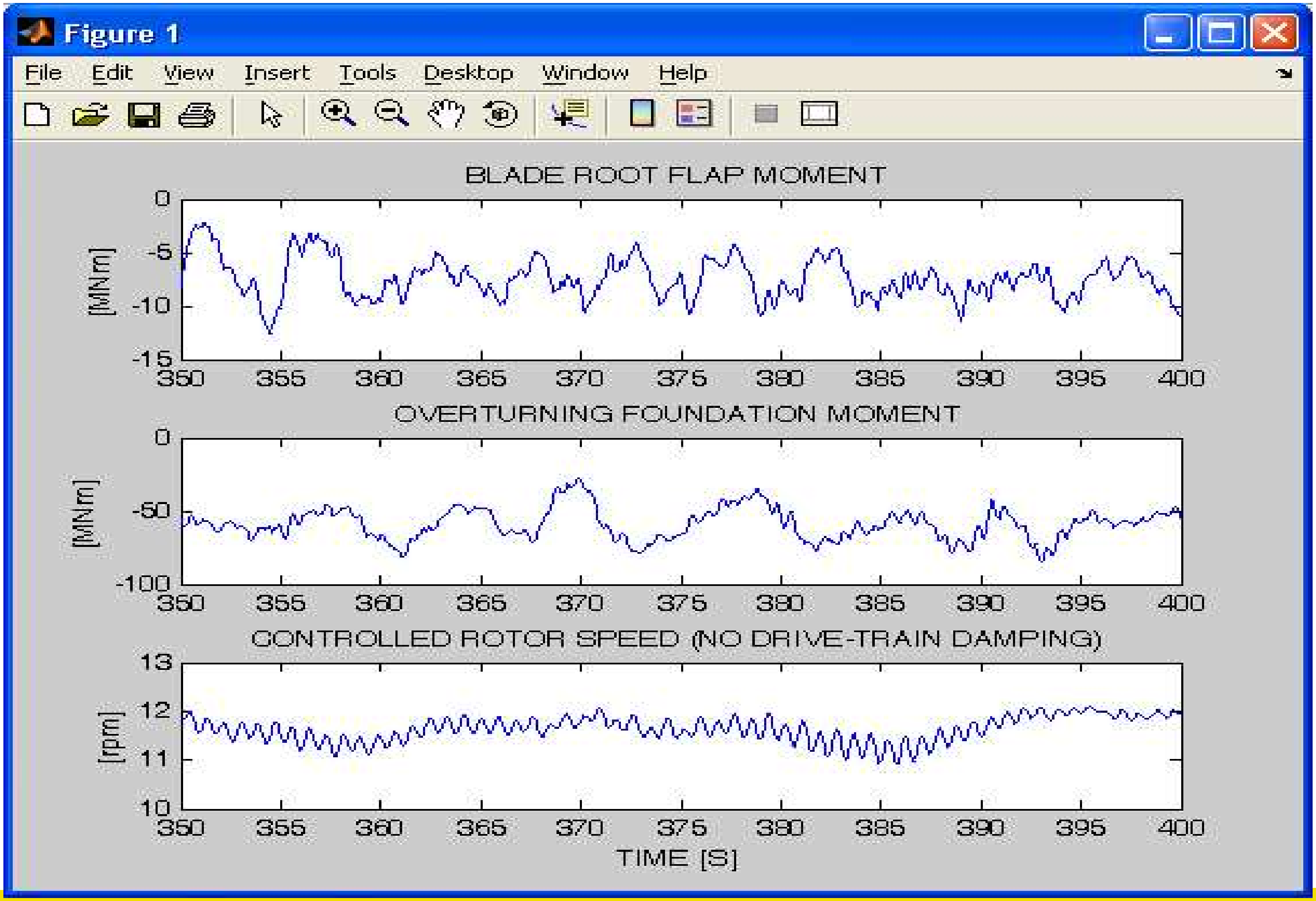
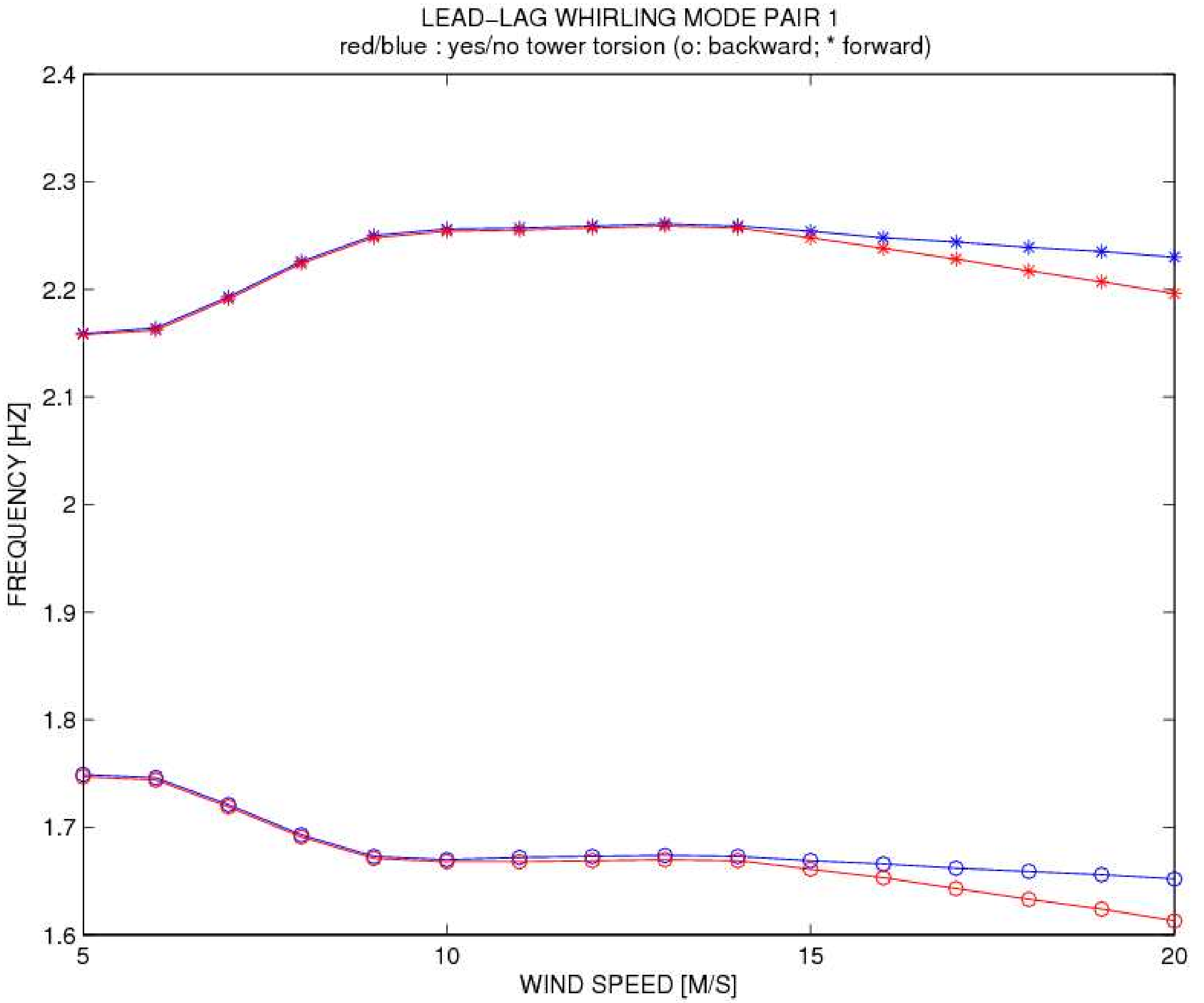
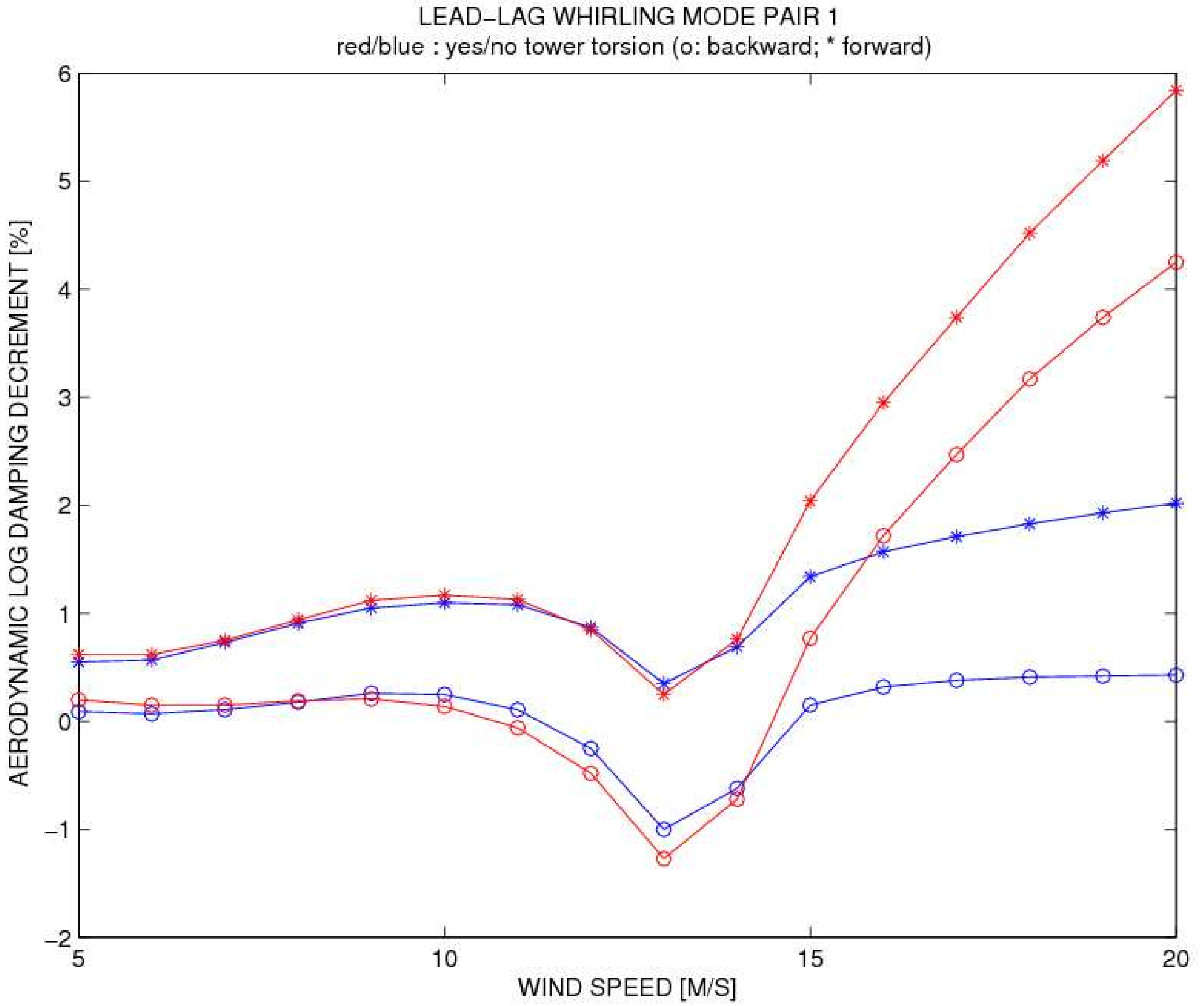


