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Aeroelasticity and aeroacoustics of wind turbines

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AEROELASTICITY AND AEROACOUSTICS OF WIND TURBINES

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Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic simulation tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- New technology - outlook
- Summary

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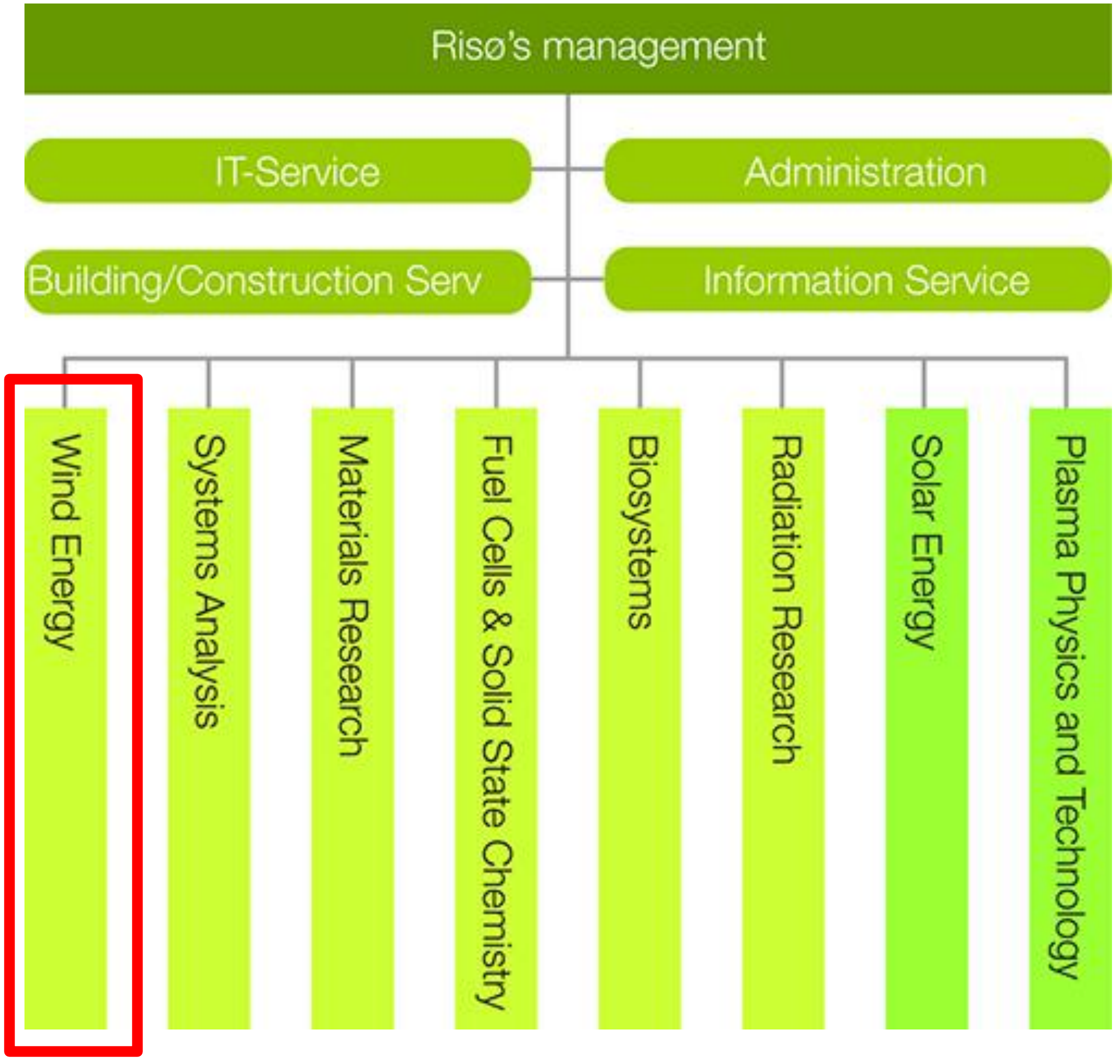
Risø's history in brief

- **1956** Peaceful utilization of nuclear energy
- **1976** Nuclear energy and other energy sources
- **1986** Energy research in general
- **1990** R&D with energy as the primary area
- **1994** State-owned enterprise
- **2000** The last nuclear reactor is decommissioned
- **2005** Impact within
  1. Technology for greater competitiveness
  2. Sustainable energy supply
  3. Health technology
- **2007** Merged with DTU (The Technical University of Denmark)

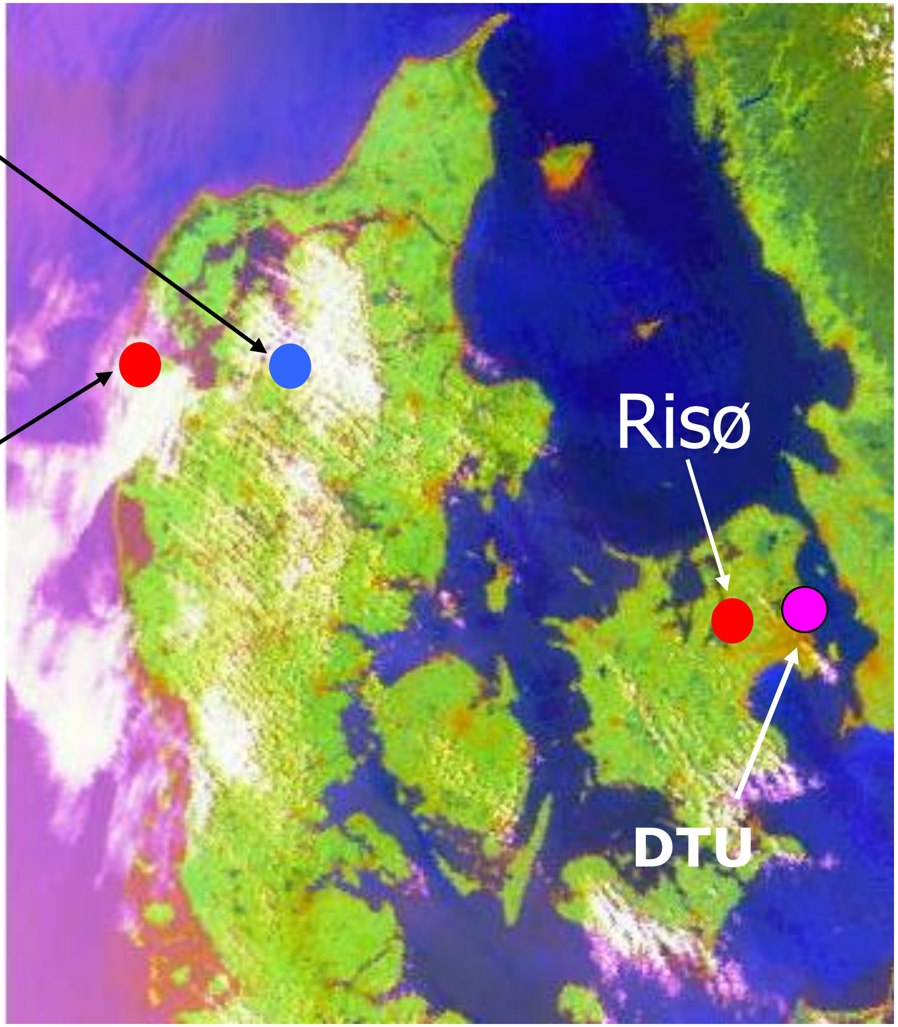
Risø DTU


Risø's management
IT-Service
Administration
Building/Construction Serv
Information Service
Wind Energy
Systems Analysis
Materials Research
Fuel Cells & Solid State Chemistry
Biosystems
Radiation Research
Solar Energy
Plasma Physics and Technology

Wind Energy Division

Blade Test Center Sparkær (Force+DNV)

National Test Station Høvsøre



150 employees in 5 research programmes

National Test Station for Large Wind Turbines - 2007

Small wind turbines at Risø - 1979

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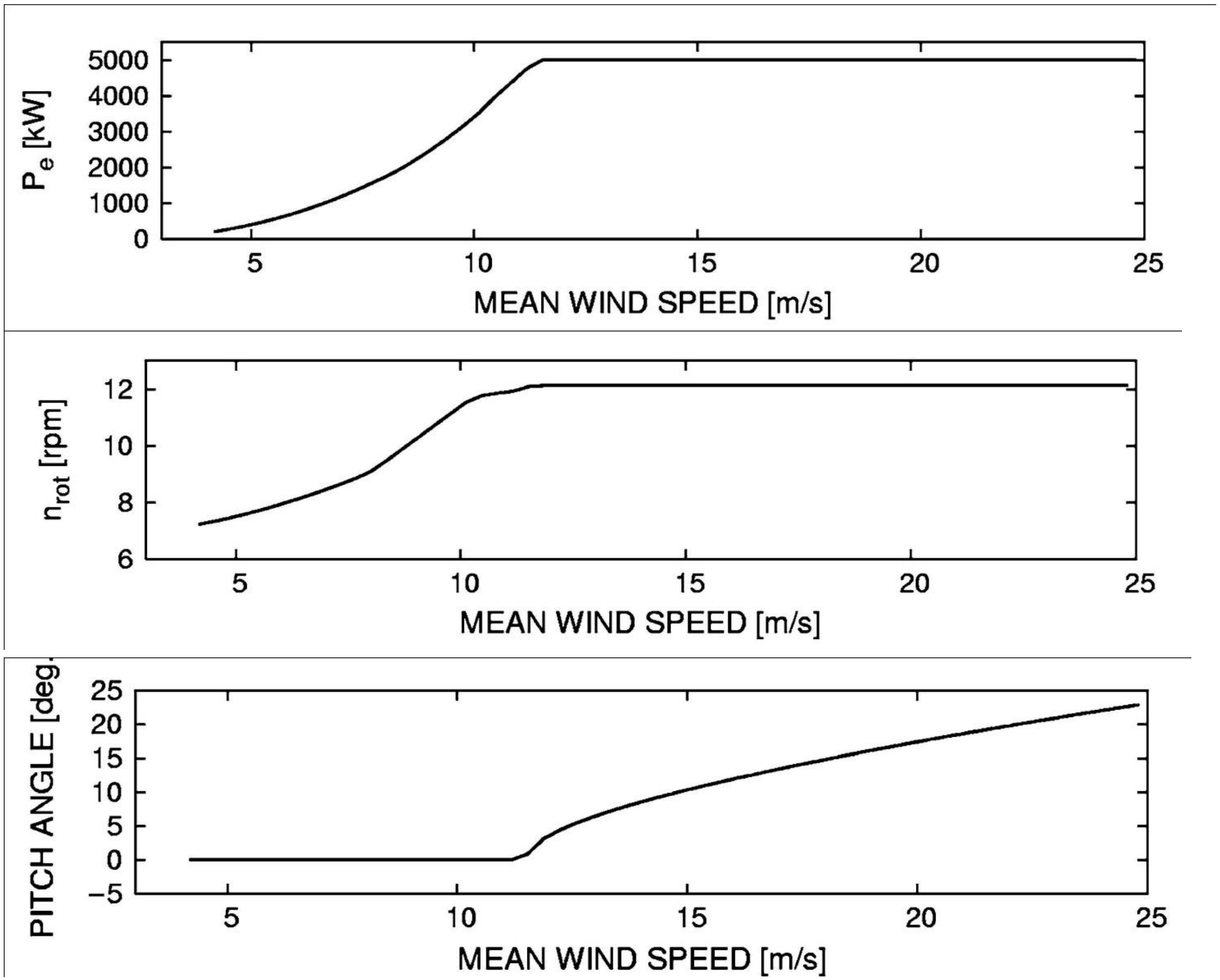
The typical wind turbine design 2011

- rated power 2-5 MW
- 80-125 m rotor
- pitchregulated
- variable speed
- steel, tubular tower
- gearbox or direct drive with multipole generator
- load alleviation with cyclic pitch
- advanced control and monitoring system