Figure 1
File Edit View Insert Tools Desktop Window Help
BLADE ROOT FLAP MOMENT
[MNm]
0
-5
-10
-15
350 355 360 365 370 375 380 385 390 395 400
OVERTURNING FOUNDATION MOMENT
[MNm]
0
-50
-100
350 355 360 365 370 375 380 385 390 395 400
CONTROLLED ROTOR SPEED (NO DRIVE-TRAIN DAMPING)
[rpm]
13
12
11
10
350 355 360 365 370 375 380 385 390 395 400
TIME [S]

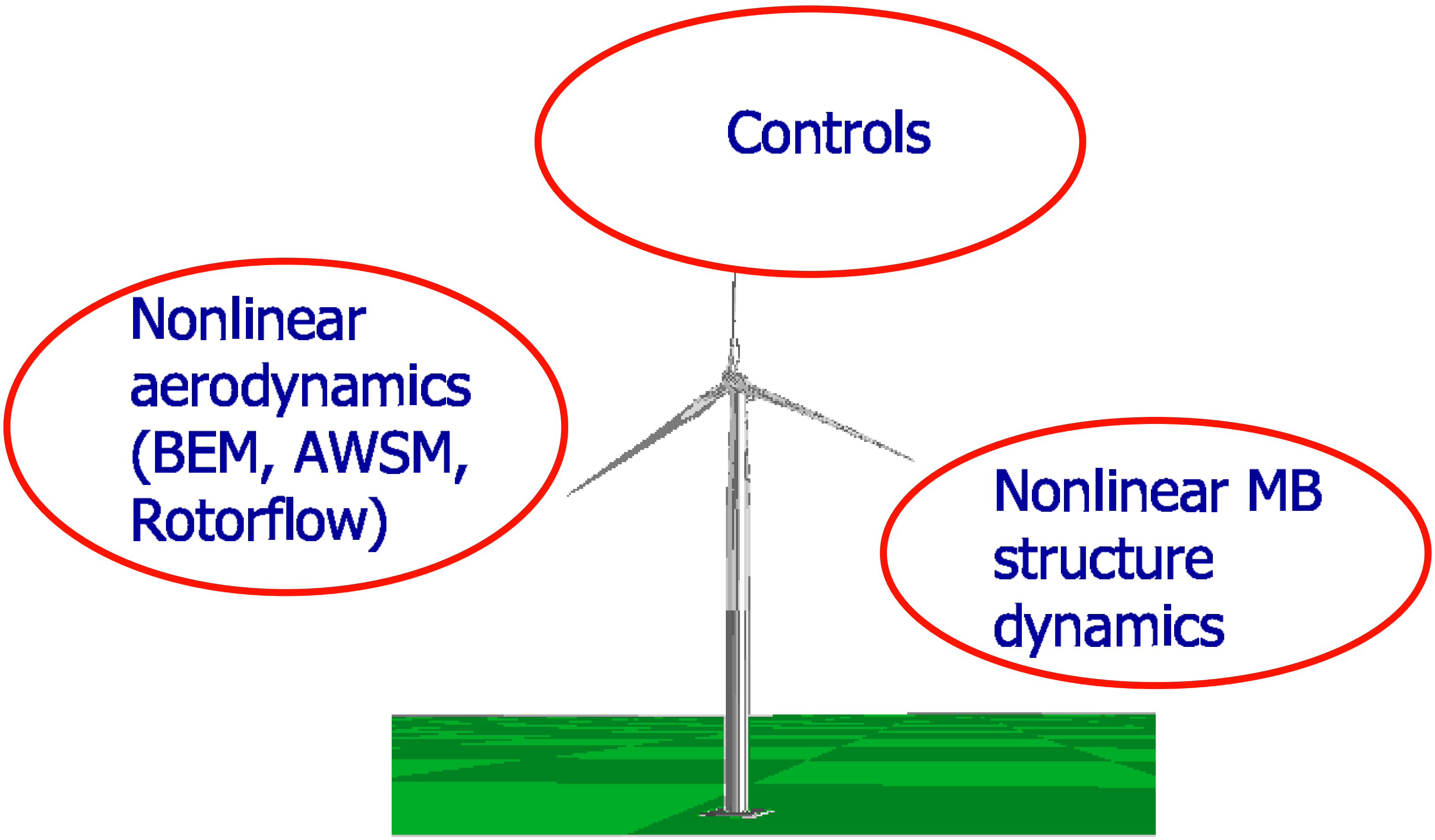
Turbu


LEAD–LAG WHIRLING MODE PAIR 1
red/blue : yes/no tower torsion (o: backward; * forward)
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
FREQUENCY [HZ]
5
10
15
20
WIND SPEED [M/S]

Turbu

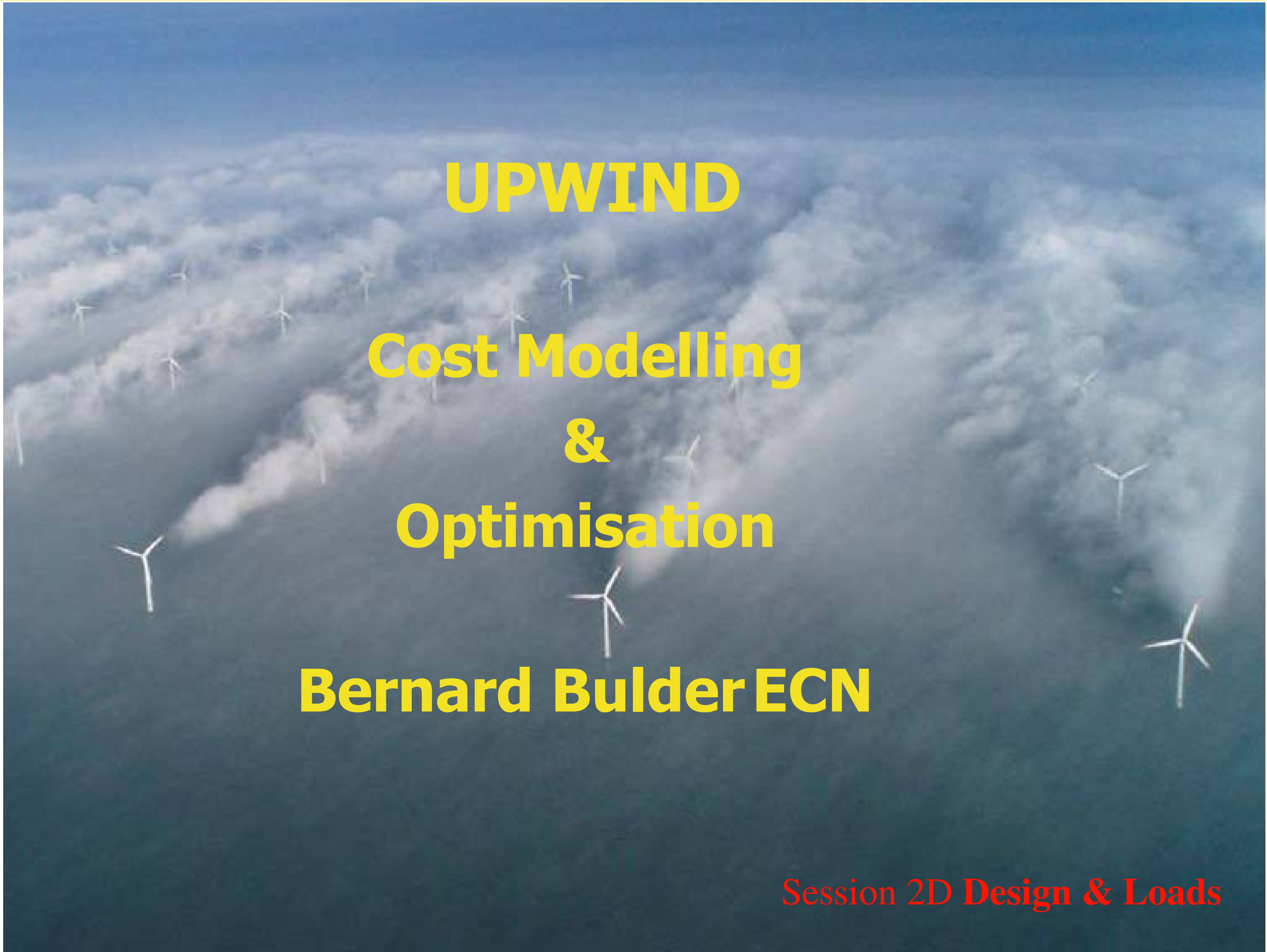

LEAD–LAG WHIRLING MODE PAIR 1
red/blue : yes/no tower torsion (o: backward; * forward)
AERODYNAMIC LOG DAMPING DECREMENT [%]
WIND SPEED [M/S]
6
5
4
3
2
1
0
−1
−2
5
10
15
20

Future


Controls
Nonlinear aerodynamics (BEM, AWSM, Rotorflow)
Nonlinear MB structure dynamics

Proposition

With the current state-of-the art wind turbine aeroelastic analysis tools it is impossible to state for certain if a design will be stable or unstable



TU Delft

DUWIND
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UPWIND

Cost Modelling & Optimisation

Bernard Bulder ECN

Session 2D **Design & Loads**

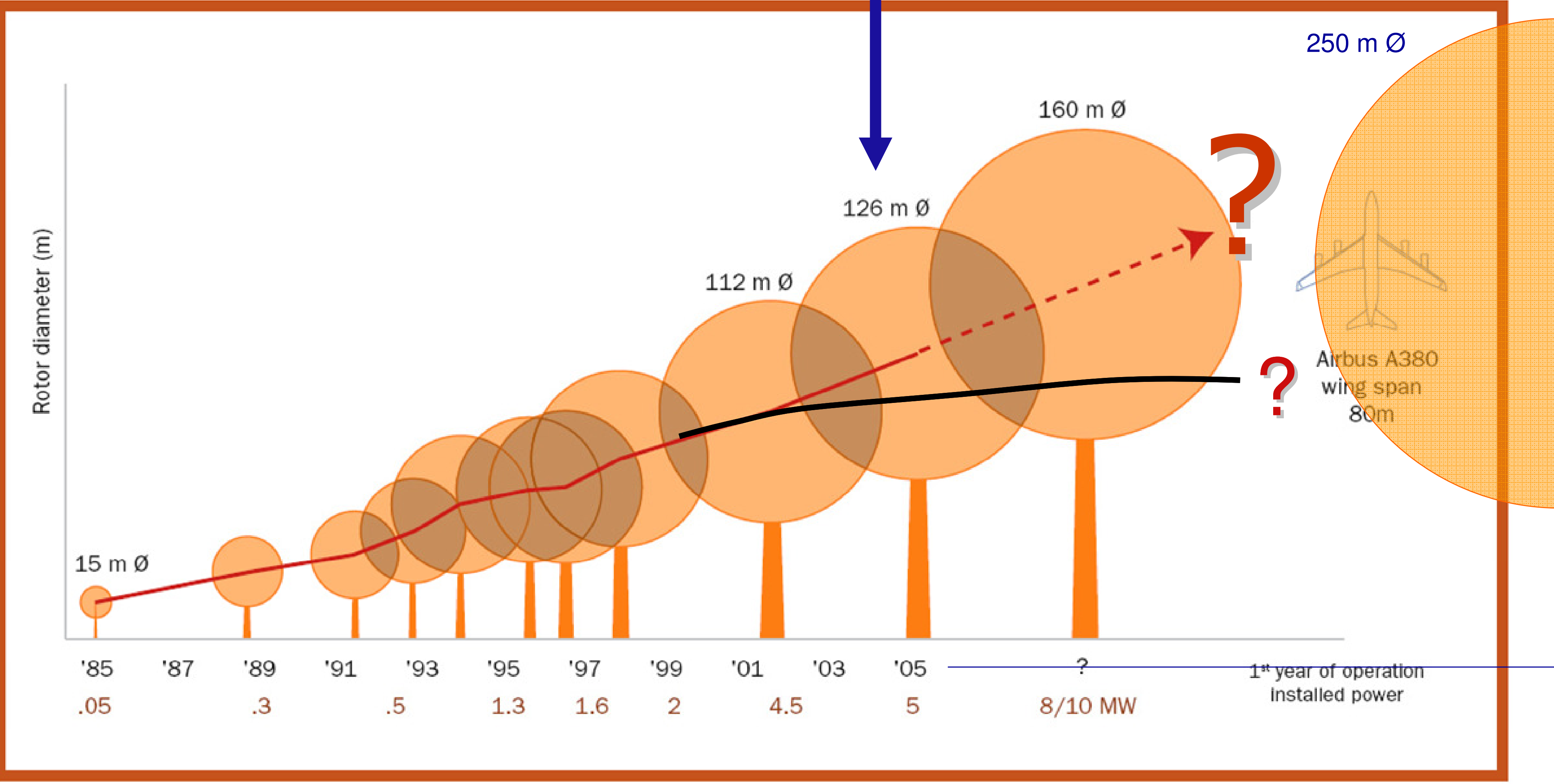
UpWind WP 1A1 & WP 1B4

Objectives:

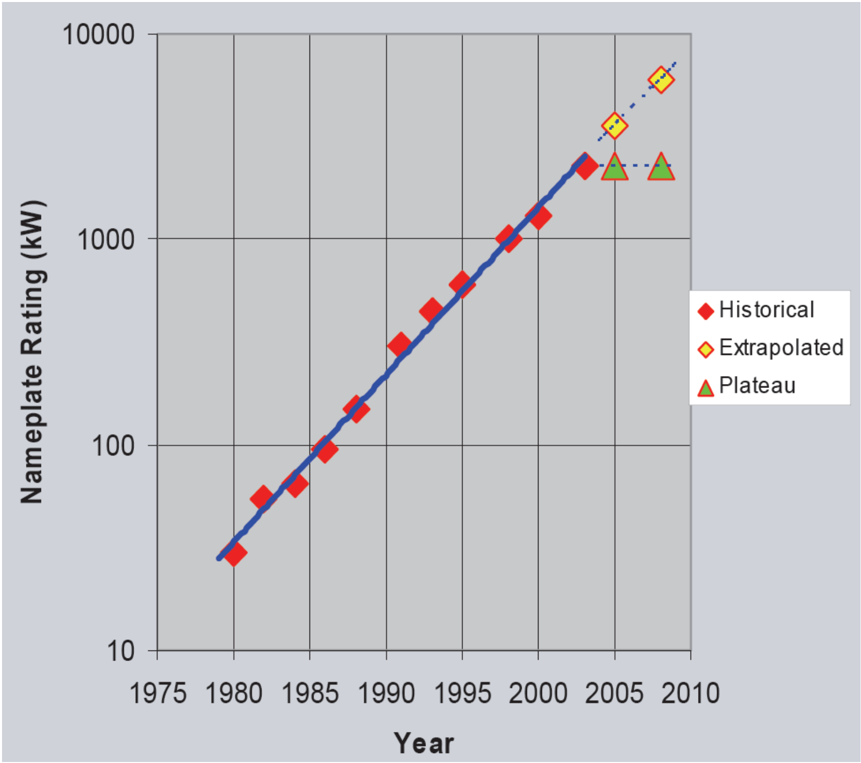
- *Development of integral design approach methodology*
- *Development of (pre)standards for the application of the integral design approach*
- Develop cost model for application in other WP for comparisons and for demonstration of potentials and benefits of design developments
- Evaluate pros and cons of different design options by calculation of cost of energy
- Define the technological bottlenecks for successful up-scaling of wind turbines to 20MW