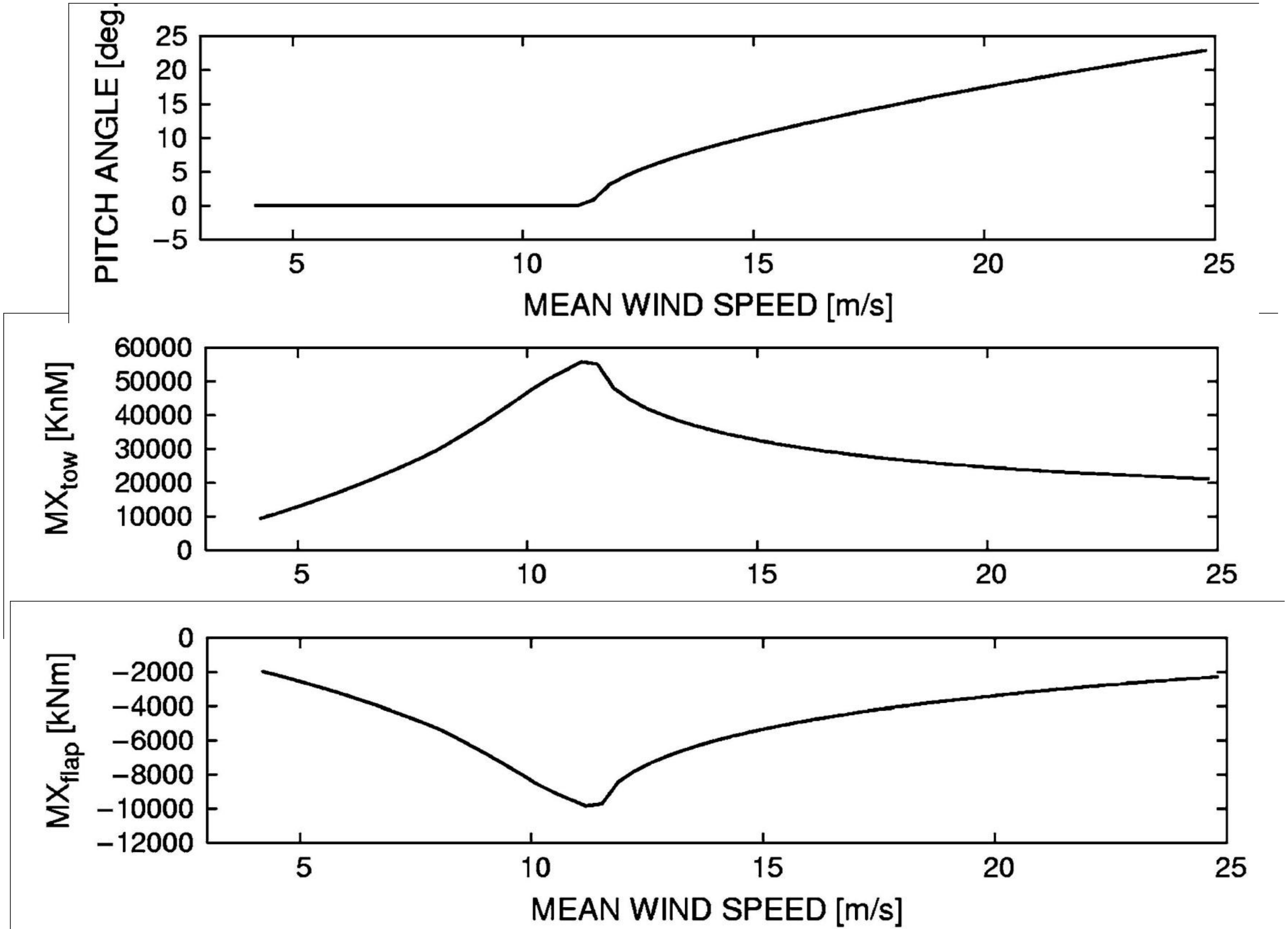
The typical wind turbine design 2011

Variable speed – const tip speed ratio

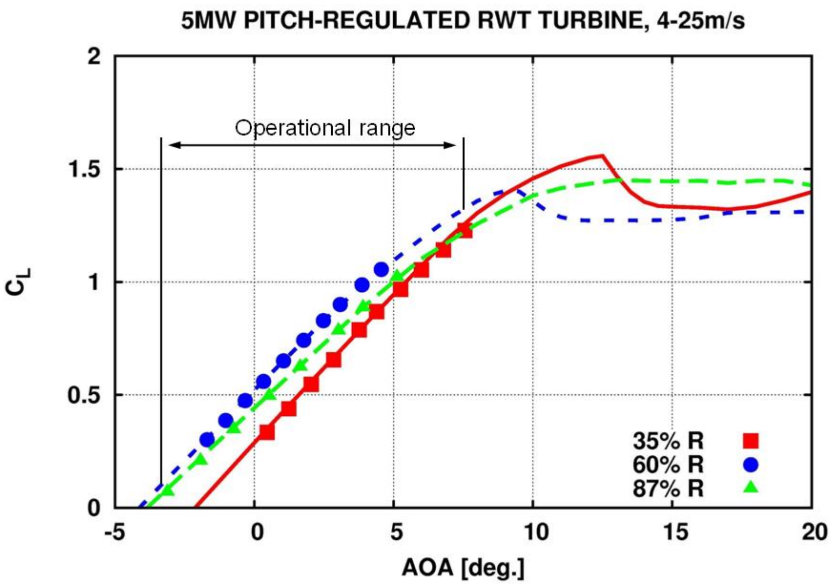
Pitchregulation



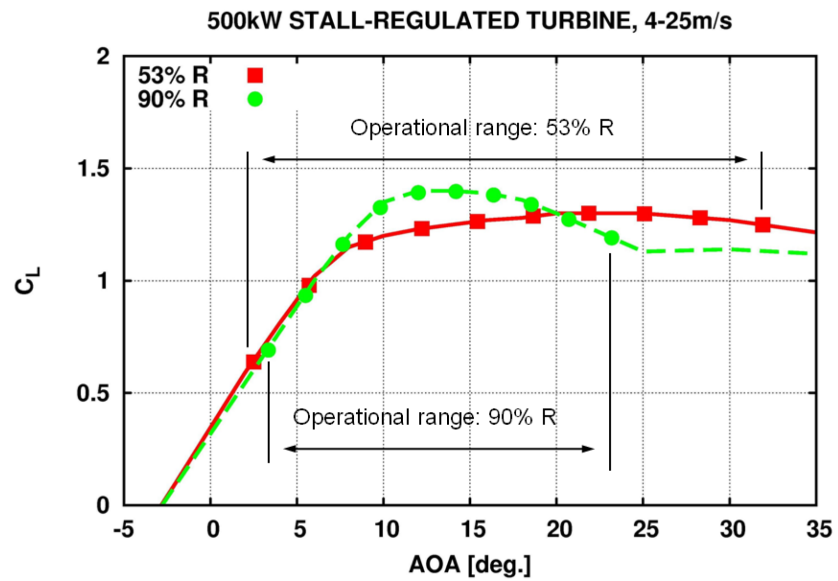
The typical wind turbine design 2011



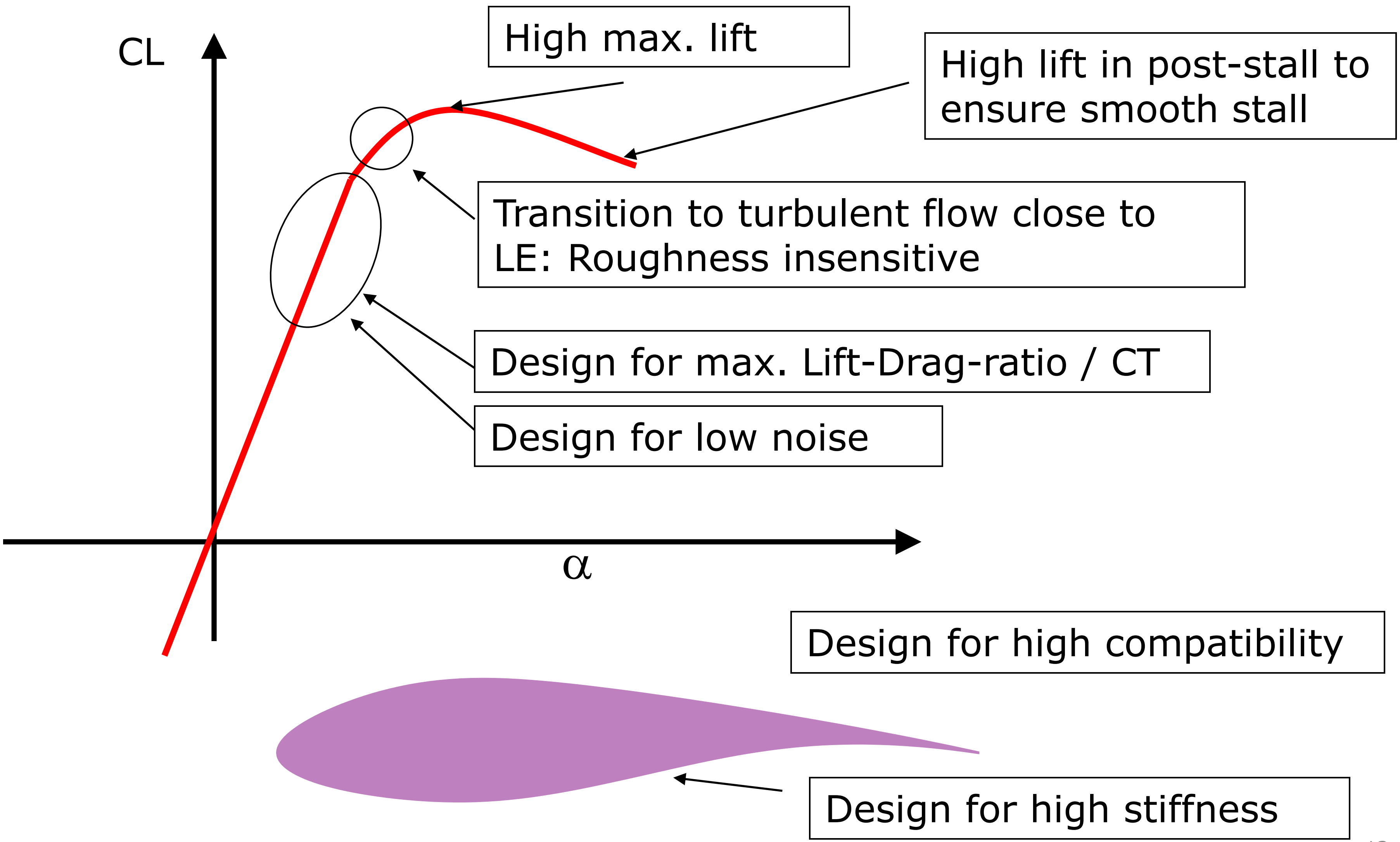
The typical wind turbine design 2011



Old stall regulated turbine

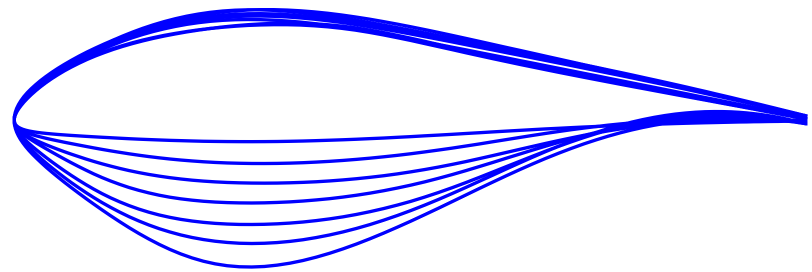


The typical wind turbine design 2011
-use of dedicated airfoil designs

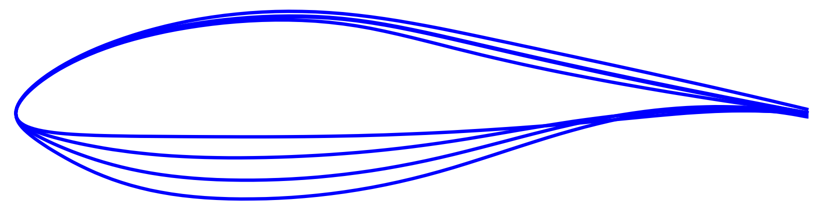


The typical wind turbine design 2011 -use of dedicated airfoil designs

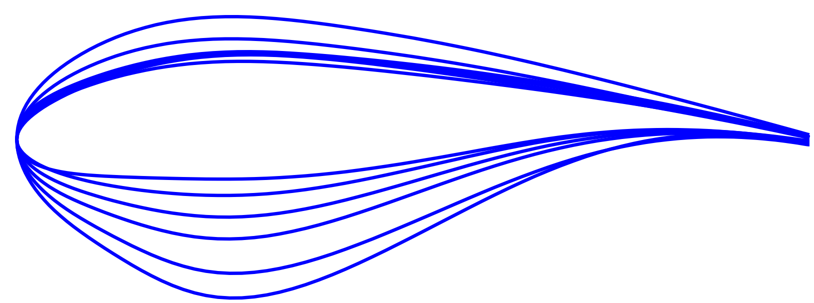
- **Risø-A1 (15% to 30%)**
  - Designed for stall, active stall and pitch
  - Full scale tested on a 600 kW ASR wind turbine



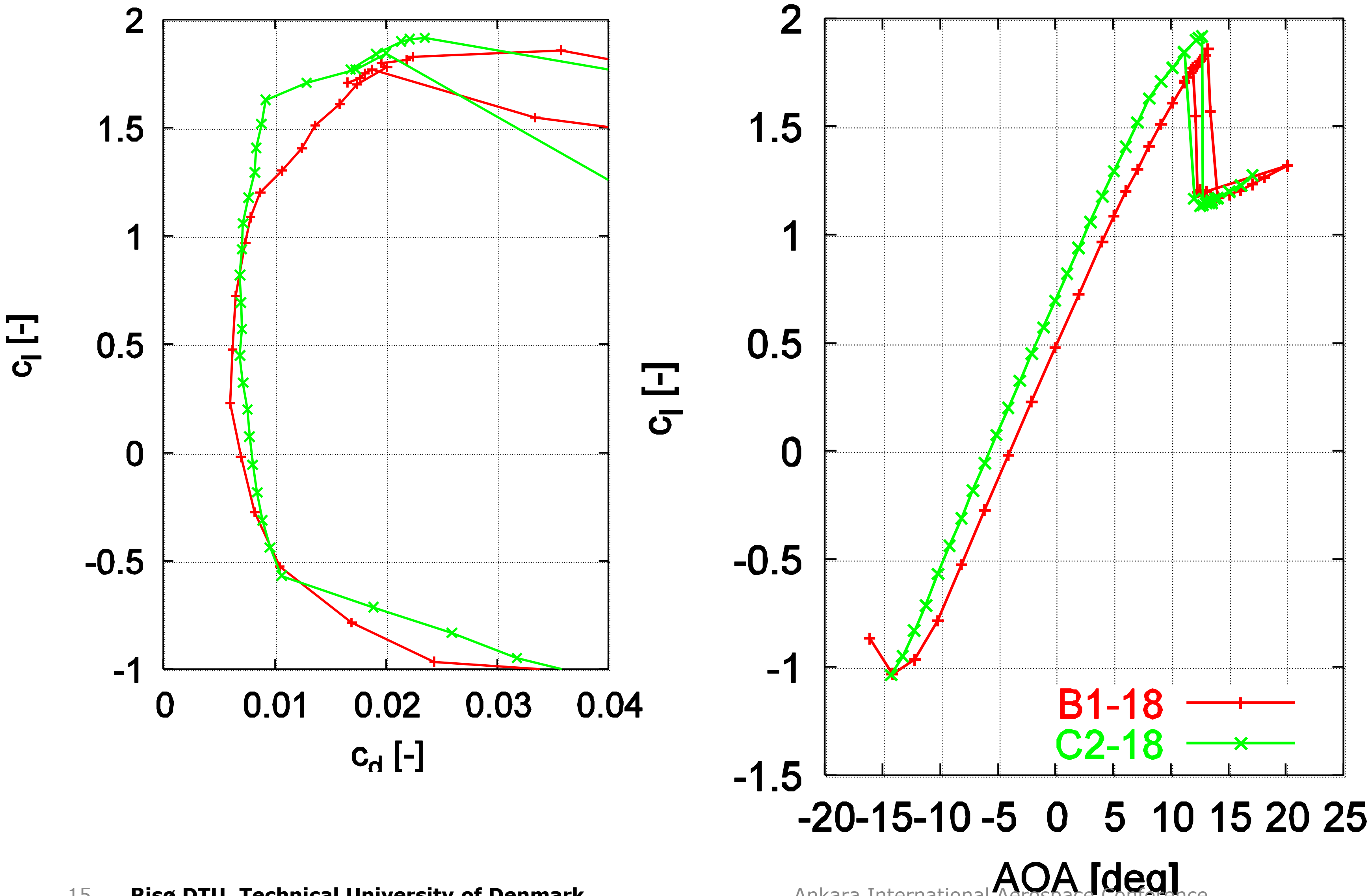
- **Risø-P (12% to 24%)**
  - Designed to replace Risø-A1 for pitch control
  - Used on 3 MW PRVS wind turbines



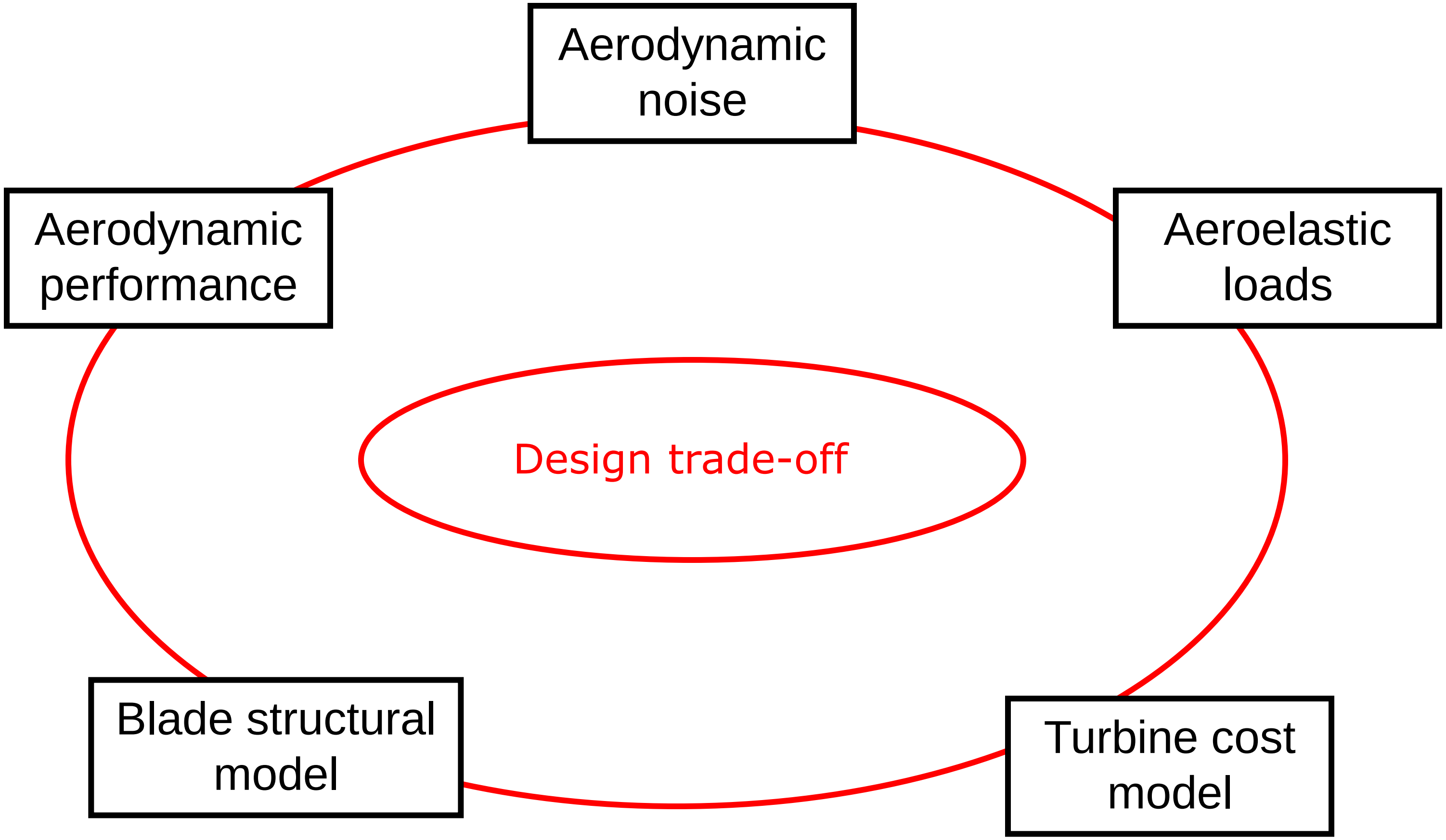
- **Risø-B1 (15% to 53%)**
  - Designed for pitch regulation variable speed control
  - Used on several MW size PRVS wind turbines



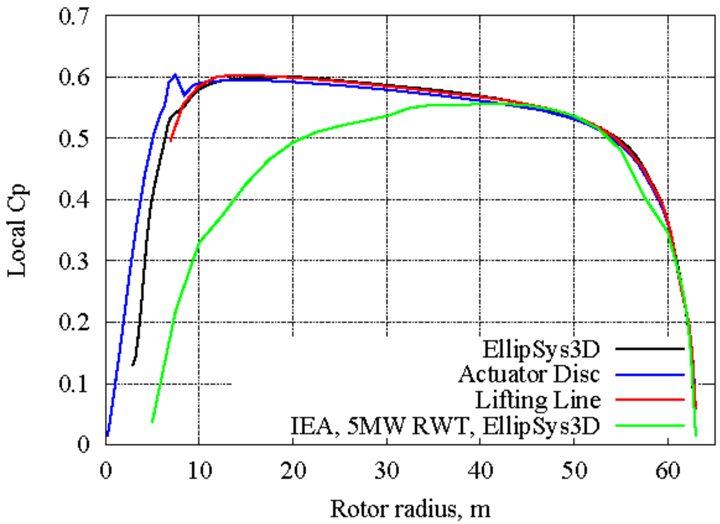
The typical wind turbine design 2011 -use of dedicated airfoil designs