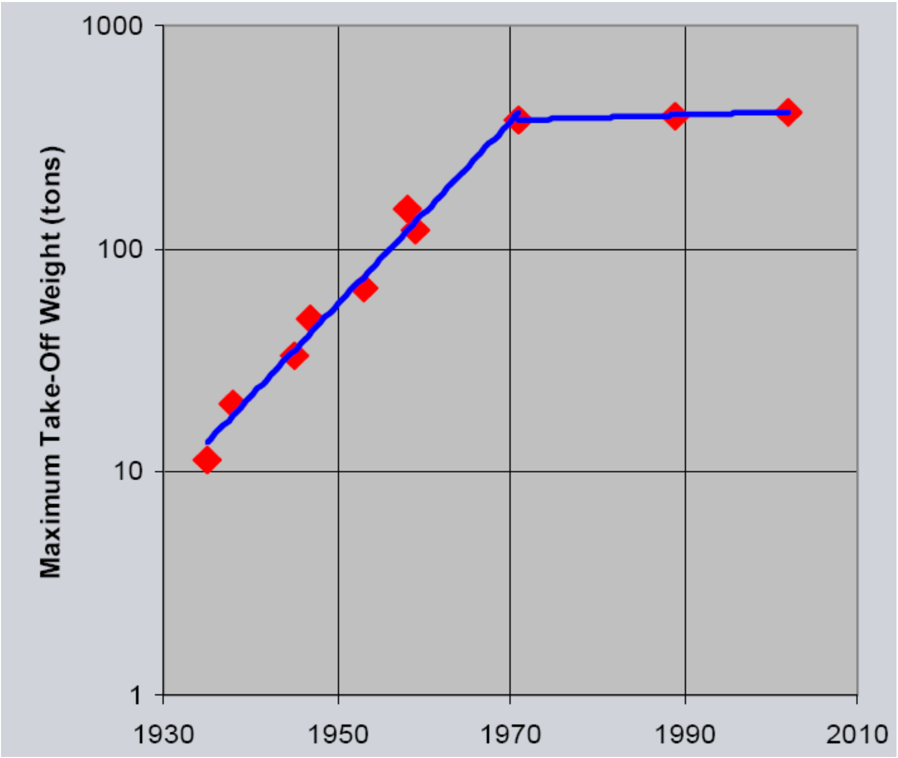
2008

Up-Scaling



Up-Scaling - Development in airplane size – MTOW



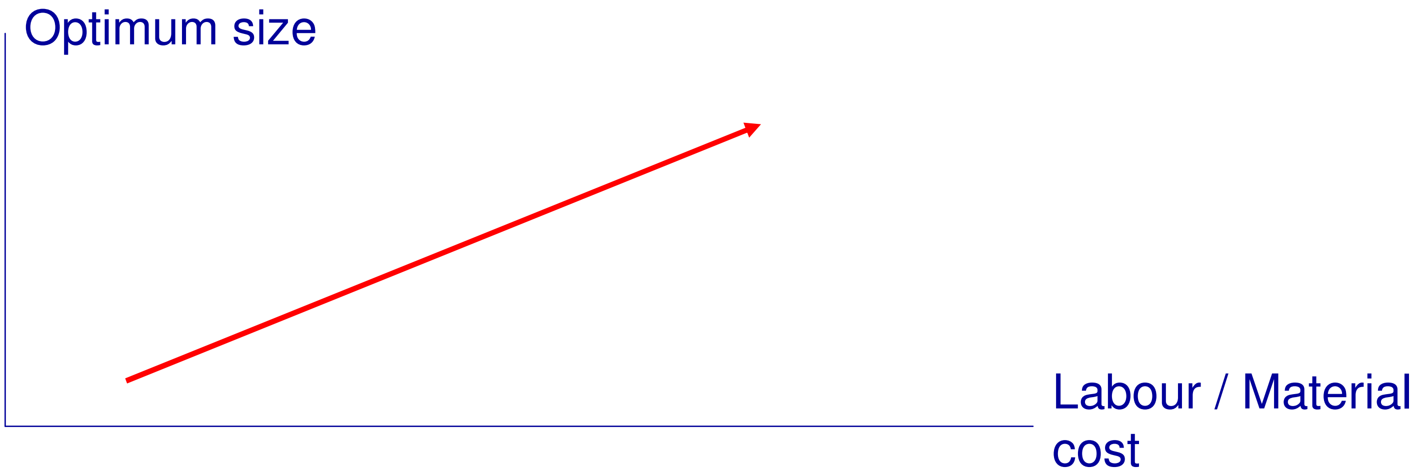


From: Siemems Wind Power, *2007*

Up-scaling

The optimum size depends on:

- ✓ Chosen concept
- ✓ Installation method
- ✓ O&M costs
- ✓ Ratio of Labour / Material cost



Up-Scaling

Similarity rules
(Takis Chaviaropoulos)

2.4. Blade structural properties

Assuming the geometric up-scaling of the internal blade structure (dimensions scale-up with R, increasing proportionally the number of layers of the same material) and ignoring possible second order effects, the following table results for the sectional properties.

Symbol	***Defining Formula***	***Description***	***Size-Dep.***
$A(x)$	$= R^2 \int ds^* = R^2 . A^*(x)$	*Effective Area*	R^2
$\underset{\approx}{I}(x) = \begin{pmatrix} I_{yy}(x) & I_{yz}(x) \\ I_{zy}(x) & I_{zz}(x) \end{pmatrix}$	$= R^4 \begin{pmatrix} \int z^{*2} ds^* & -\int y^* z^* ds^* \\ -\int z^* y^* ds^* & \int y^{*2} ds^* \end{pmatrix}$ $= R^4 . \underset{\approx}{I}^*(x)$	*Moments of Inertia - Tensor*	R^4
$I_p(x)$	$= R^4 . I_P^*(x)$	*Polar Moment of Inertia*	R^4
$J(x)$	$= R^4 . J^*(x)$	*Torsion Constant*	R^4
$W_y(x)$		*Section Moduli – Y Bending*	R^3
$W_z(x)$		*Section Moduli*	R^3

Up-Scaling

Upscaling, preliminary results for blades:

- ❖ Classical similarity rules : mass of blade ~ $\mathbf{R^3}$
- ❖ Trend data : mass of blade ~ $\mathbf{R^2}$

$$C(sf,T)_{\mathrm{comp}} = C(1,T_0)_{\mathrm{comp}} \frac{c(sf,T)}{c(1,T_0)} \cdot sf^{\,\alpha_{\mathrm{comp}}(T)} \cdot r(T)$$

Up-Scaling – cost models

- Uncertainties:
  - ✓ Costs and yield are site dependent and uncertain
  - ✓ The scaling rules are uncertain
  - ✓ The learning curve, and the introduction of new technologies and new concepts will bring the costs down
- Unlikely that up-scaling of present wind turbine designs is optimal for future offshore wind energy
  - ✓ *higher tip speed?*
  - ✓ *active boundary layer control?*
  - ✓ *advanced materials?*
  - ✓ *advanced control?*
  - ✓ *....*

Cost model – Life cycle approach

- Life cycle approach using expected
  - ✓ Benefits
  - ✓ Planning costs
  - ✓ Fabrication & installation costs
  - ✓ Operation & maintenance costs
  - ✓ Inspection & repair costs
  - ✓ Demolition costs

- Optimal design: Minimum expected total costs during lifetime per MWh

Cost model - Main design parameters

Power	**5 MW**	10 MW	15 MW	**20 MW**
Rotor diameter	**126 m**	178 m	218 m	**252 m**
Tip speed	**80 m/s**	80 m/s	80 m/s	**80 m/s**
Hub height	**90 m**	116 m	136 m	**153 m**

- Wind turbine type: reference WT (based on NREL 5 MW)

Cost model - Design parameters

Detailed list of decision parameters – on component level:

- Wind fam layout

- Height and cross-sections of tower
- Length and cross-sections of blades
- Design parameters for nacelle
- Type and size of foundation
- …
- Monitoring methods and maintenance strategy
- …

Cost model - External conditions

- 500 MW (1000 MW) offshore wind farm
- Separation: 7 x 7 rotor diameters
- Design lifetime: 20 years
- Wind speed and turbulence – class I B at 90m height + wake turbulence
- Wind shear: see IEC 61400-3 – normal wind shear

- Water depth: 30m and 60m
- Wave height: North Sea
- Ice loading: not included
- Current: not included
- Soil conditions: sand / clay
- Distance to shore: 25 km and 100 km (30m and 60m water depth)

Cost model

Generalised cost model:

$$C(sf,T)_{\text{comp}} = C(1,T_0)_{\text{comp}} \frac{c(sf,T)}{c(1,T_0)} \cdot sf^{\alpha_{\text{comp}}(T)} \cdot r(T)$$

changes in **cost per mass unit** due to changes in materials, manufacturing process,..

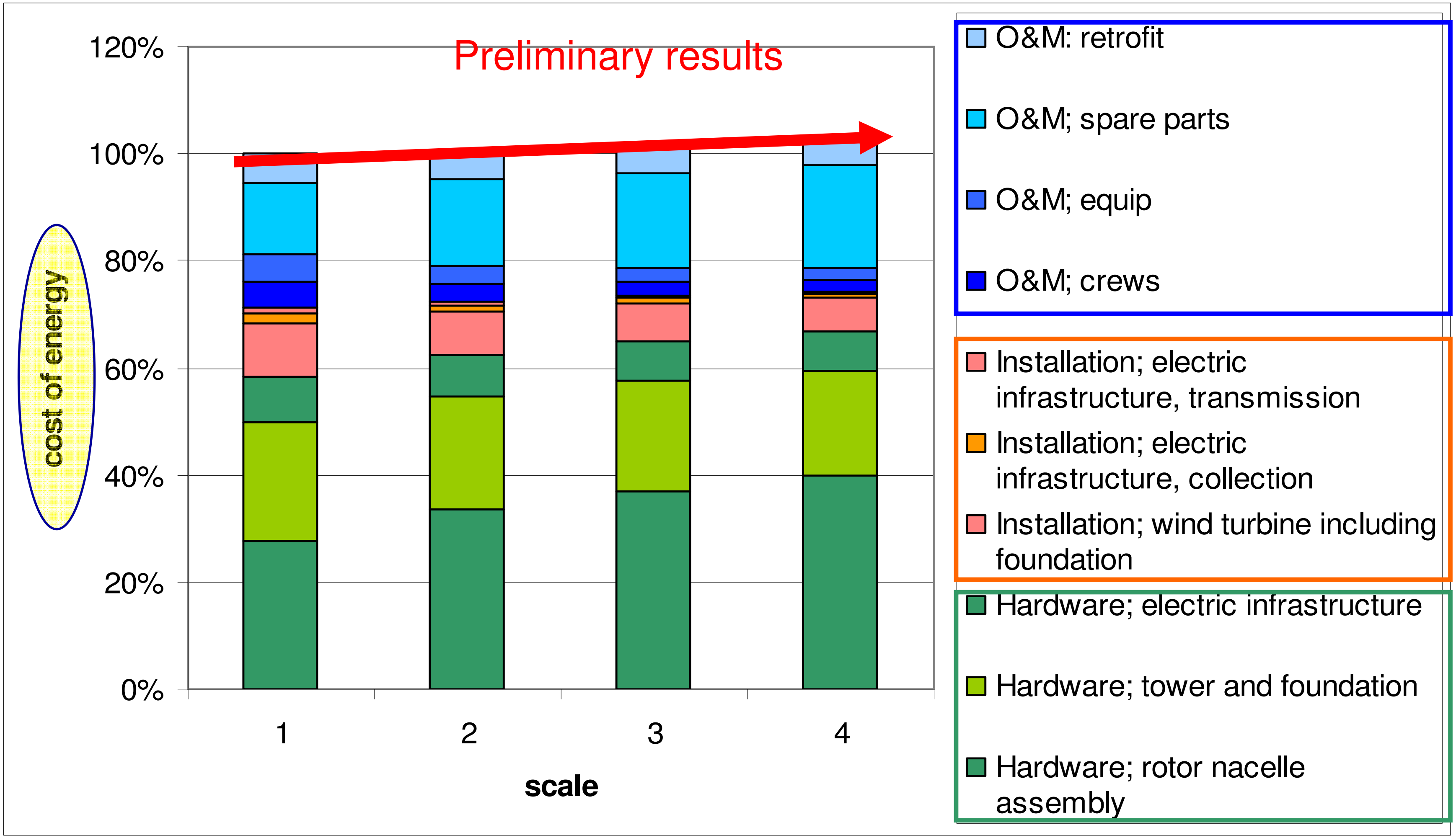
effect of **technology improvement on mass** with same size of the component

up-scaling of mass using the same technology using ‘similarity rules’

Optimum size determination

- For each sub component a cost model is created, using a surface fit of orthogonal multinomials (limited number of design variables)
- In WP 1.A1 and 1.B.4 combine the cost models
- Determine optimum size, for all conceptual options.

Up-Scaling – cost of energy



Challenges

Are 20 MW turbines technically possible:

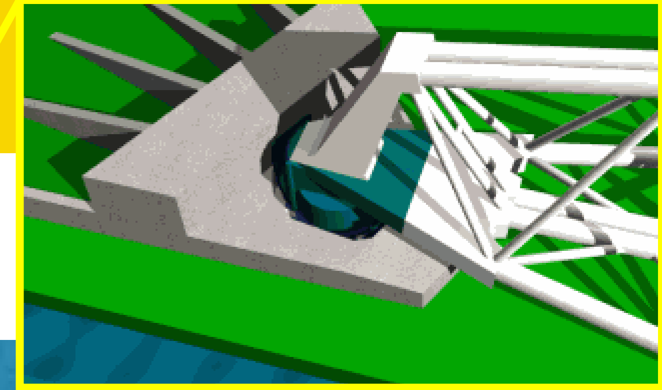
- ✓ Can they be **manufactured?**
- ✓ Can they be **transported?**
- ✓ Can the turbines be **installed?**

Not feasible?

- ... we were able to build this in 1889 ...

Not feasible?

- … we were able to build and transport this some decades ago …



Not feasible?

- ❖ **… we were able to design and manufacture this some years ago …**

Not feasible??

- **... we were able to design and manufacture this some years ago ...**

Not feasible?

- So can we build a 20 MW turbine?

So, what is determining the erection of 20 MW turbines?

It's the Economy, stupid!

Thank you!

Acknowledgement:
“The UpWind project is sponsored by the EC, SenterNovem and participants.