Aeroelastic *blade* design



Blade designed for maximum aerodynamic efficiency



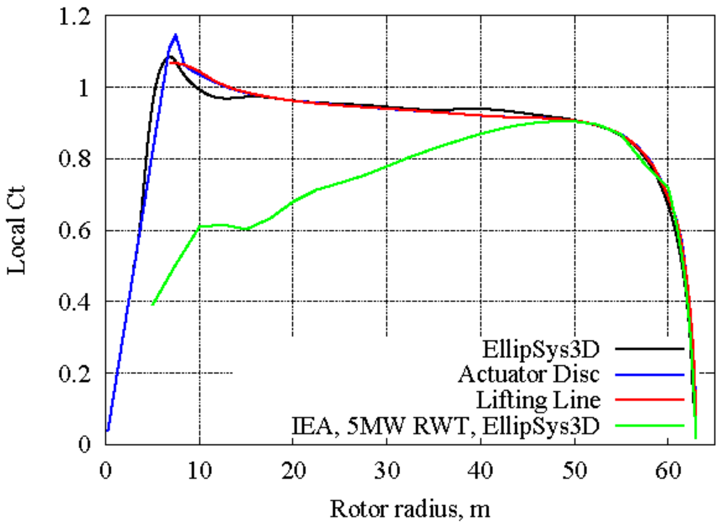


Table 1: Mechanical power and Thrust force for the present rotor. The IEA, 5MW RWT is included for comparison

	Mechanical power, *P* [MW]	Thrust force, *T* [kN]	*CP*	*CT*
EllipSys3D	**2.015**	**426**	**0.515**	**0.872**
Lifting Line	**2.011**	**424**	**0.514**	**0.868**
Actuator Disc	**1.995**	**425**	**0.510**	**0.870**
IEA, 5MW RWT EllipSys3D	**1.867**	**382**	**0.477**	**0.782**

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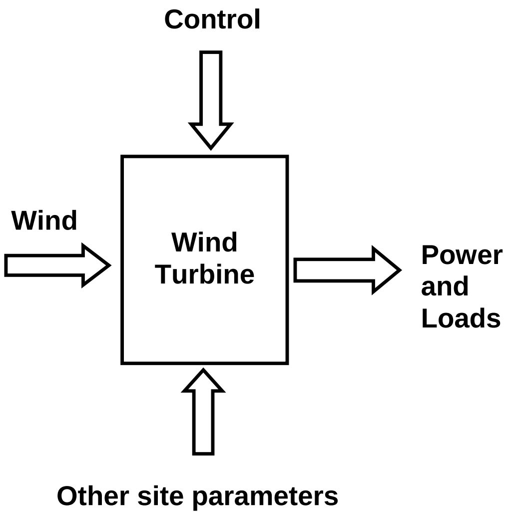
Wind turbine loads and certification



Loading from:

- turbulence and wind shear in the atmospheric inflow
- wakes from neighbouring turbines
- waves
- control action, e.g. an emergency stop

Wind turbine loads and certification

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r - 2$ m/s, V_r, $V_r + 2$ m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T
	8.2	EWM	1-year recurrence period		U	A

List of load cases from IEC61400-1.

In total 1000-1500 load cases to be simulated – most 10 min. simulations

f=fatigue

u = ultimate load

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Numerical models/tools used for aerodynamic and aeroelastic analysys at the Aeroelastic Design Group (AED) at Risø DTU

- **EllipSys2D**
  - 2D CFD code used mainly for computation on **2D airfoil sections**
- **EllipSys3D**
  - 3D CFD code used for **rotor computations** and flow over terrain
- **Hawc2**
  - Aeroelastic multibody code for aeroelastic time simulation of wind turbines
- **HAWCStab**
  - code for computation of aeroelastic stability
- **HAWTopt**
  - tool for design and **optimization of rotors**
- **AirfoilOpt**
  - tool for design and **optimization of airfoils**

Aeroelastic codes and simulations

Aeroelastic codes for time simulations used by industry:

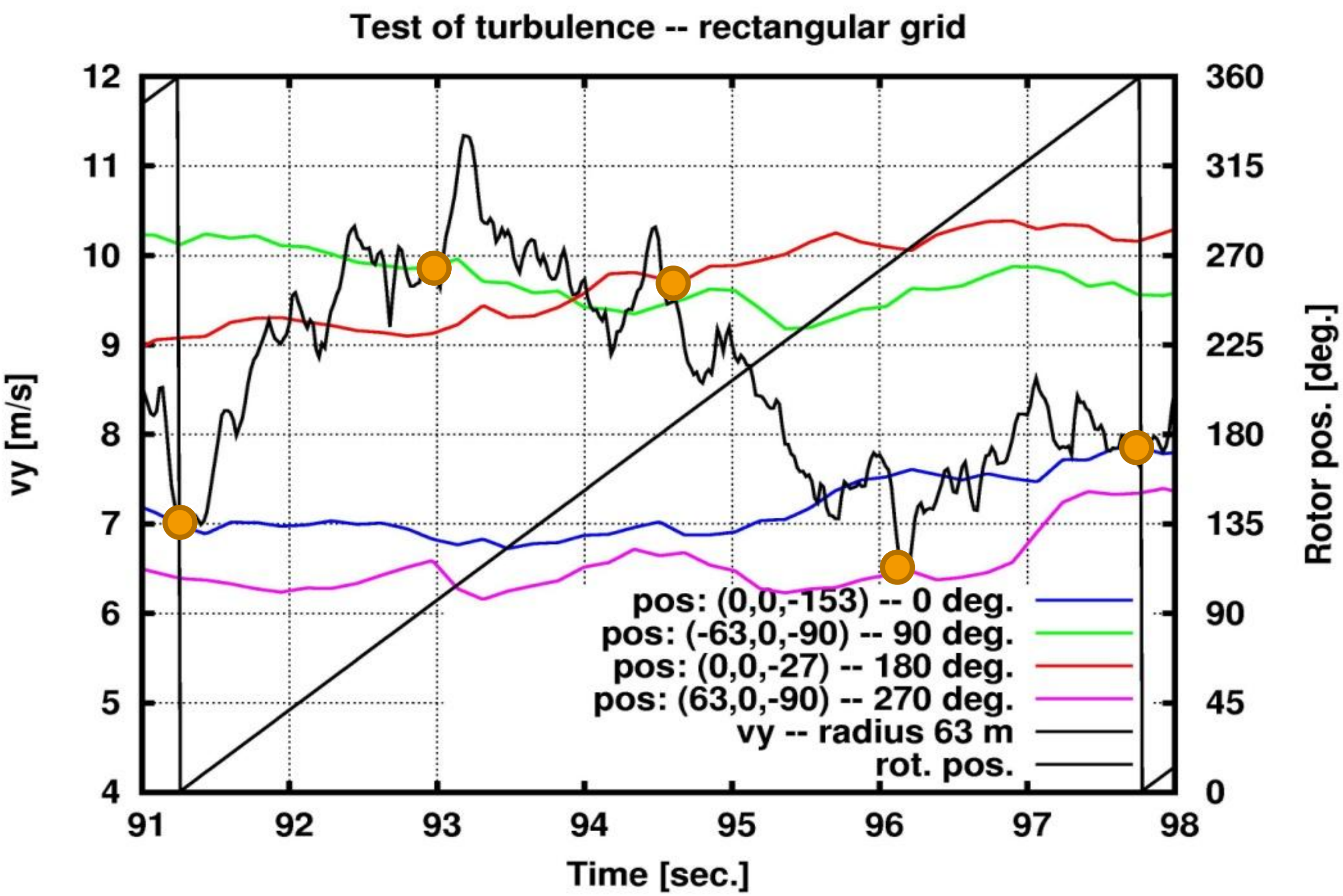
- **FLEX5**
- **FAST**
- **BLADED**
- **HAWC2**

- simulations in real time or faster

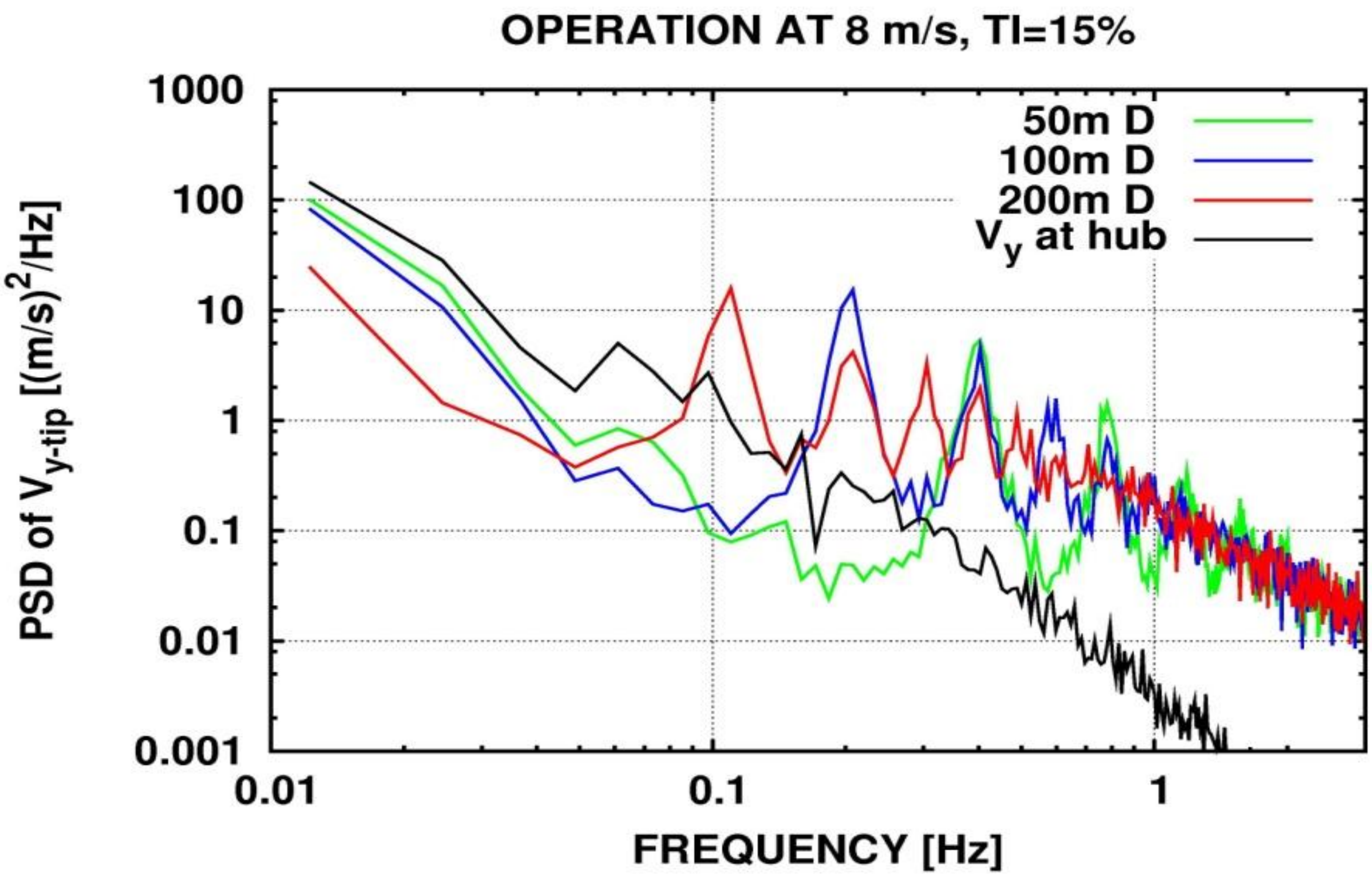
Engineering sub-models for simulation of:

- yawed flow
- dynamic stall
- unsteady blade aerodynamics
- unsteady inflow
- tip loss
- tower shadow
- wakes from neighboring turbines
- simulation of atmospheric inflow
- hydrodynamics
- wave loads
- control

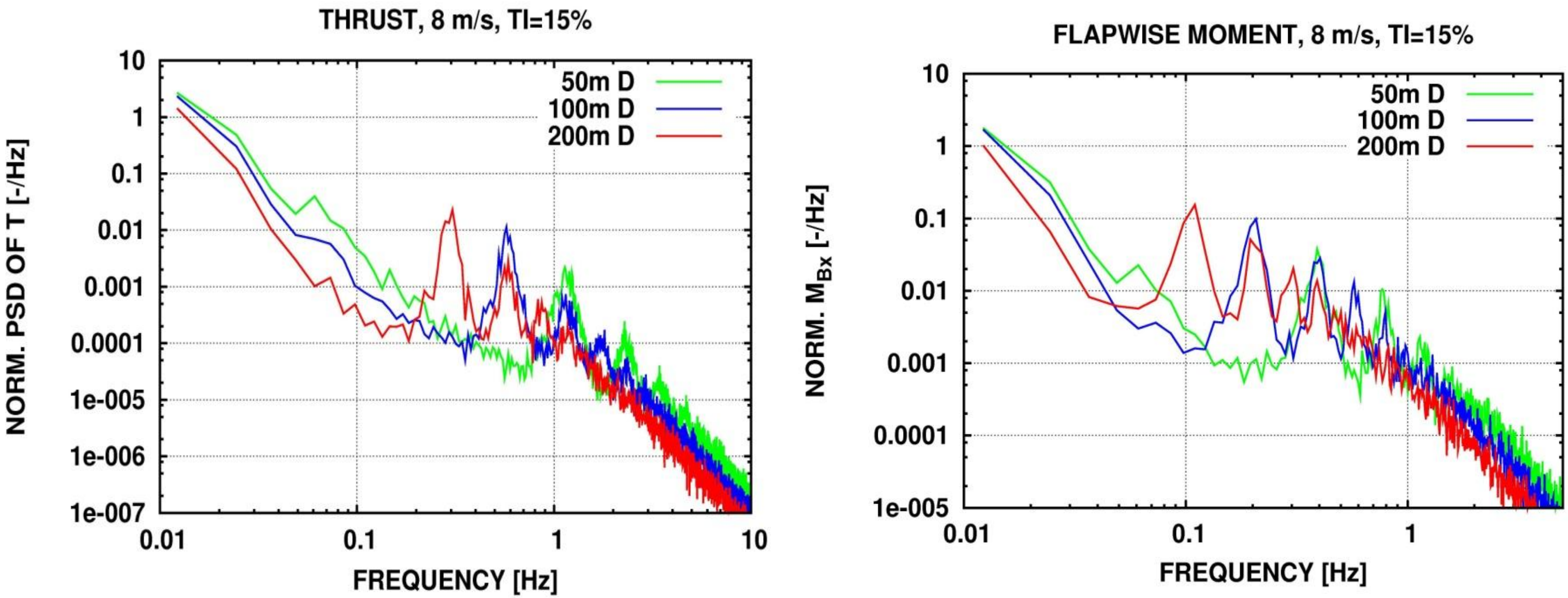
Turbulence in atmospheric inflow is the main driver of loads - rotational sampling of turbulence



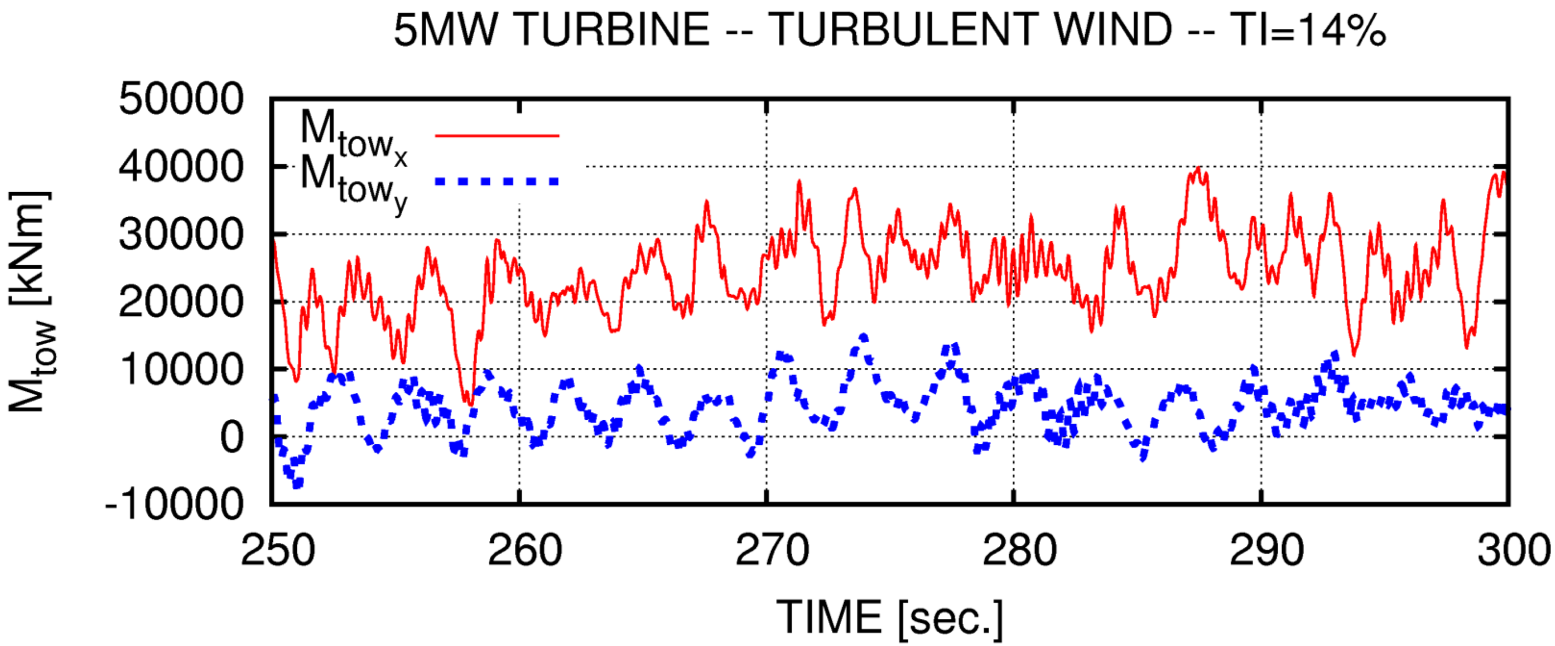
Turbulence in atmospheric inflow main driver of loads - rotational sampling of turbulence



Turbulence in atmospheric inflow main driver of loads - rotational sampling of turbulence



Simulated tower loads



The bending moment in the tower base of a 5MW turbine at 18 m/s wind speed and 10% turbulence. Solid curve bending in main wind direction, dashed curve perpendicular.