Flight Leader Concept for Wind Farm Load Counting and Performance Assessment

Tom Obdam

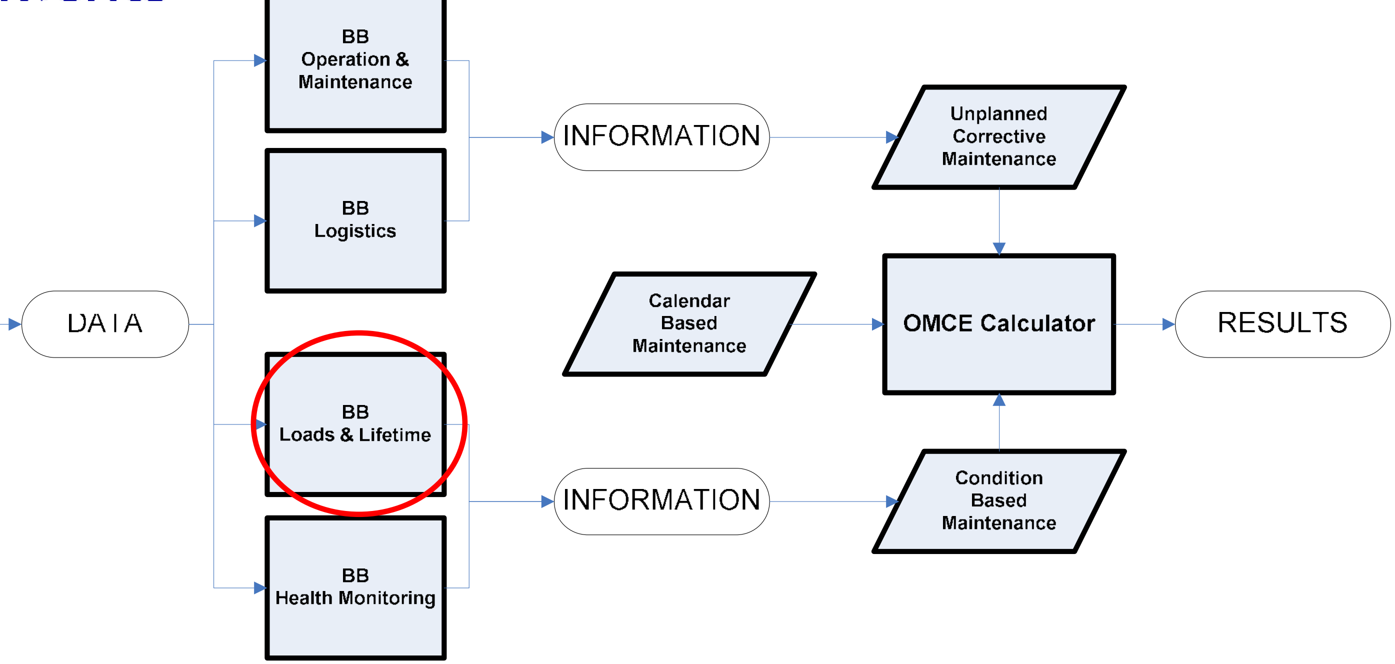
Contents

Introduction

- O&M costs 25-30% kWh price
- O&M optimisation required!
- Analyse and use operational data
  - Maintenance sheets
  - Vessel usage
  - Condition monitoring systems
  - Oil inspections
  - Mechanical load measurements
  - ...

O&M Cost Estimator

- Building blocks for analysing the various data sources
- BB Loads & Lifetime processes mechanical load measurements



Flight Leader Concept (1)

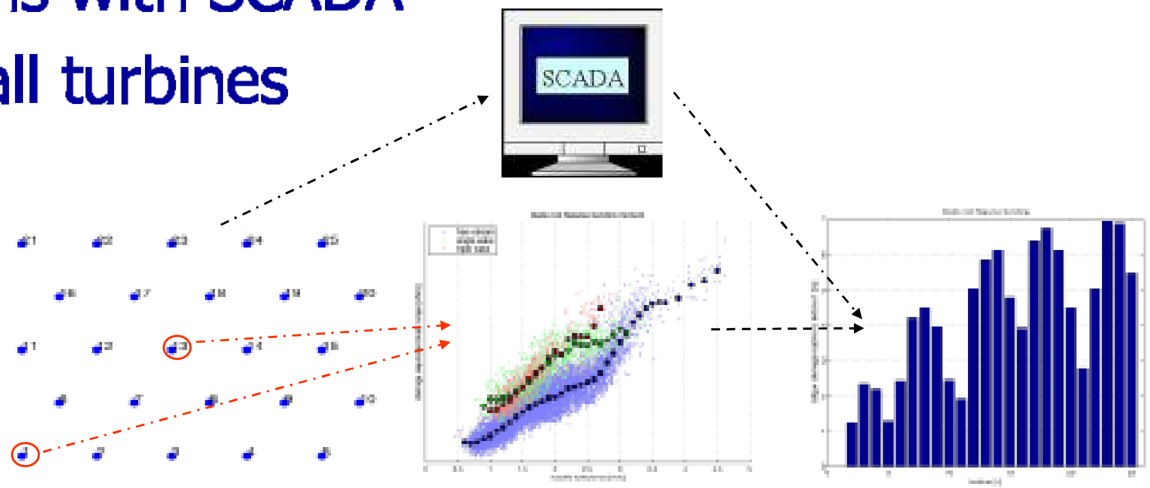
Keep track of the (relative) accumulated loading at all turbines in an (offshore) wind farm

Possibilities:

- Equip all turbines with mechanical load measurements
  - Expensive, time consuming and labour intensive
- Flight Leader concept
  - Less expensive, less time consuming and less labour intensive!
  - BUT: Concept needs to be proven!

Flight Leader concept (2)

- Only few turbines (at strategic locations) equipped with mechanical load measurements
- Relations between load indicators and SCADA parameters
- Combining relations with SCADA data collected at all turbines



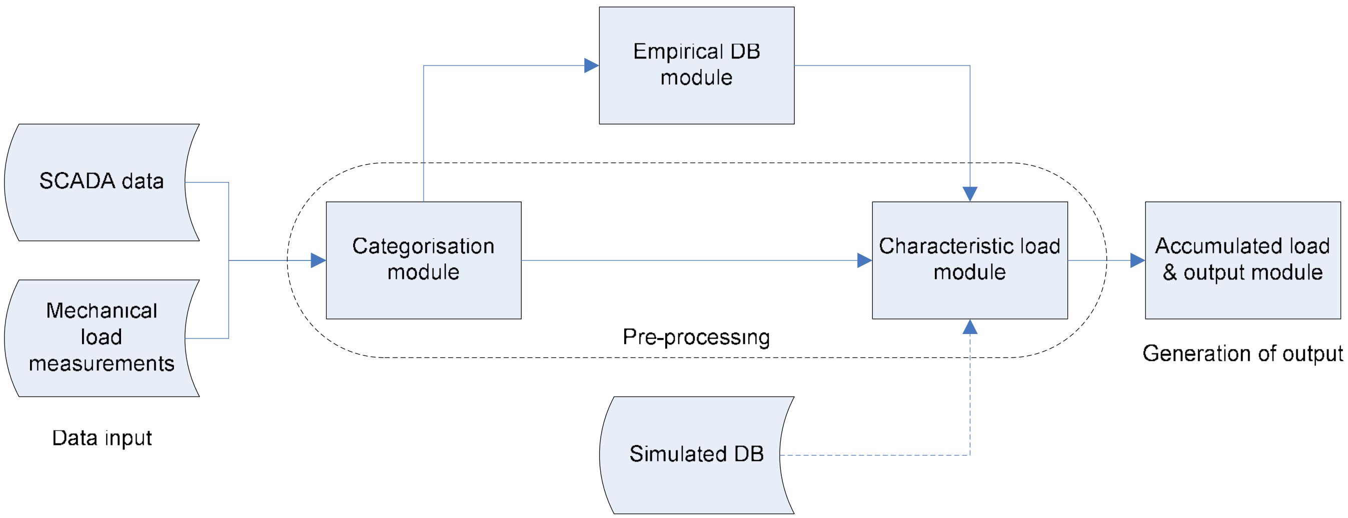
Flight Leader concept (3)

What needs to be proven?

- It is possible to establish accurate relations between SCADA parameters and load indicators
- It is possible to transpose the relations established at the Flight Leader turbines on the other turbines in the wind farm

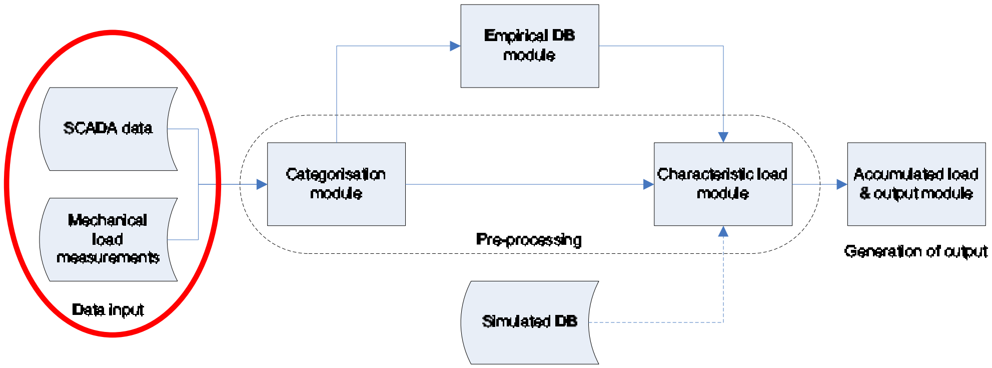
Flight Leader model (1)

- Software model under development
  - Includes all aspects of the Flight Leader concept
  - Intended for offshore wind farm owners/operators
  - Demo version applied at ECN's wind farm EWTW



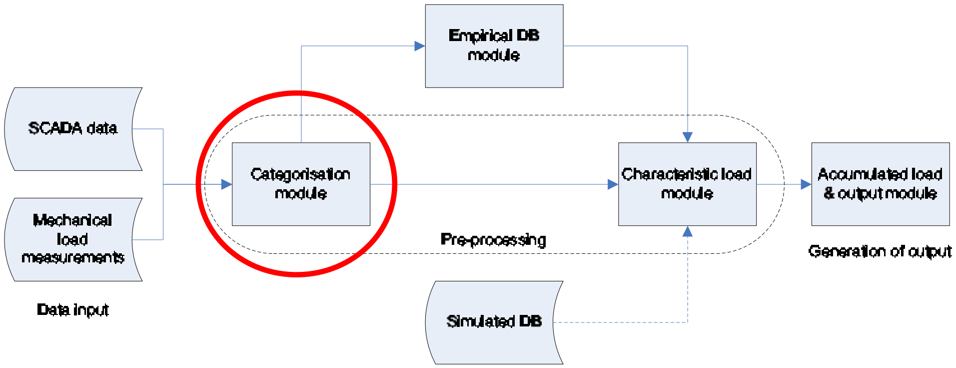
Flight Leader model (2)