Extreme load case – gust 18-24 m/s

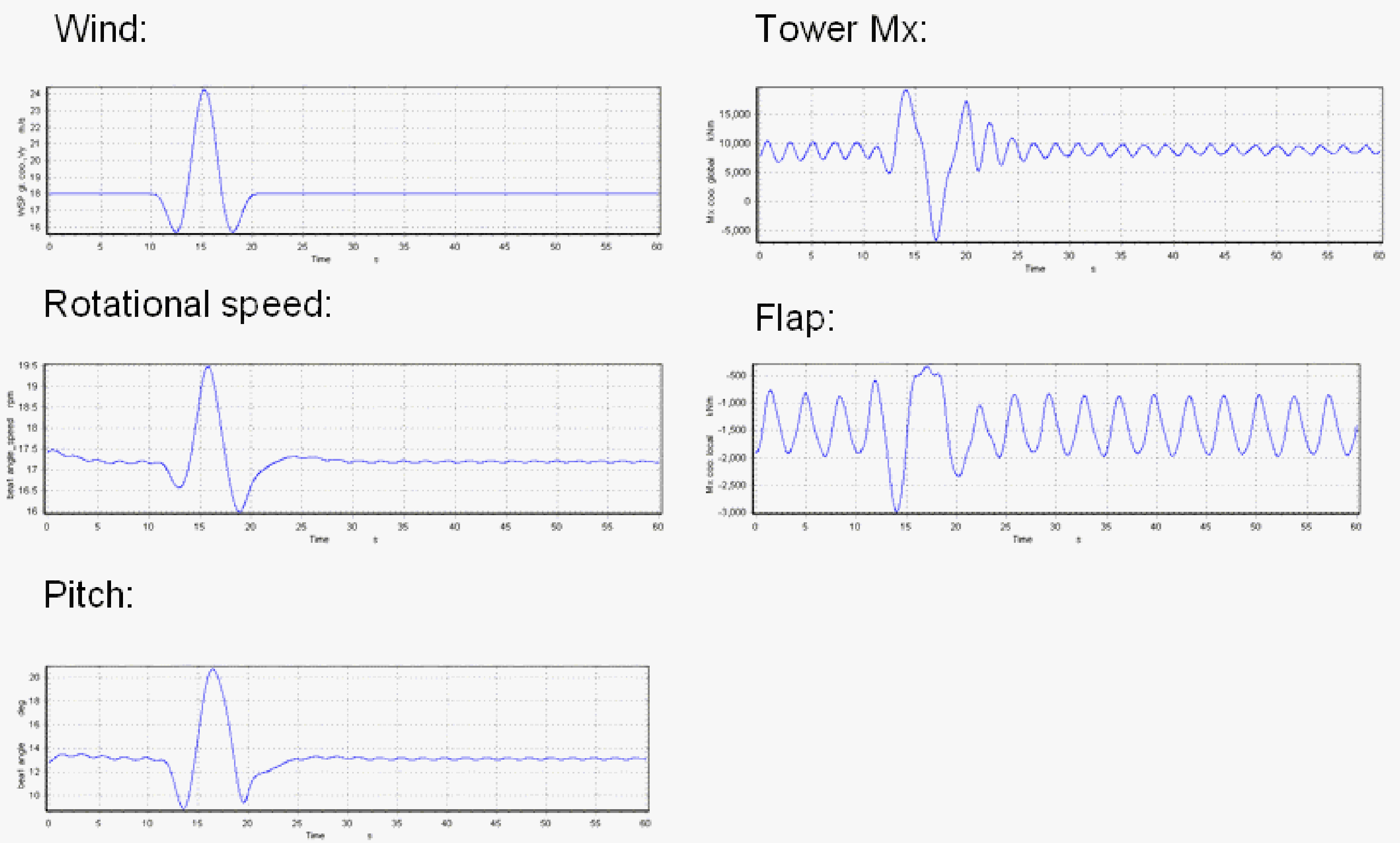
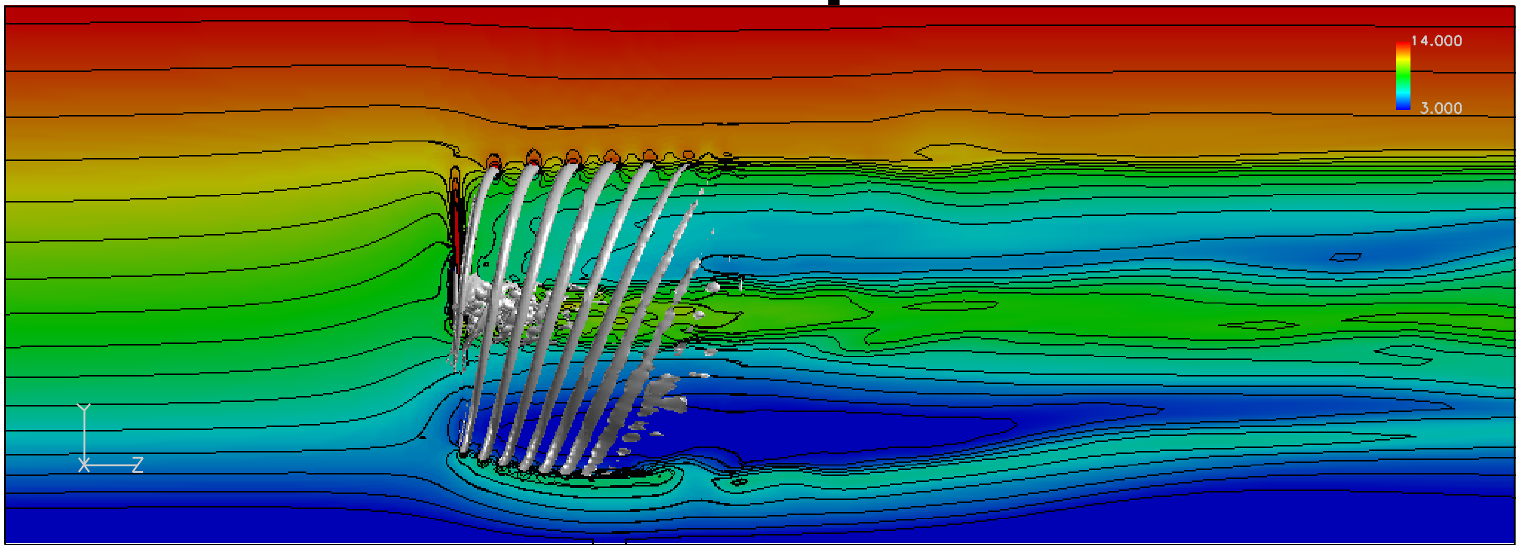


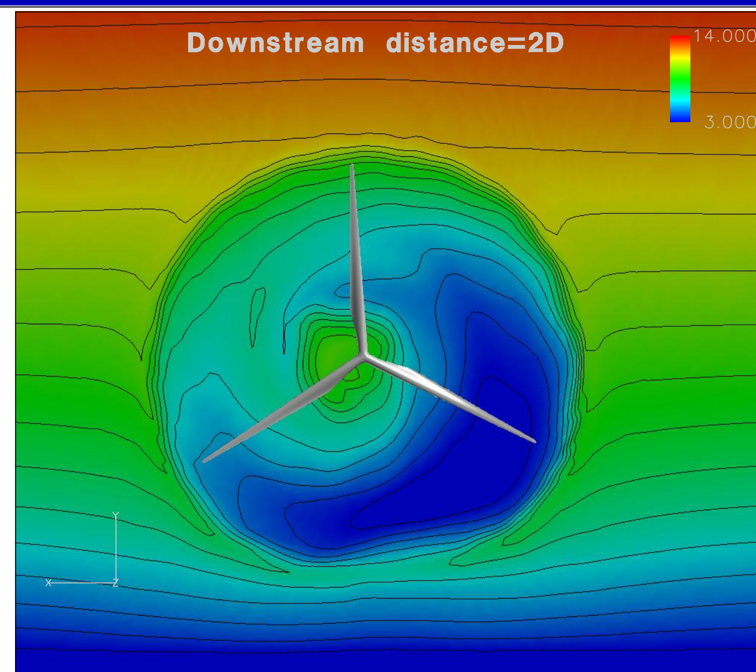
Figure 17 Sample simulation EOG gust during normal operation,

CFD: Rotors in atmospheric shear



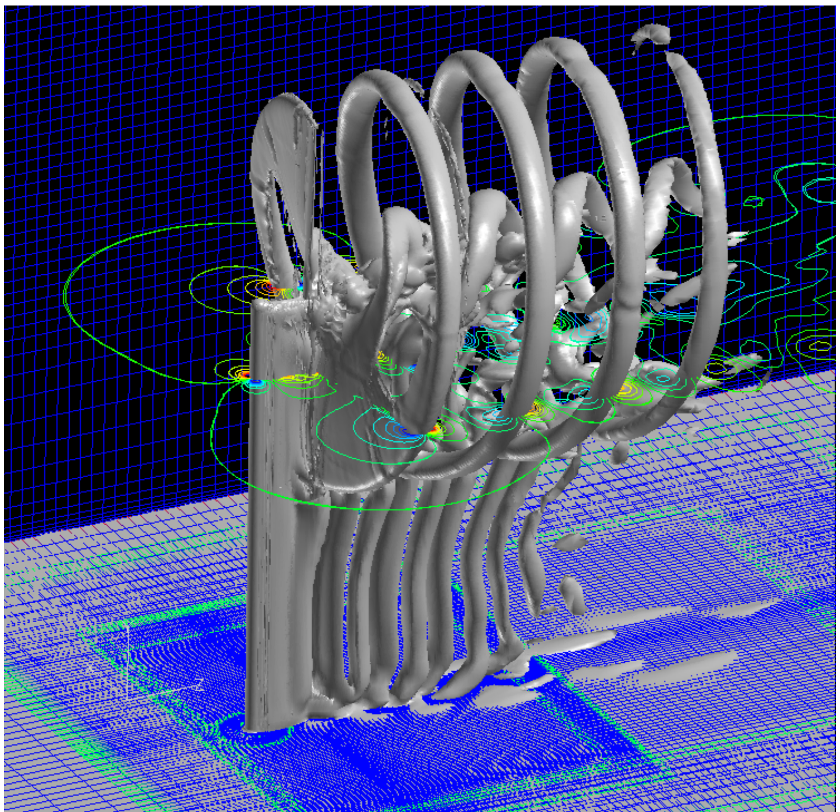
Results from CFD-analysis:

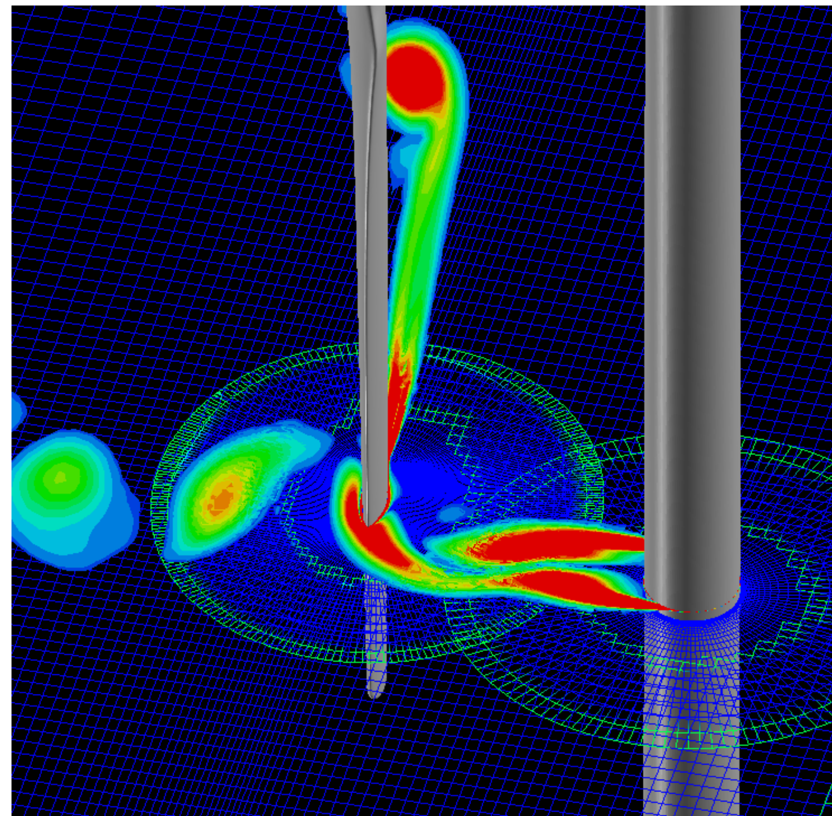
- Shear causes aerodynamic hysteresis effects.
- Blade loads are different in horizontal position.
- Shear causes rotor yaw loads



CFD
Wind turbine rotor-tower interaction

Details of blade-tower interaction investigated in order to:
- study lock-in phenomena
- develop semi-emperical tower shadow model and noise model