- Data input
  - Mechanical load measurements
    - Only Flight Leader turbines
    - 10-minute load indicators (e.g. damage equivalent load)
  - SCADA data
    - All turbines
    - 10-minute statistics (min, max, avg, std, *skew*, *kurt*)



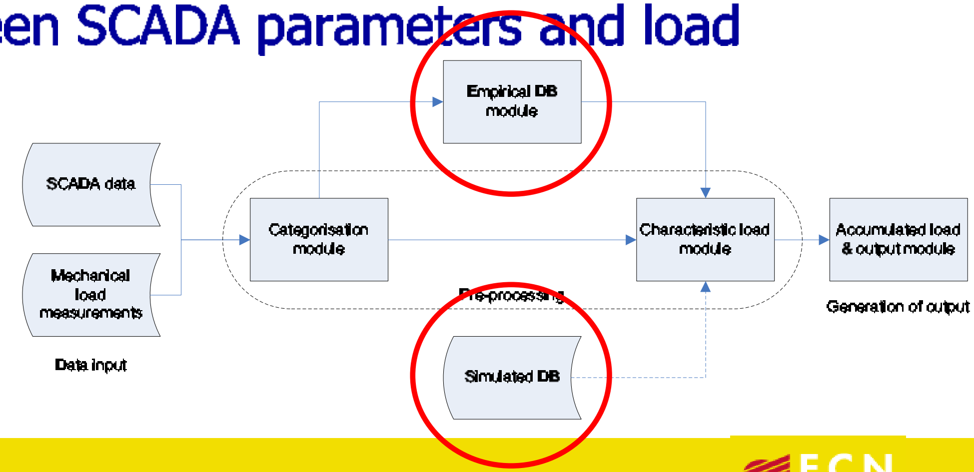
Flight Leader model (3)

- Data categorisation
  - Turbine states & transitional modes
    - Normal power production
    - Parked/Idling
    - Start-up
    - Normal shutdown
    - Emergency shutdown
  - Wake condition
    - Free-stream
    - Partial wake
    - Full wake



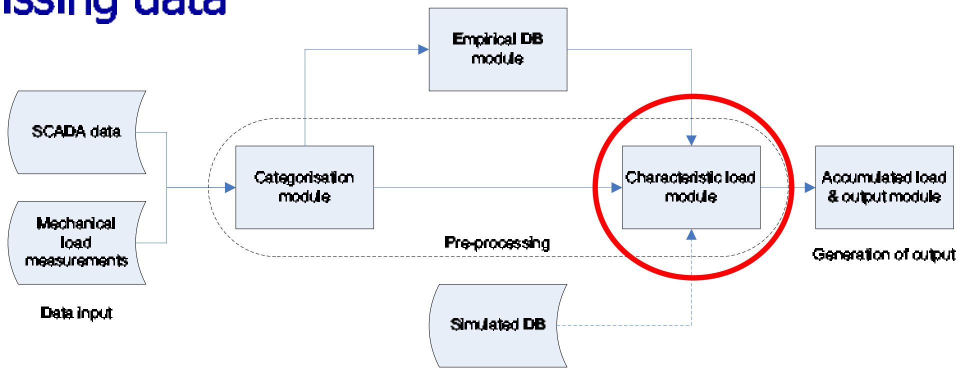
Flight Leader model (4)

- Empirical database
  - Empirical relations between SCADA parameters and load indicators
    - For each combination of turbine state & wake condition
    - Different characterisation methods (interpolation, multivariate regression, artificial neural networks)
- Simulated database
  - Simulated relations between SCADA parameters and load indicators
    - Aero-elastic code
    - Mainly used to fill up missing empirical data



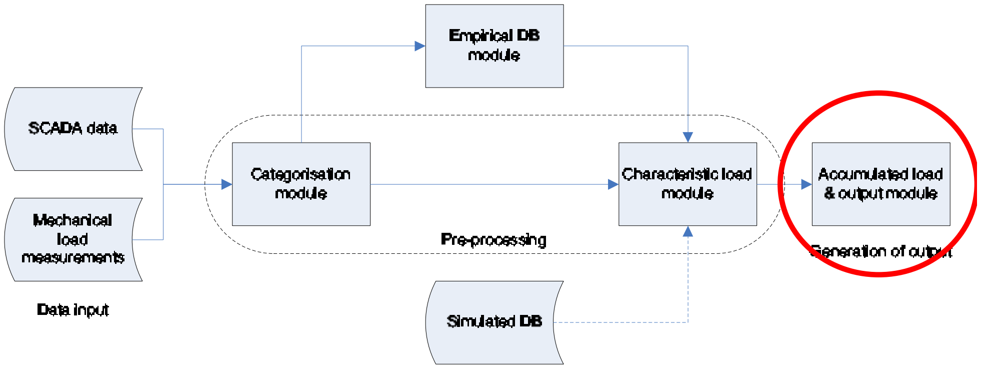
Flight Leader model (5)

- Load estimating
  - Combining SCADA data with relations from empirical and simulated databases
    - For all turbines and timestamps
    - By default empirical database is used
    - If a certain situation has not been encountered yet at one of the Flight Leader turbines the simulated database can be used
    - Procedure for handling missing data



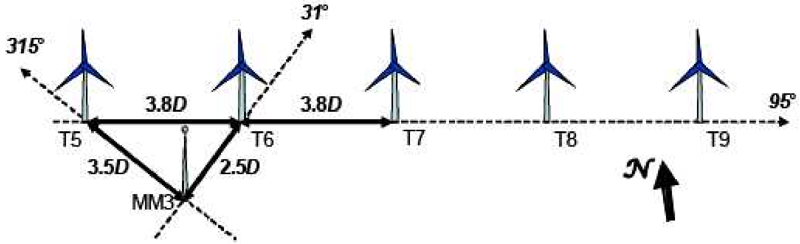
Flight Leader model (6)

- Output
  - Comparison of the relative accumulated loading of all turbines in the wind farm
  - Different breakdowns of the accumulated loading
    - Per turbine state & transitional mode
    - Per wake condition
    - Per time period



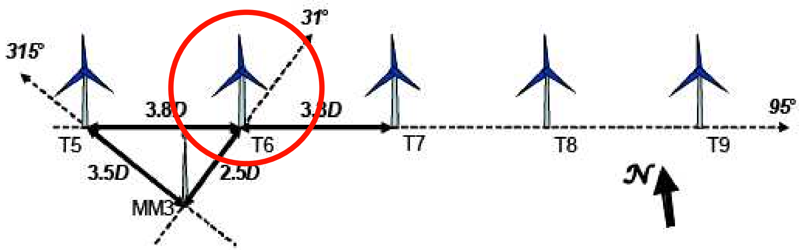
Preliminary results (1)

- Proving the Flight Leader concept
  - It is possible to establish accurate relations between SCADA parameters and load indicators
  - It is possible to transpose the relations determined at the Flight Leader turbines on the other turbines in the farm
- Preliminary results using data from ECN's wind farm EWTW
  - 5 multi-MW pitch-controlled variable speed turbines
  - 9 months of data



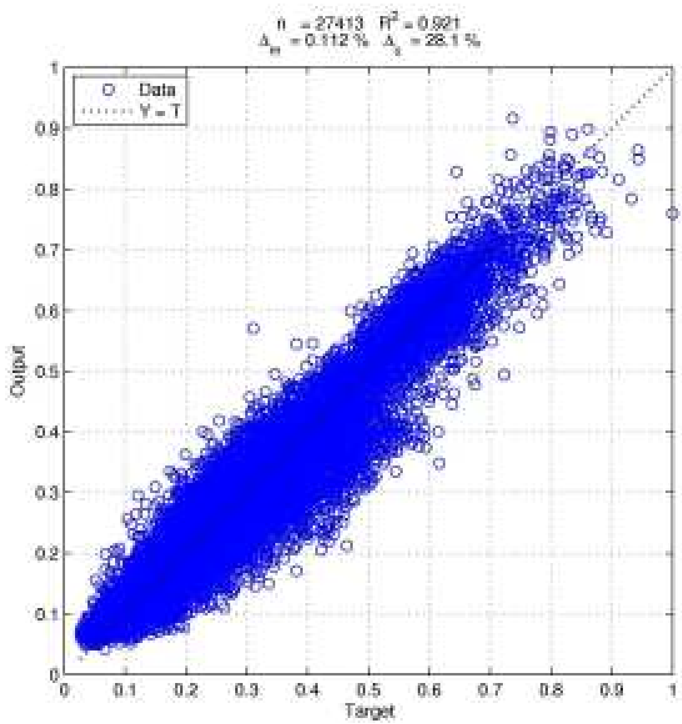
Preliminary results (2)

- Proving the Flight Leader concept
  - It is possible to establish accurate relations between SCADA parameters and load indicators
  - It is possible to transpose the relations determined at the Flight Leader turbines on the other turbines in the farm
- Approach
  - Determine relations at turbine 6
  - Normal power production; Free-stream wind conditions



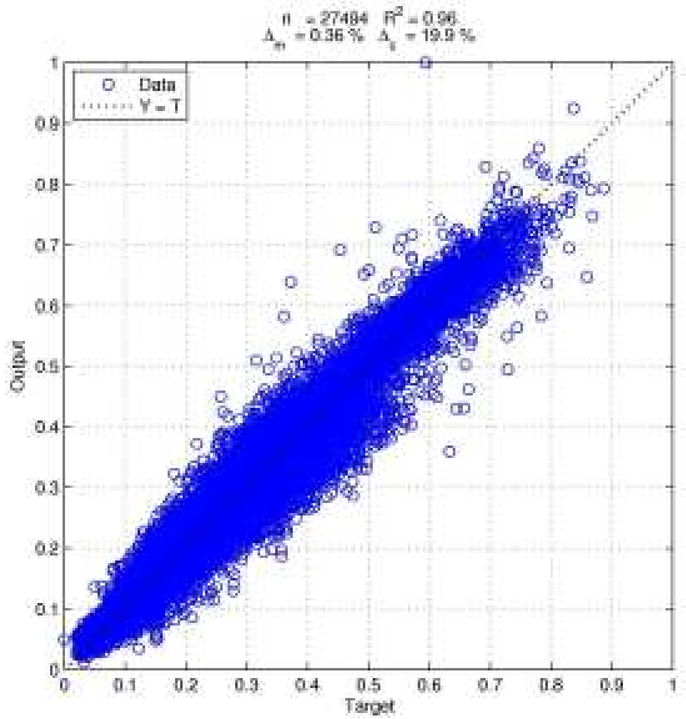
Preliminary results (3)

- Output: 1 Hz equivalent load blade flapwise bending
- Input: 10-minute statistics (avg, std)
  - Nacelle wind speed
  - Power output
  - Generator speed
  - Pitch angle
- Method:
  - Neural network
- Result:
  - n = 27413 samples
  - $R^2 = 0.921$



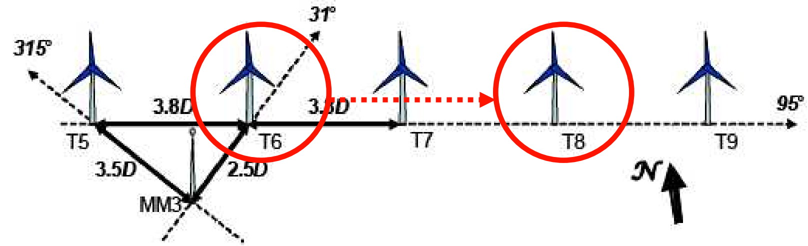
Preliminary results (4)

- Output: 1 Hz equivalent load tower for-aft bending
- Input: 10-minute statistics (avg, std)
  - Nacelle wind speed
  - Power output
  - Generator speed
  - Pitch angle
- Method:
  - Neural network
- Result:
  - n = 27494 samples
  - $R^2 = 0.960$



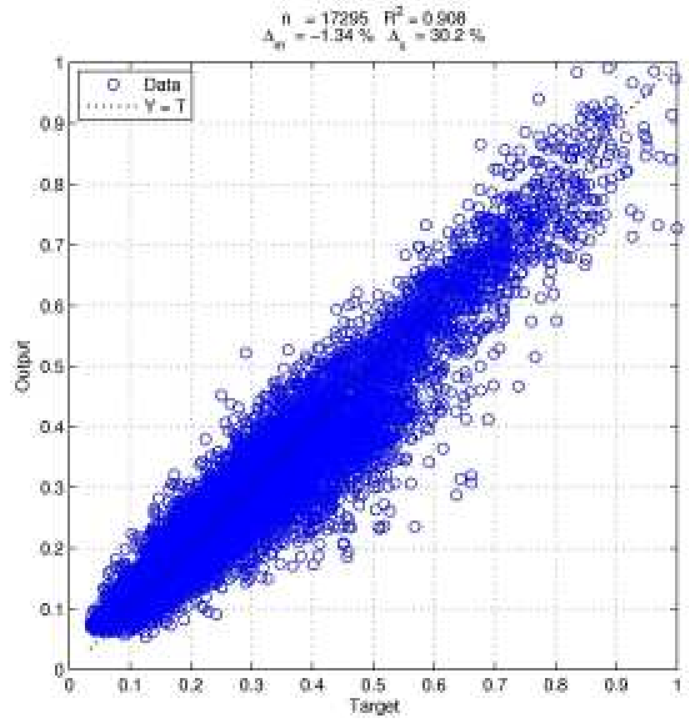
Preliminary results (5)

- Preliminary conclusion
  - It is possible to accurately relate load indicators to 10-minute statistics of SCADA data
  - Therefore the first condition for the 'proof-of-principle' has been met!
  - BUT: Can these relations be transposed to other turbines?
- Approach
  - Predict load indicators at turbine 8 using the relations established at turbine 6
  - Compare the predicted values of the load indicators with the actual measured values



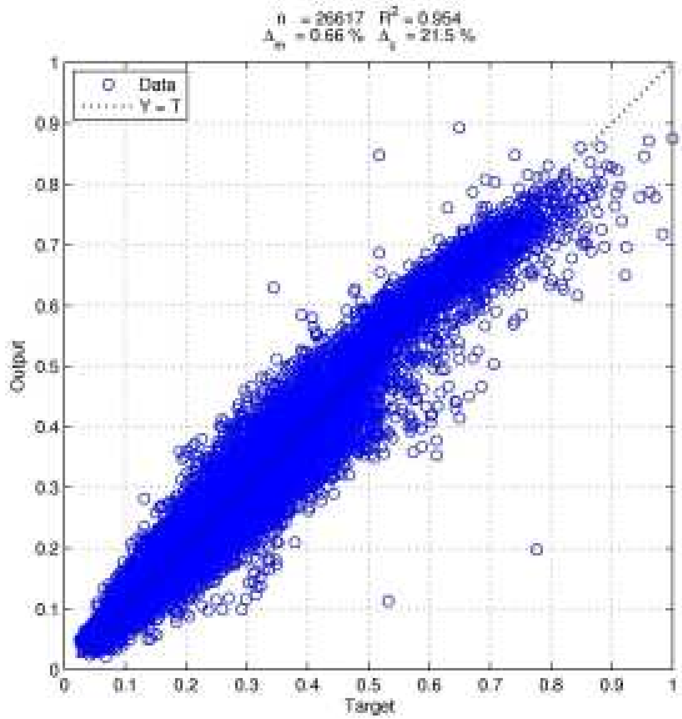
Preliminary results (6)

- Output: 1 Hz equivalent load blade flapwise bending
- Input: 10-minute statistics (avg, std)
  - Nacelle wind speed
  - Power outpaut
  - Generator speed
  - Pitch angle
- Method:
  - Neural network (trained at T6)
- Result:
  - n = 17295 samples
  - $R^2 = 0.908$



Preliminary results (7)

- Output: 1 Hz equivalent load tower bottom bending
- Input: 10-minute statistics (avg, std)
  - Nacelle wind speed
  - Power output
  - Generator speed
  - Pitch angle
- Method:
  - Neural network (trained at T6)
- Result:
  - n = 26617 samples
  - $R^2 = 0.954$



Preliminary results (8)

- Accurate relations are important…
- …but the generalisability is crucial!

R^2	T6	T8
Blade root flapwise bending	0.921	0.908
Tower bottom for-aft bending	0.960	0.954

- Try same approach for different components and other turbine states (e.g. idling, start-up, emergency shutdown, etc.)
- Are relations established in free-stream conditions applicable for a wind turbine operating in wake?

Conclusions

- O&M optimisation is necessary for lowering the kWh price of offshore wind energy
- Load monitoring could contribute to optimisation
  - BUT: expensive, time consuming and labour intensive
- Flight Leader concept could prove a low-cost solution for monitoring the load accumulation at all turbines
  - BUT: concept needs to be proven…
    - Prove of concept using EWTW data
    - Initial results look promising!
- Still some work to do…
  - Programming Flight Leader software
  - Data analysis EWTW
  - Data analysis offshore wind farm

Questions

Discussion

- What functionality should be included/excluded in the Flight Leader software?
- What load indicators are relevant for drive train components?