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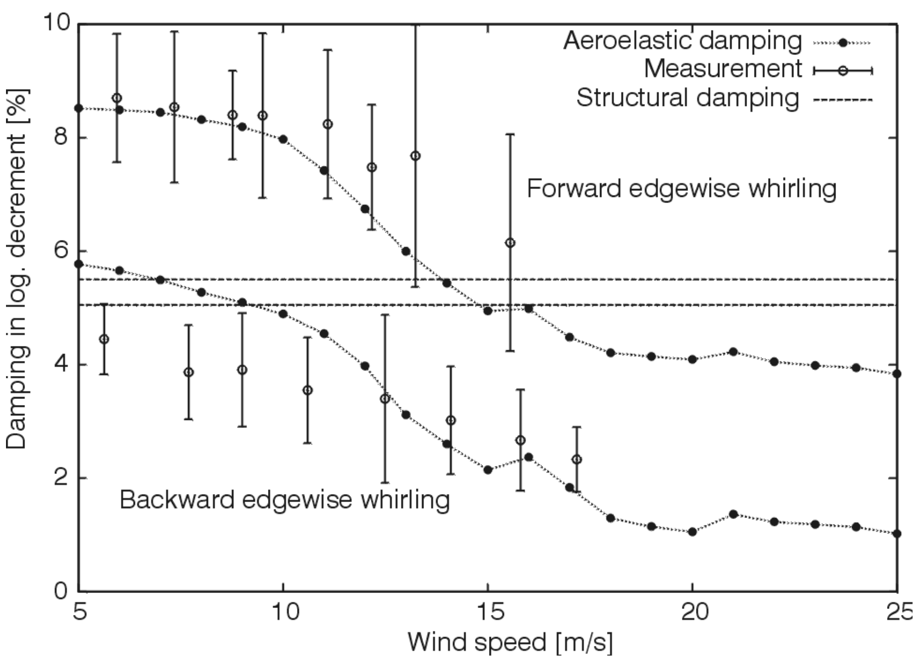
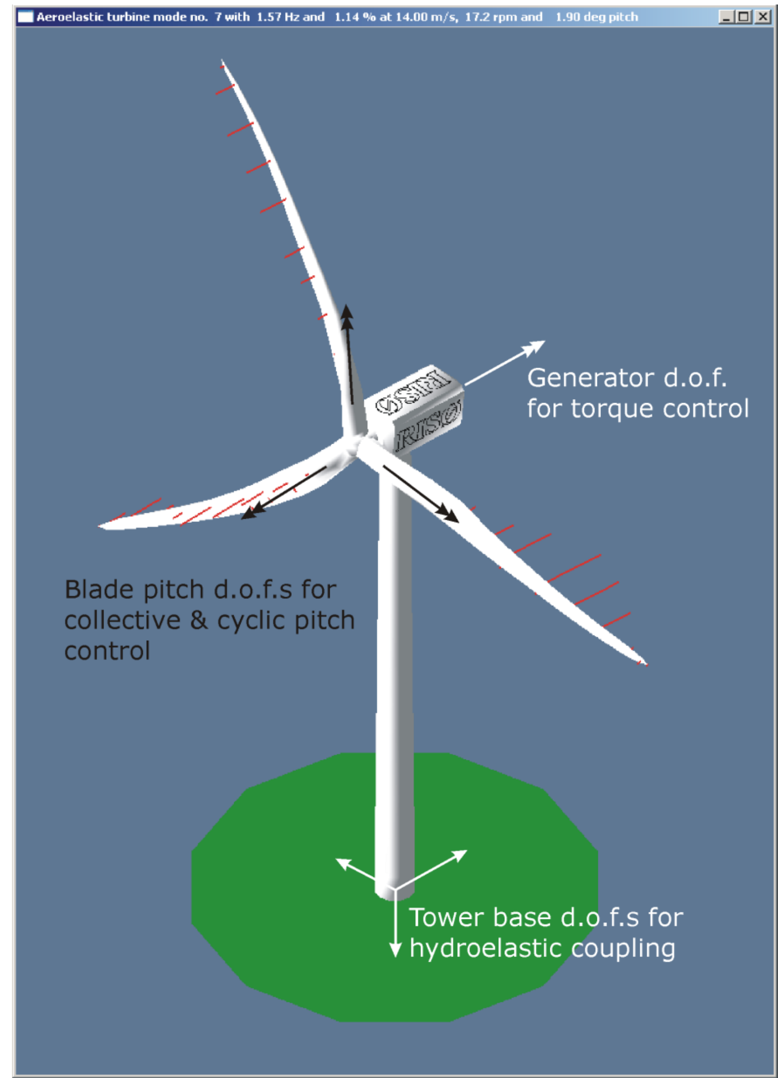
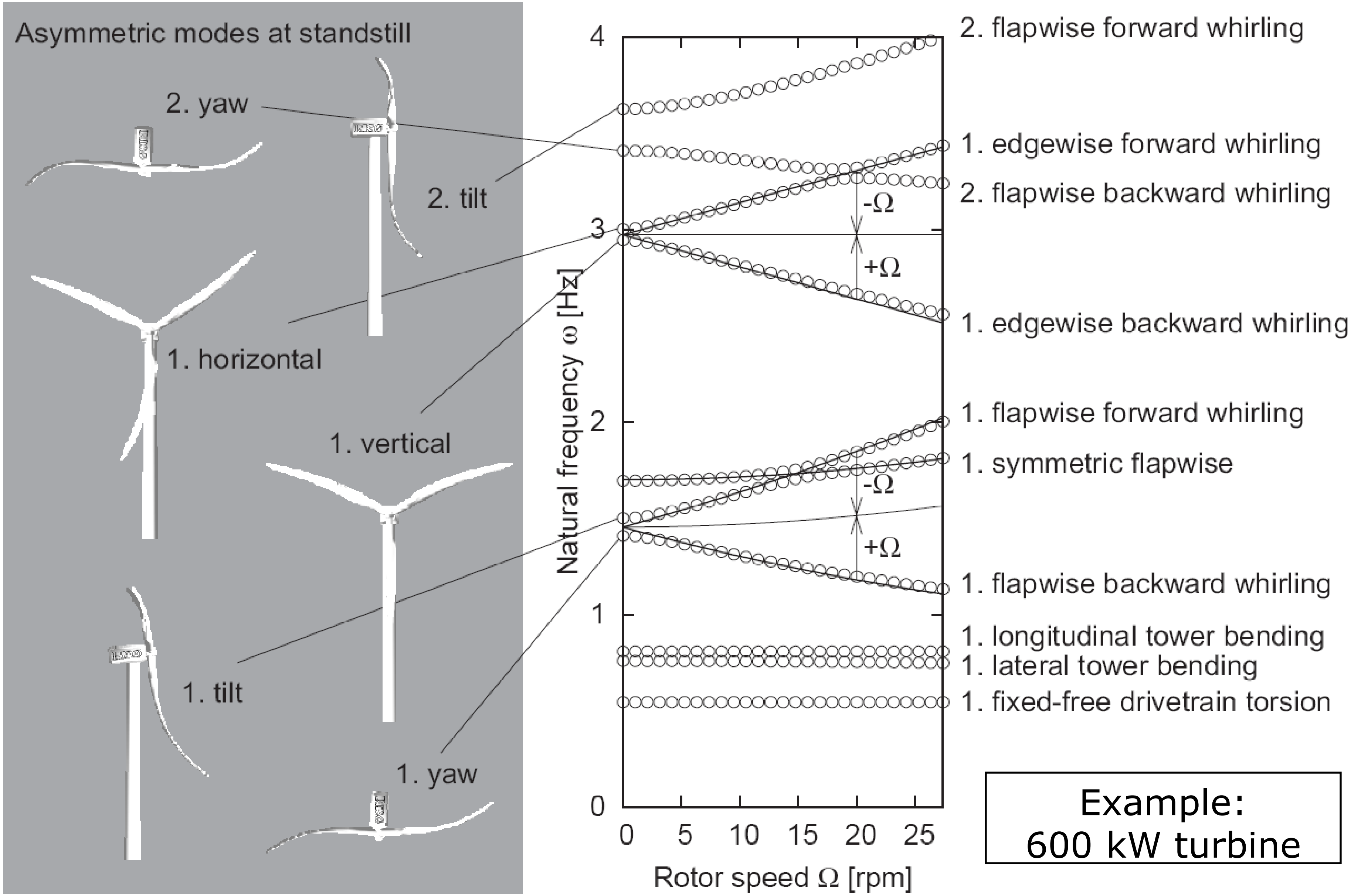
HAWCStab2 – a linear aero(servo)elastic stability tool

- Linearization of HAWC2 equations.
- Aeroelastic eigenvalue analysis
- Mode shape animation
- Present implementations
    - pitch and generator dof.s
    - controller model





Typical modal dynamics of wind turbines



Example:
600 kW turbine

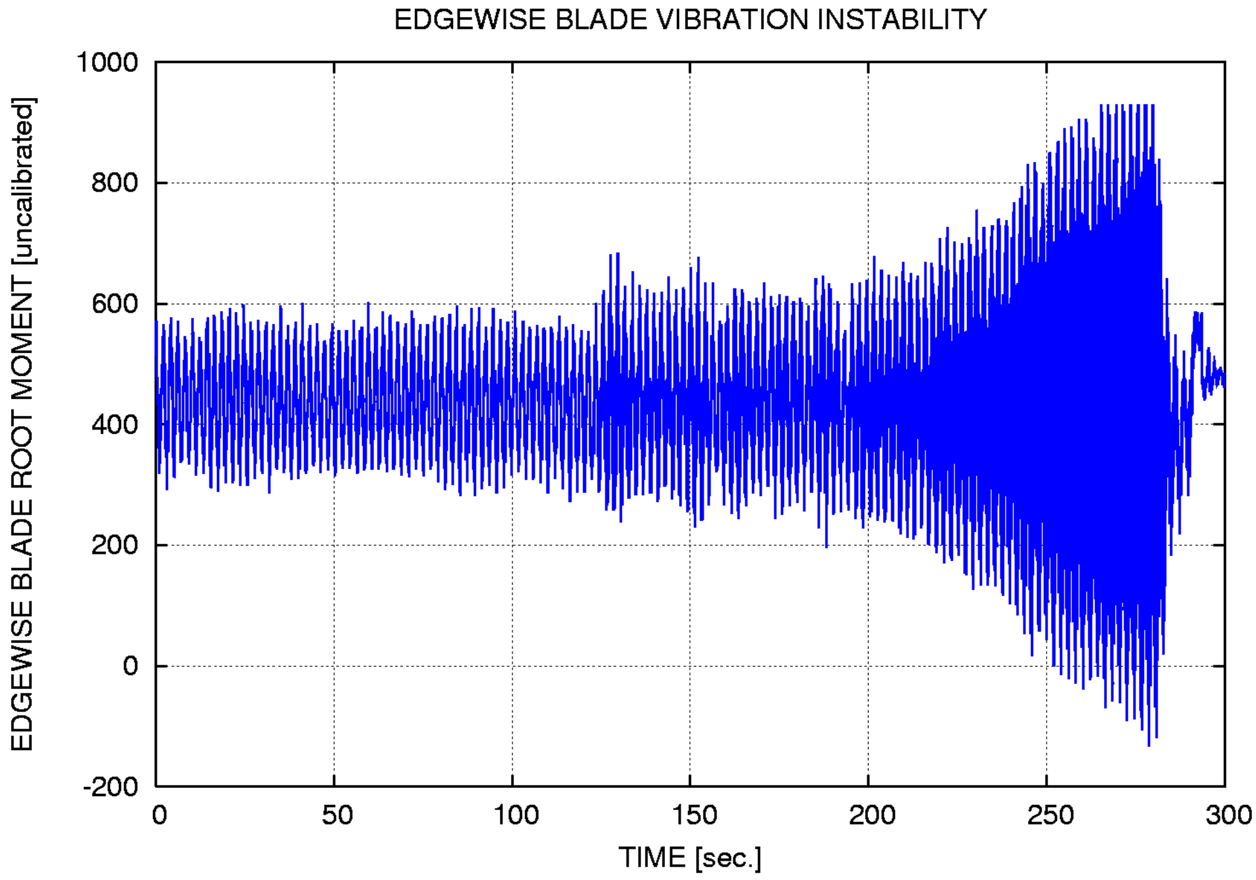
Demonstration of the HAWCStab tool

Low damped modal shapes – can lead to instabilities

- modal shapes involving lateral tower top movement
- modal shapes involving blade edgewise tip motion
- flutter instability involving 2nd flapwise blade mode and 1st torsional mode

Edgewise blade vibrations

Measured instability



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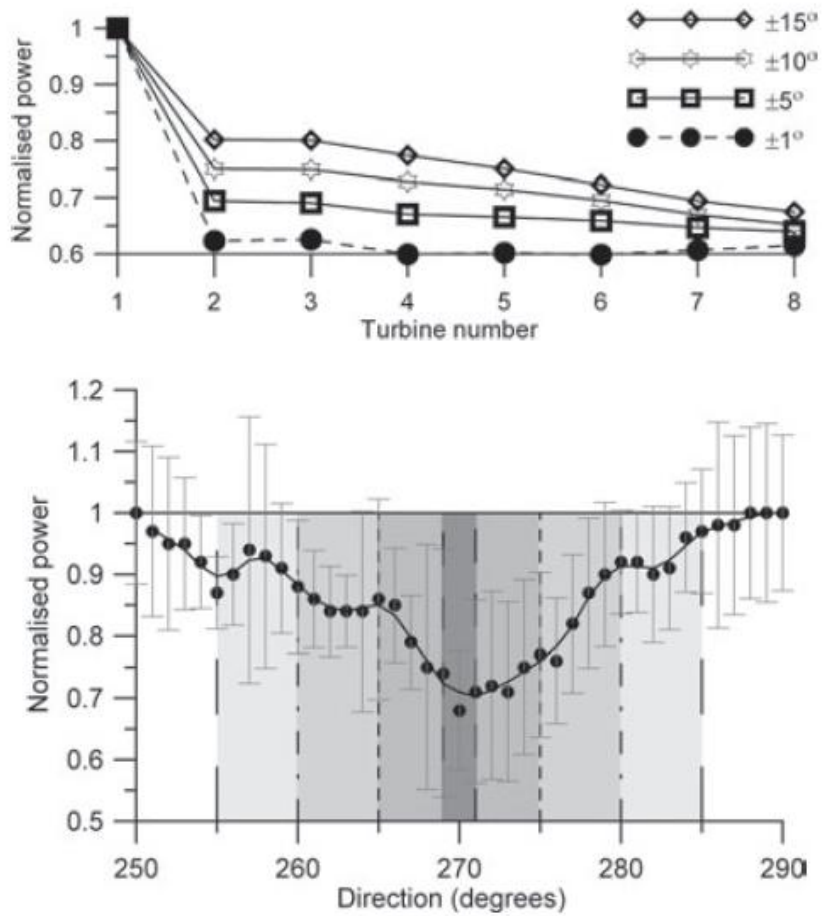
Wind farms and wakes

Wake operation

The presence of neighboring turbines causes:

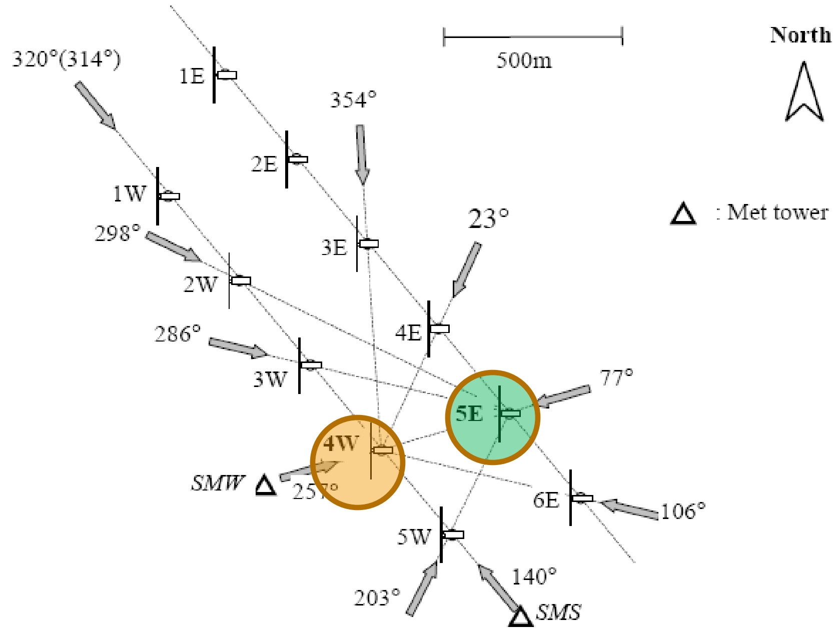
1. Reductions in wind speed.
2. Increased turbulence – turbine components fails (especially yaw system).

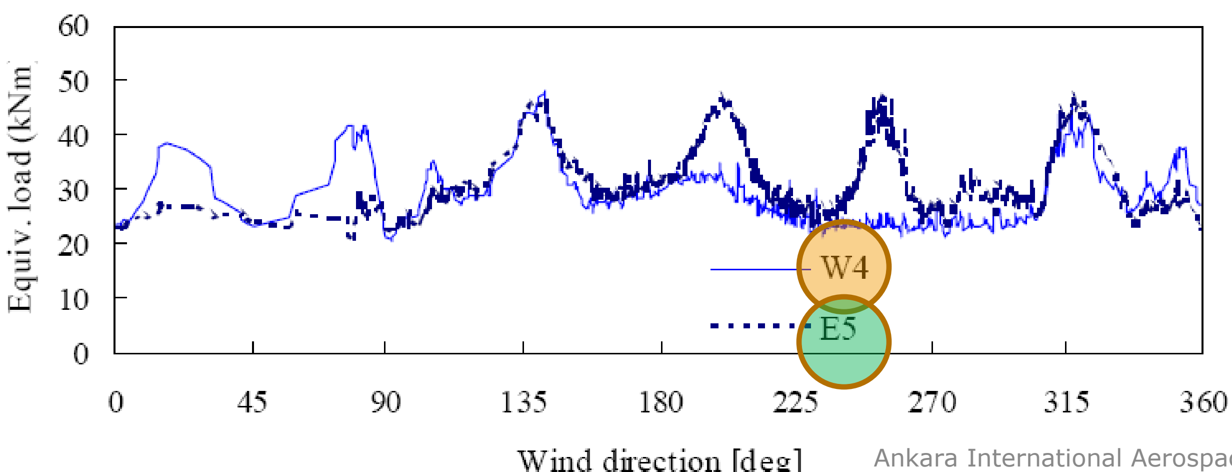
Power reduction



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

Example of increased loads
Load measurements from Vindeby wind farm



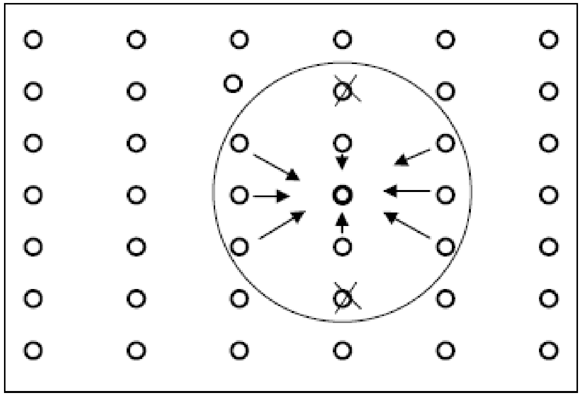


Assessment of turbulence intensity IEC61400-1, Frandsen 2003

For fatigue loads:

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

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

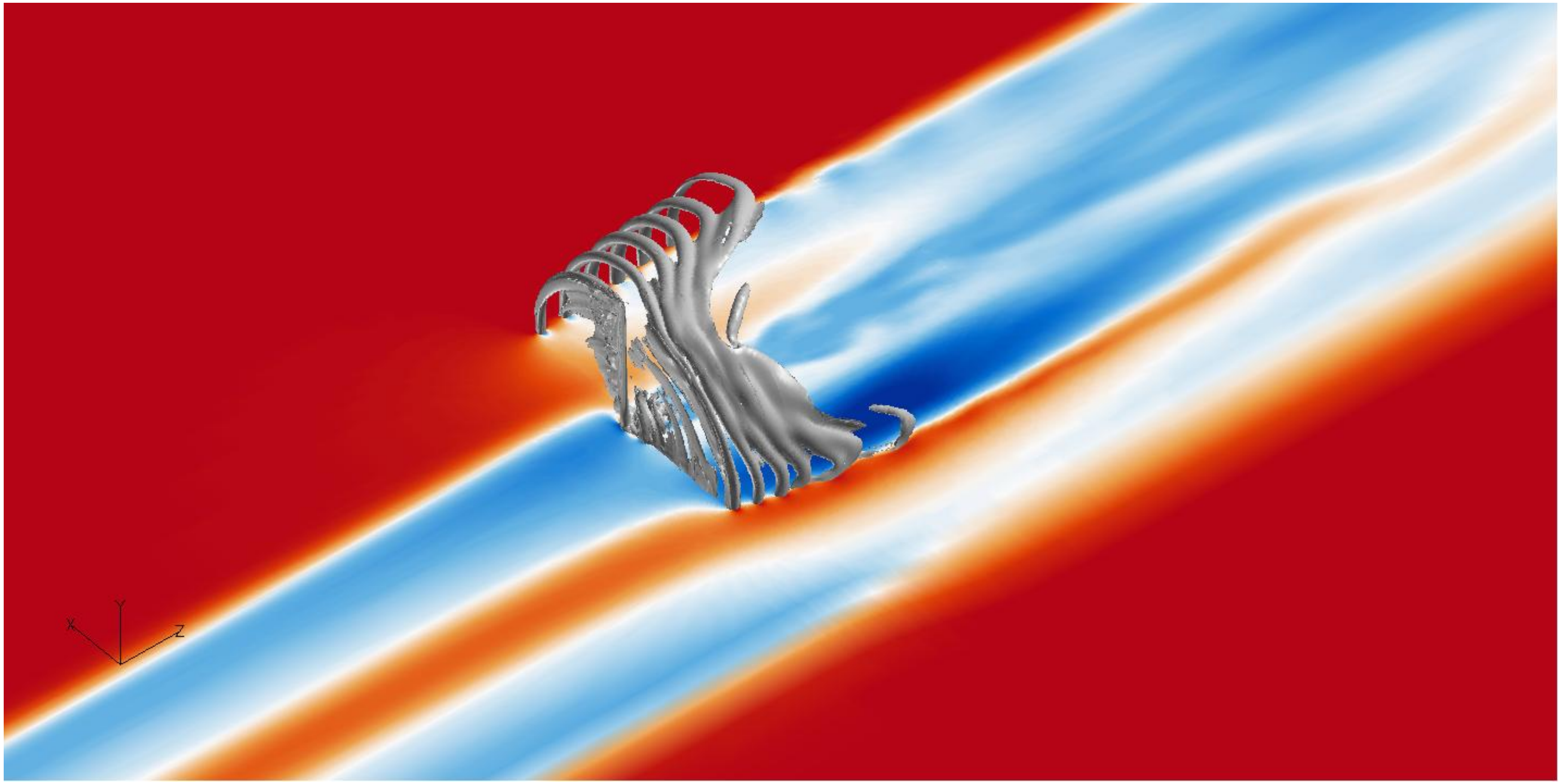


$$\sigma_1 \geq I_{\text{eff}} \cdot V_{\text{hub}} + 1{,}28\,\hat{\sigma}_{\sigma}$$

For extreme loads:

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

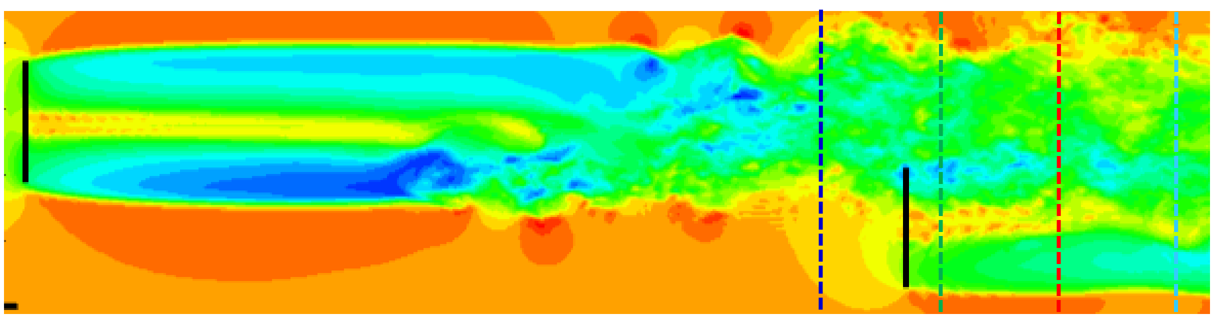
Computation of half wake with EllipSys3D

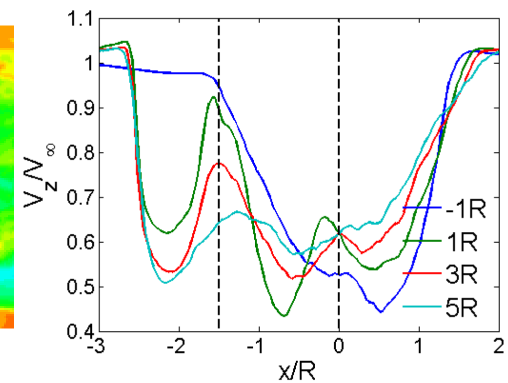


Actuator line CFD simulation
Influence of Ambient Turbulence

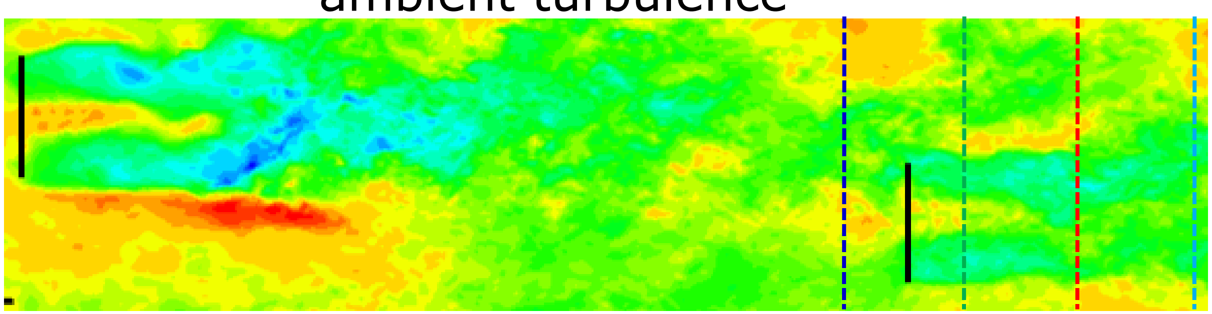
- Upstream wake asymmetric due to inflow shear
- Ambient turbulence causes rapid vortex breakdown
- Fully turbulent wake more symmetric
- Rapid transition towards bell shaped deficit behind downstream turbine

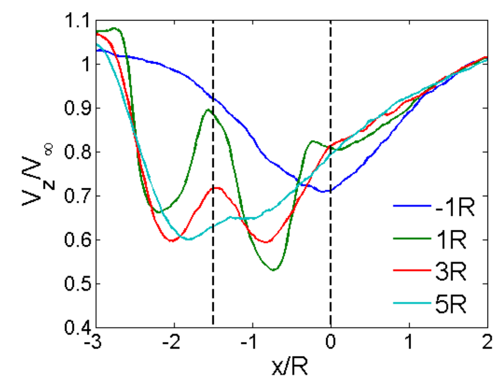
no ambient turbulence





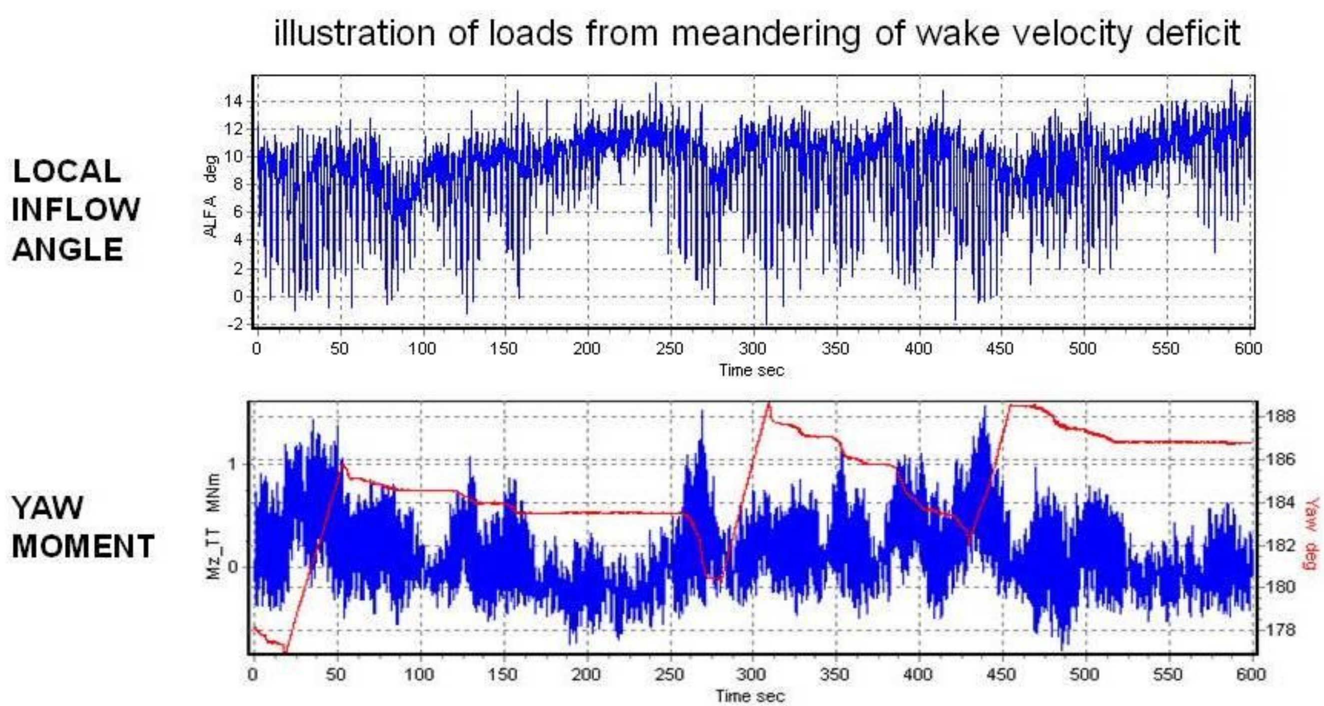
ambient turbulence



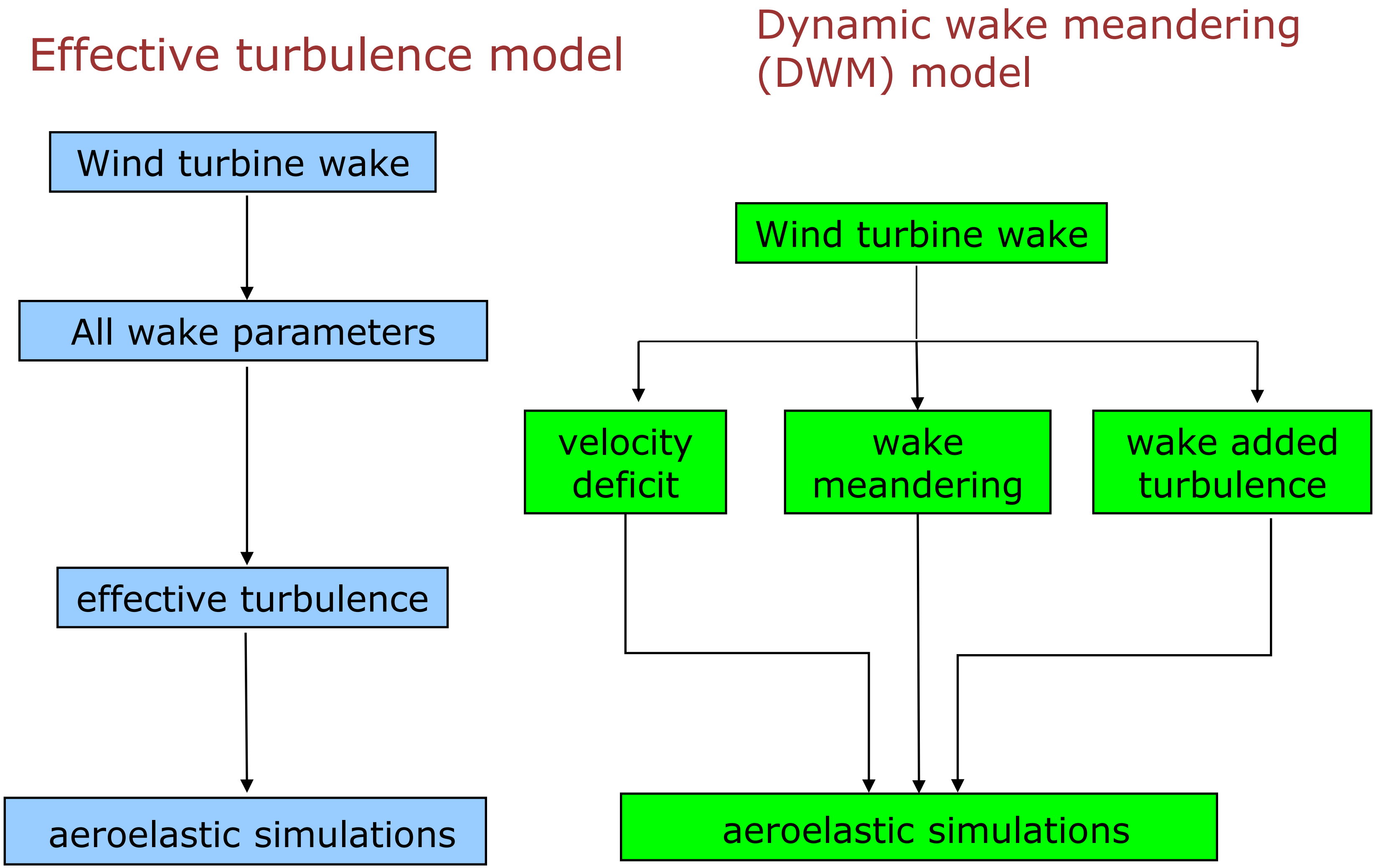


Measured influence of wake meandering

2002-2003 First version of model developed to investigate yaw loads in a wind farm



Different models for increased loading



Load measurements on a NM80 2MW turbine in 3.3D wake

Full wake

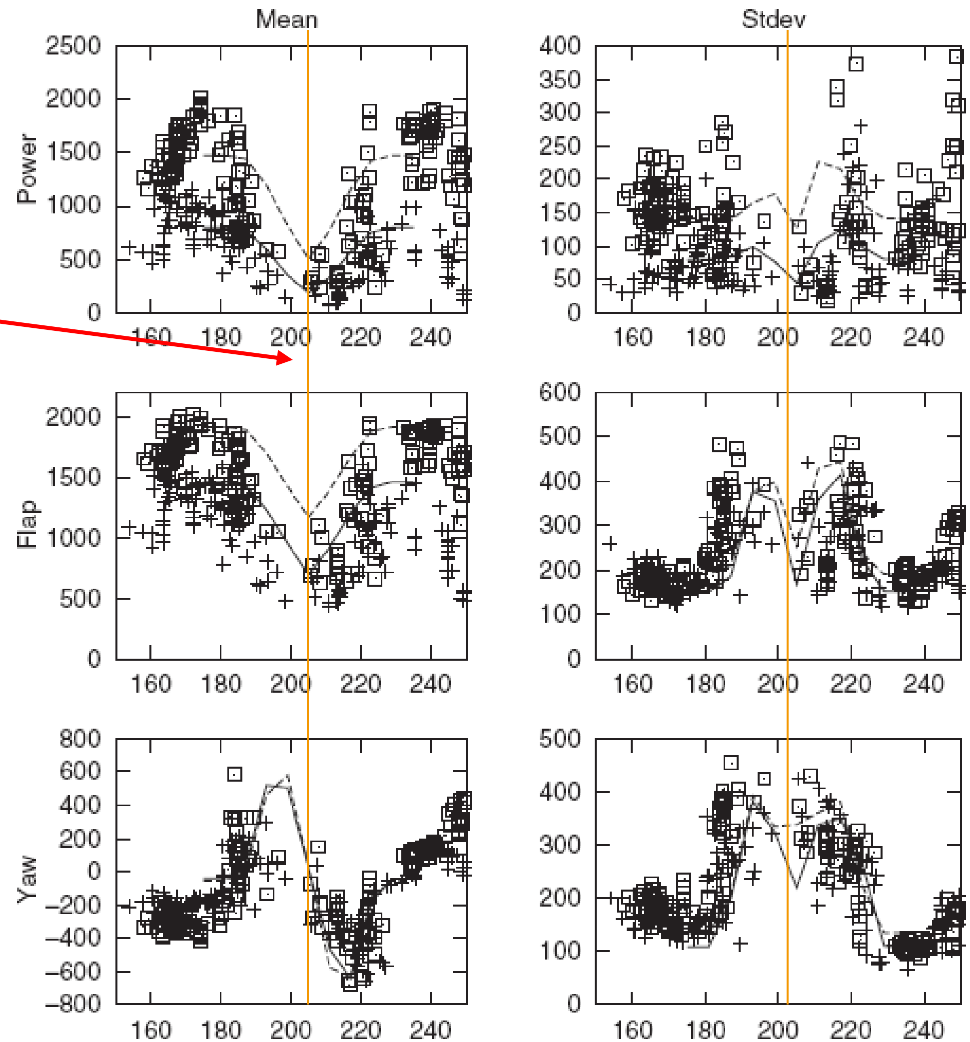


Figure 5. Measured and simulated loads at 8 m s^-1 (full lines and crosses) and 10 m s^-1 (broken lines and squares)

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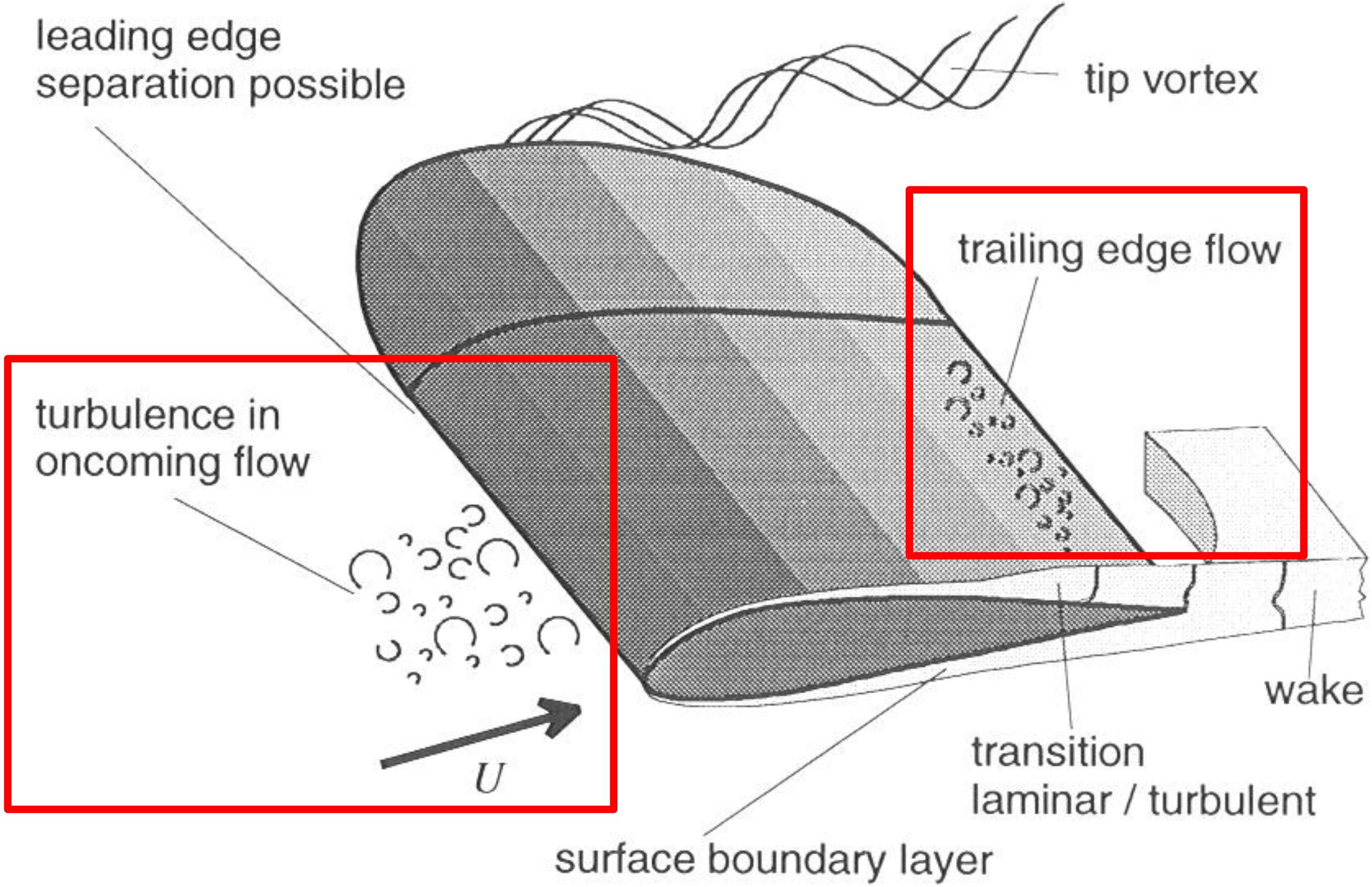
Aeroacoustics

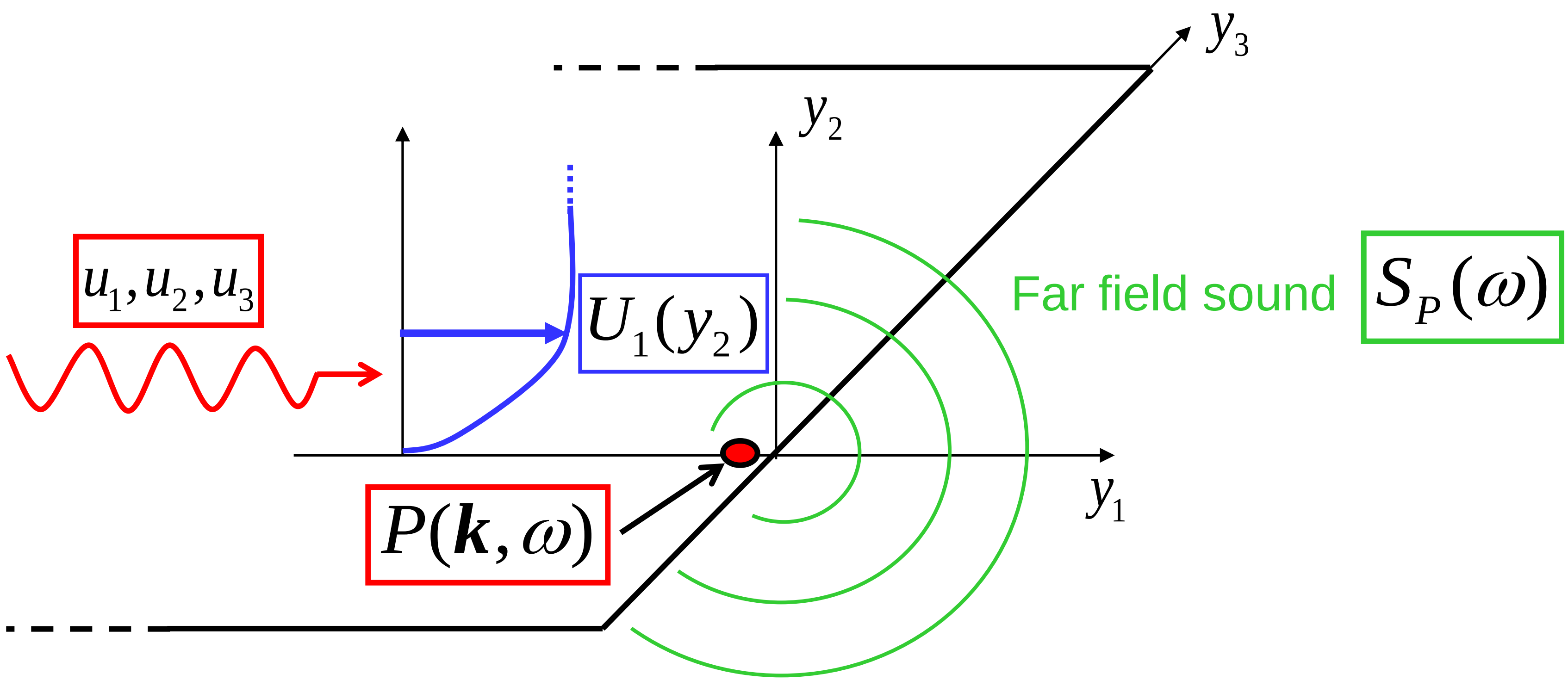
- broadband noise can often cause problems when siting turbines on land
- trailing edge noise and noise from inflow turbulence are the dominant sources
- max. blade tip speed ratio typically limited to 70 m/s due to noise constraints
- turbines have special low noise control modes by pitching more positive – however production is reduced
- airfoils, blades and control are designed taking noise into account
- for turbines with a downwind rotor, low frequency noise can be a major problem

Aerodynamic Noise

Wind Turbine Blade:



Trailing Edge Noise



TNO Trailing Edge Noise Model

Parchen (1998) combines a diffraction problem solution with knowledge of the turbulent fluctuations in the boundary layer

- **Airfoil Surface Pressure Spectrum (Blake,1986)**

Lighthill analogy in spectral domain

→ **Solution for the Mean shear-Turbulence interaction:**

$$P(\mathbf{k},\omega) = 4\rho_0^{\,2} \frac{k_1^{\,2}}{k_1^{\,2}+k_3^{\,2}} \int_0^{+\infty} L_2(y_2) \left(\frac{\partial U_1}{\partial y_2}\right) \overline{u_2^{\,2}} \cdot \Phi_{22}(\mathbf{k},\omega) \cdot \Phi_m\left[\omega - U_c k_1\right] \cdot \mathrm{e}^{-k y_2} \mathrm{d}y_2$$

- **Far Field Noise (Ffwocs Williams and Hall, 1970 ; Chandiramani, 1974; Chase, 1975; Howe, 1978; Brooks and Hodgson, 1981)**

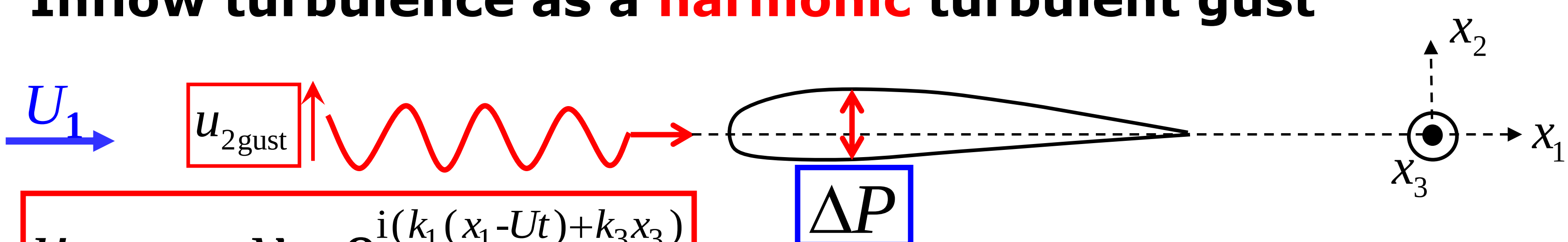
$$S_P(\omega) = \frac{L_{span}}{4\pi R^2} \int_{-\infty}^{+\infty} \frac{\omega}{c_0 k_1} \cdot P(k_1,\omega) \mathrm{d}k_1$$

Turbulent Inflow Noise Model

Amiet’s Theory (1976)

Linearized Inviscid Theory *for* *flat plate* *with* *0-mean loading*

- **Inflow turbulence as a harmonic turbulent gust**



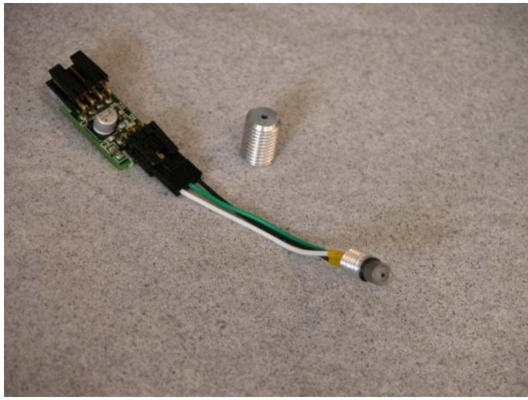
$$u_{2,\text{gust}} = v_0 \cdot \mathrm{e}^{\mathrm{i}(k_1(x_1 - Ut) + k_3 x_3)}$$

- **Surface pressure response using Sears’ theory:**

$$\Delta P(x_1, x_3, t, k_1, k_3) = 2\pi\rho_0 v_0 g(x_1, k_1, k_3) \cdot \mathrm{e}^{\mathrm{i}(k_1 U t - k_3 x_3)}$$

where *g* is the transfer response function

TE and TI Noise Characterization



USING flush-mounted high-frequency MICROPHONES

- **Trailing Edge Noise**

  Surface pressure spectrum near TE is correlated to TE far-field noise

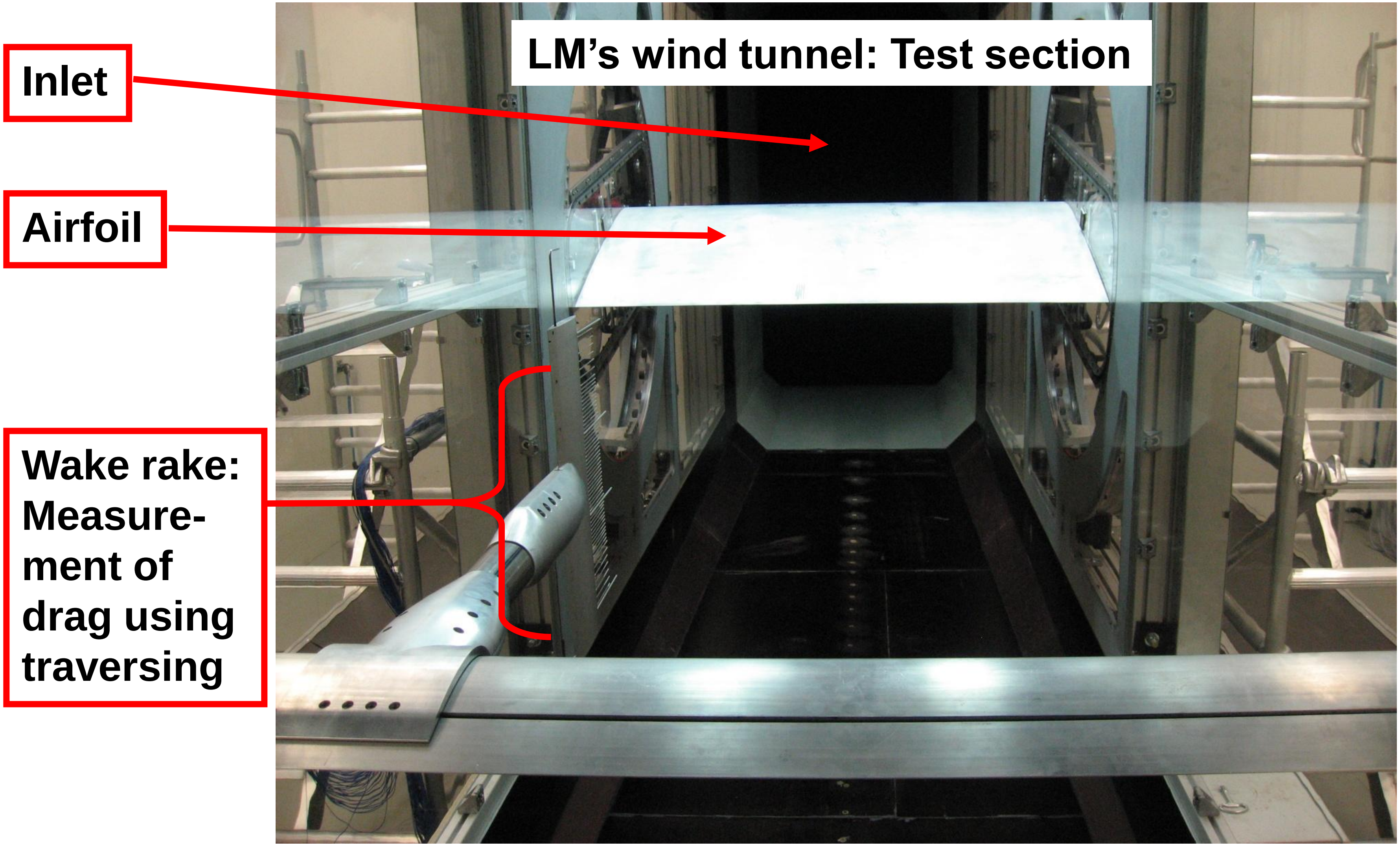
- **Inflow Turbulence & Related Noise**

  Surface pressure near LE characterizes the inflow turbulence

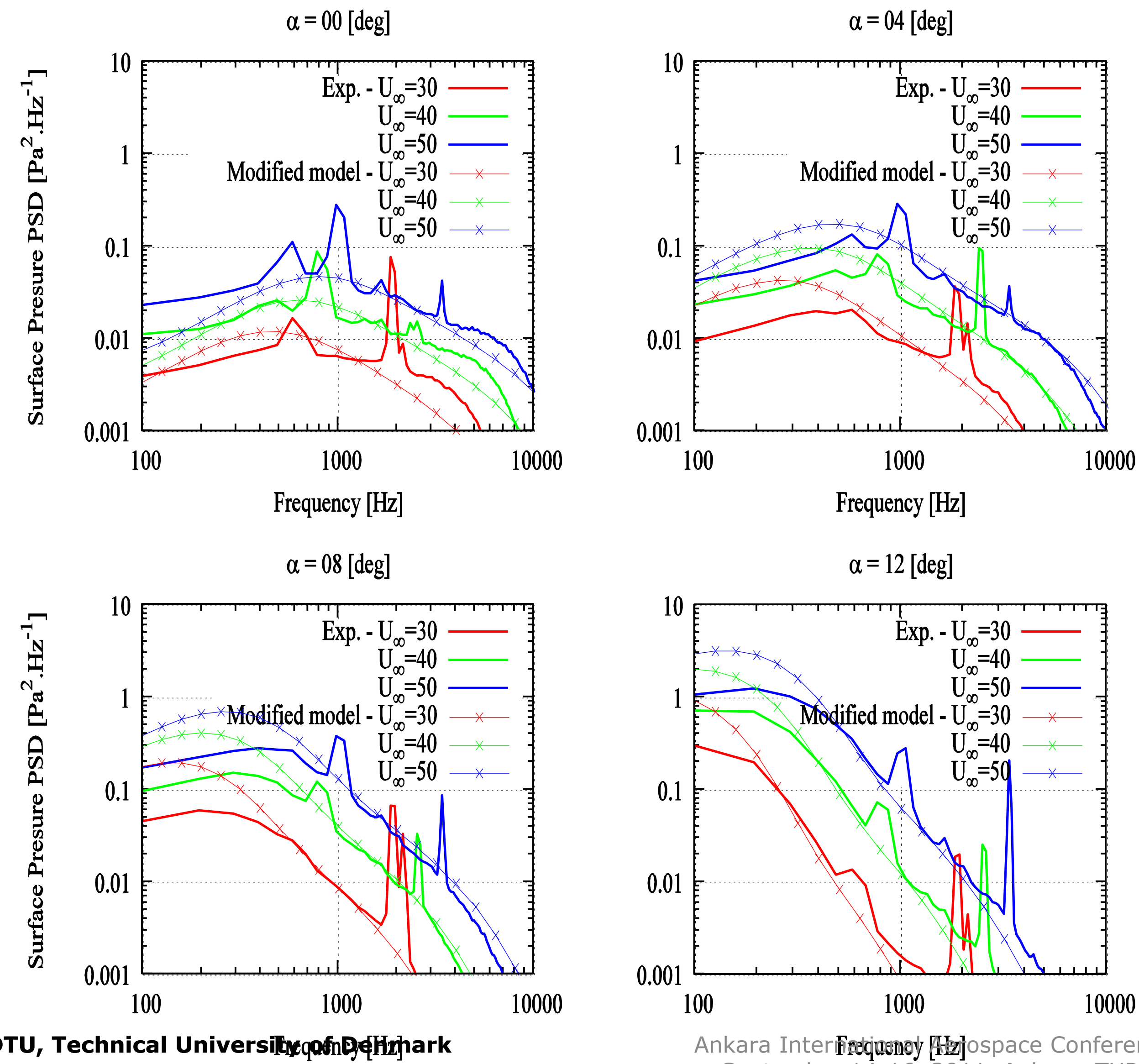
- **BL Transition**

  Surface pressure can be used to detect transition (Sudden increase of spectral intensity)

Airfoils: Tests in wind tunnel



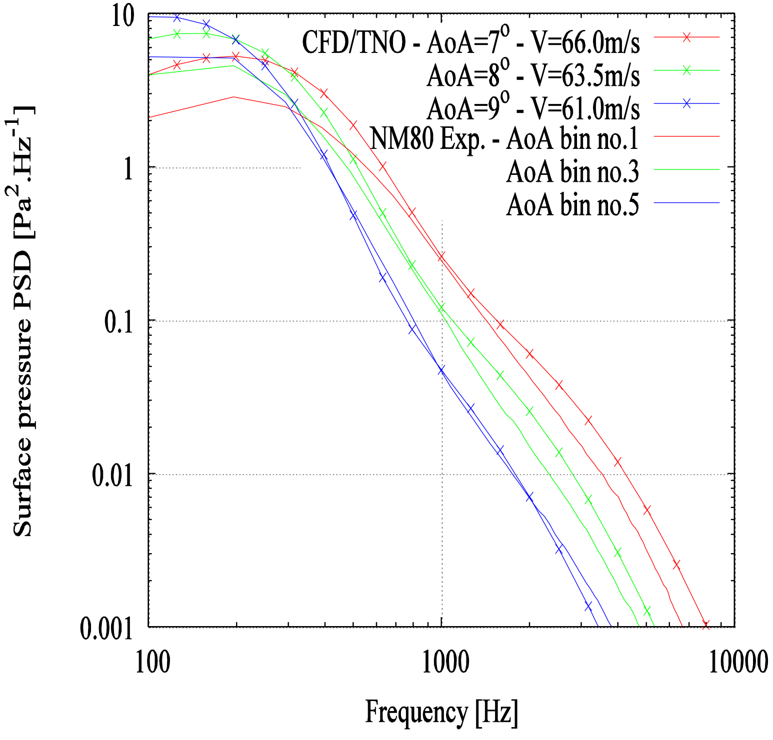
Surf. Pres. measurements near TE measured in a wind tunnel



Measurements on an 80 m diameter rotor – DANAERO project

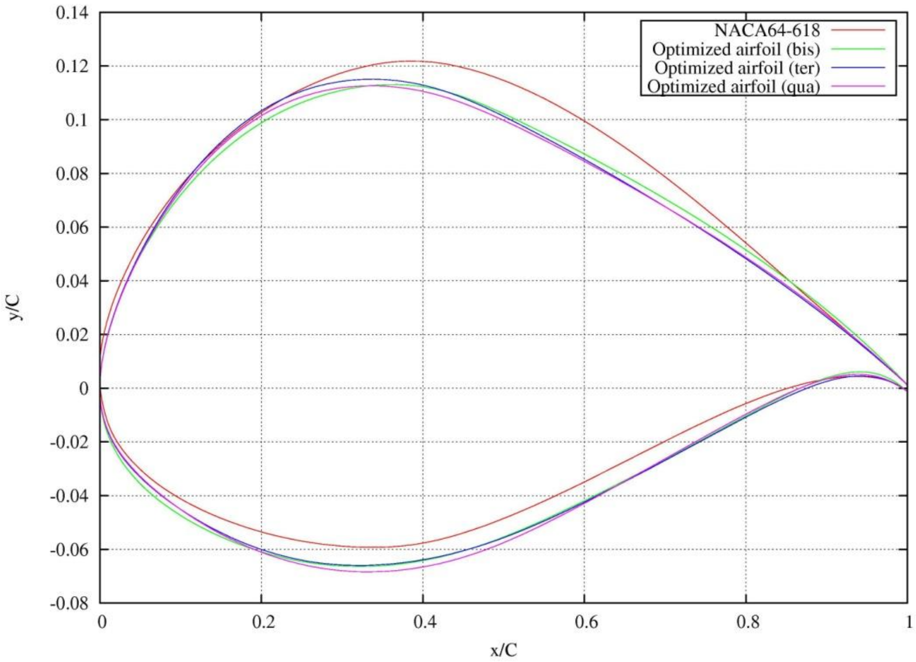
Comparison Exp./Model

Surface Pressure near TE



Summary on noise modelling

➢ the models can now be used in a design optimization loop to design low noise airfoils



Outline

- Introduction to Risø DTU
- The typical wind turbine 2011
- Wind turbine loads and certification
- Aerodynamic and aeroelastic tools
- Aeroelastic stability
- Wind farms and wakes
- Aeroacoustics
- **New technology - outlook**
- Summary

Floating turbines

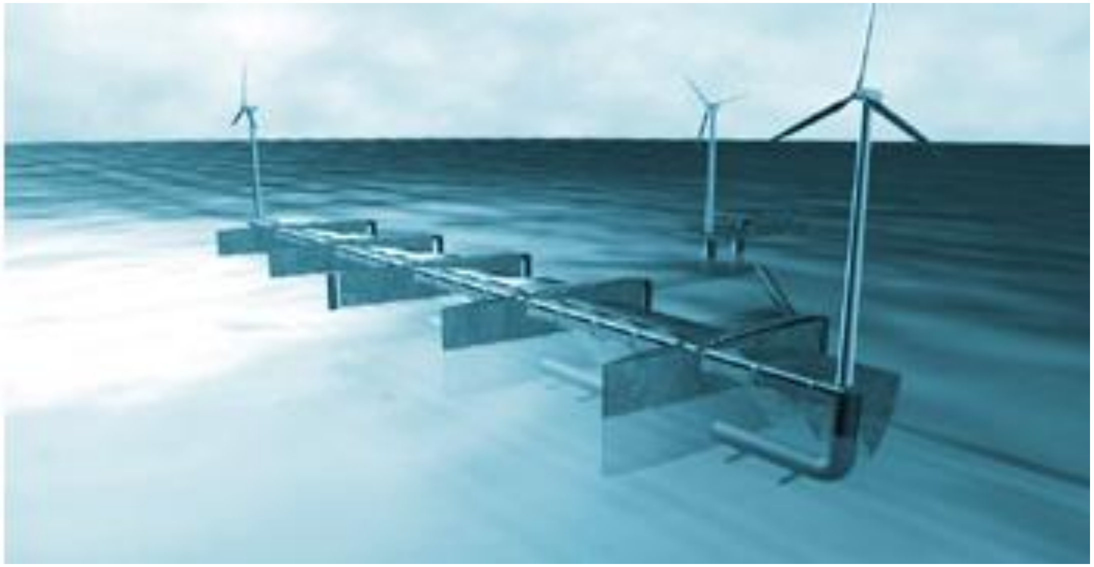
The HYWIND concept

HYWIND concept by StatoilHydro

- 2-5MW pitch controlled wind turbine
- Floating spar bouy attached to three mooring lines
- Intended for water depths between 120 – 700m.

Demonstration project with Siemens 2.3MW 10km outside west coast of Norway.

Combined wave and wind -- Poseidon

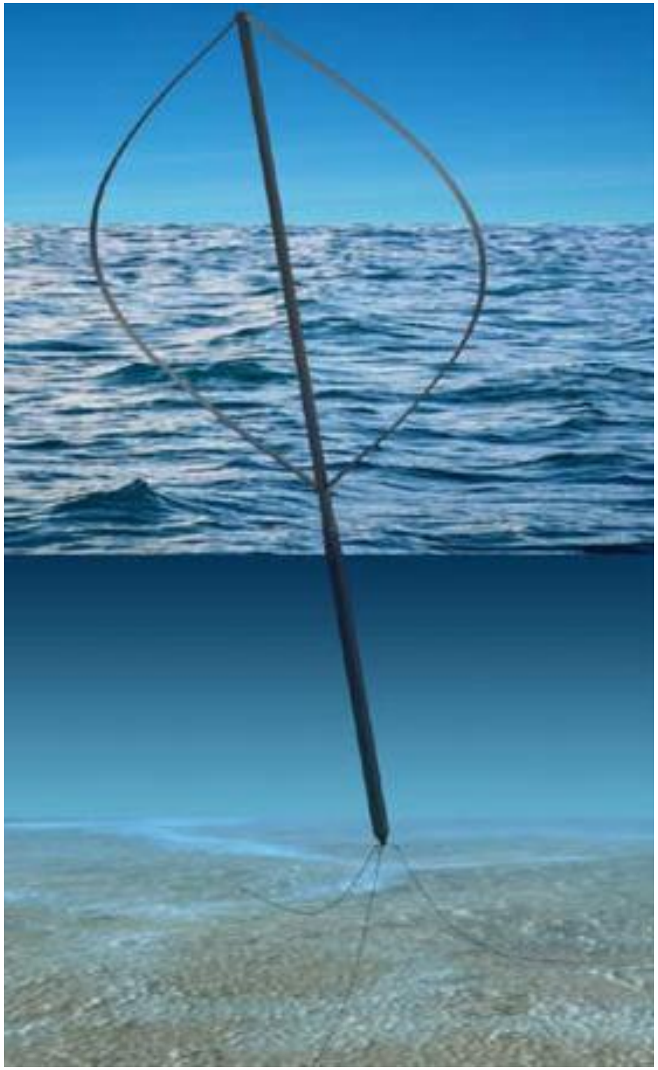


- Wave energy platform
- Dimensions are very large. Three turbines can produce extra power from wind – and contribute to the total damping of motion.

Poseidon

Illustration of the three 11 kW GAIA turbines mounted on the demonstration platform. The turbines are two-bladed fixed speed down-wind turbines with free yaw and a teeter mechanism.

DEEPWIND – EU funded project on new floating wind turbine concept



TRAILING EDGE FLAPS

Sensors and DTEG positions

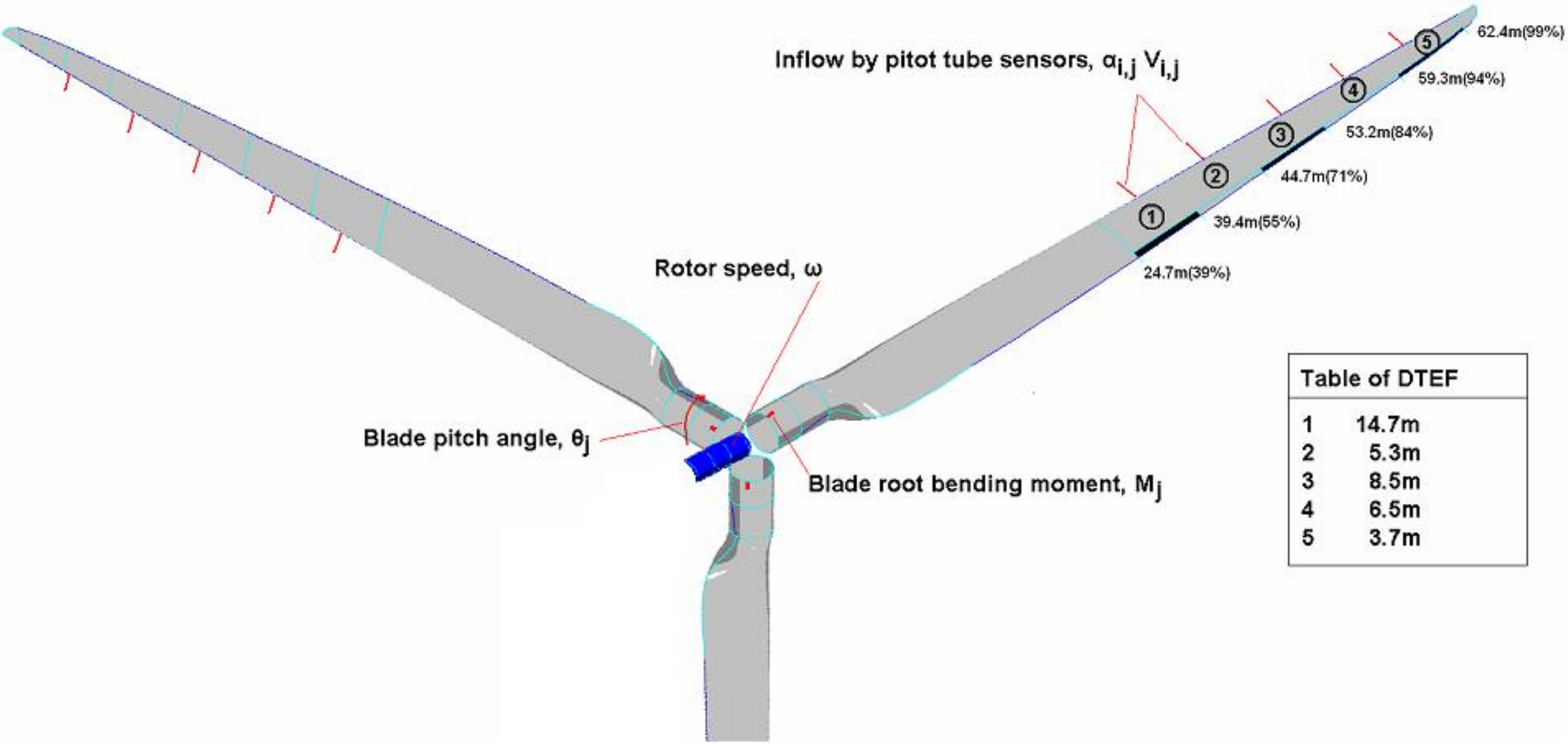


Table of DTEF	
1	14.7m
2	5.3m
3	8.5m
4	6.5m
5	3.7m

From the ADAPWING2 project funded by Danish Research Council

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Summary of key aeroelastic research issues 2011

- **Modeling detailed influence of atmospheric inflow, turbulence and wind shear**
- **Wake modeling – decreased power – increased loading**
- **Vibrations at standstill**
- **Non-linear structural modelling of blades**
- **Dynamic effects in deep stall**
- **Structural damping enhancement**
- **Load alleviation using trailing-edge flaps or other devices**
- **Modeling floating design concepts**

THANK YOU for your attention