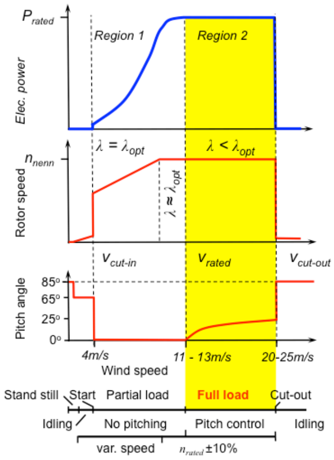
Design of wind energy systems



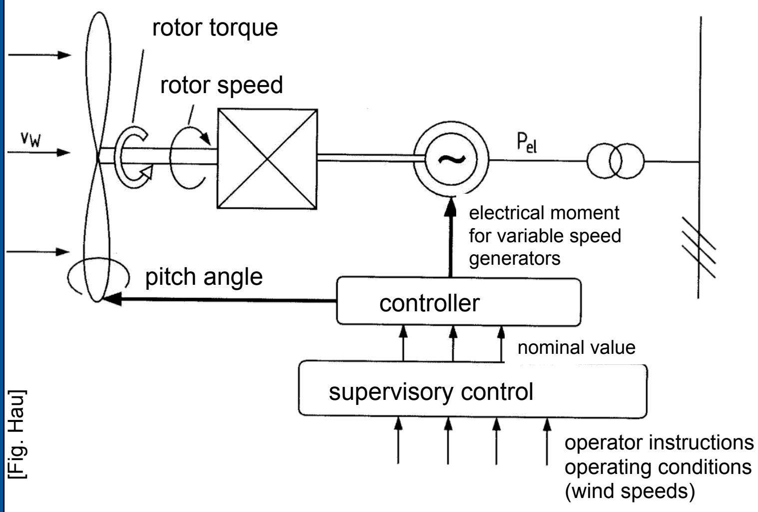
Lecture 6:
Pitch-regulated wind turbines
Simulation and measurements

Prof. Dr. Martin Kühn
Wind Energy Systems

Contents

Part I:
Pitch-regulated wind turbines
- Tasks of the pitch system

Hierarchy of safety loop, control system, operational control and SCADA system



Hierarchy:

1. Safety System
- emergency stop function in „fail-safe“ mode

2. Control System
- optimisation in partial load (up to 90% of the production time)
- speed & load limitation

3. Supervisory control
- start, stop
- auxiliary drives
- yaw drive, etc.

4. Remote monitoring (SCADA)
- operational data acquisition
- „remote control“

(SCADA = Supervisory Control And Data Acquisition)

Pitch systems: Tasks and design concepts

1. Power limitation and control

- Concept: Pitch (sometimes still active-stall)
- Function: collective pitch (common solution)
  individual pitch (future concept for load mitigation)

2. Safety system

- Concept: aerodynamic brake, „fail-safe“
- Function: collective pitch (partly in sub-MW class)
  individual actuation, redundant (all MW machines)

3. Manoeuvre start, stop, idling

Design concepts

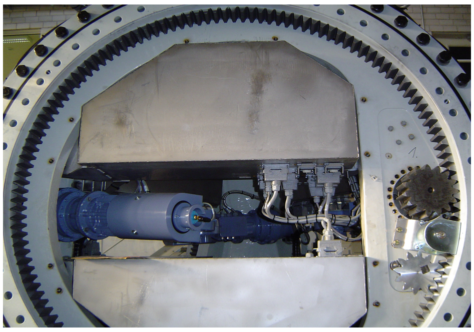
Actuator type \ Actuation	collective	individual
- hydraulic	*partly in sub-MW class*	*common*
- electrical	no	*common*
- mechanical	very few	very few

Pitch system: examples

Sub-Megawatt Class:
- usually Collective Pitch
- mech., electrical or hydraulic

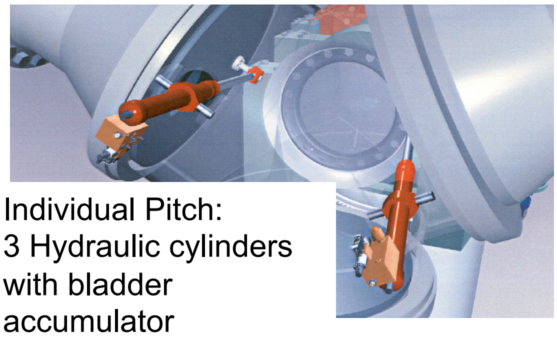
In Megawatt Class:
- only Individual Pitch
- electrical or hydraulic

Energy back-up (Fail-Safe)



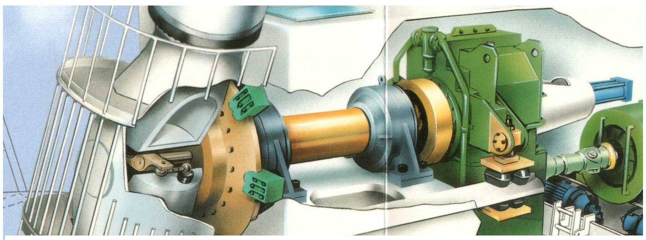
[Fig. Gasch]

Individual Pitch: 3 DC-Motors with Battery Pack



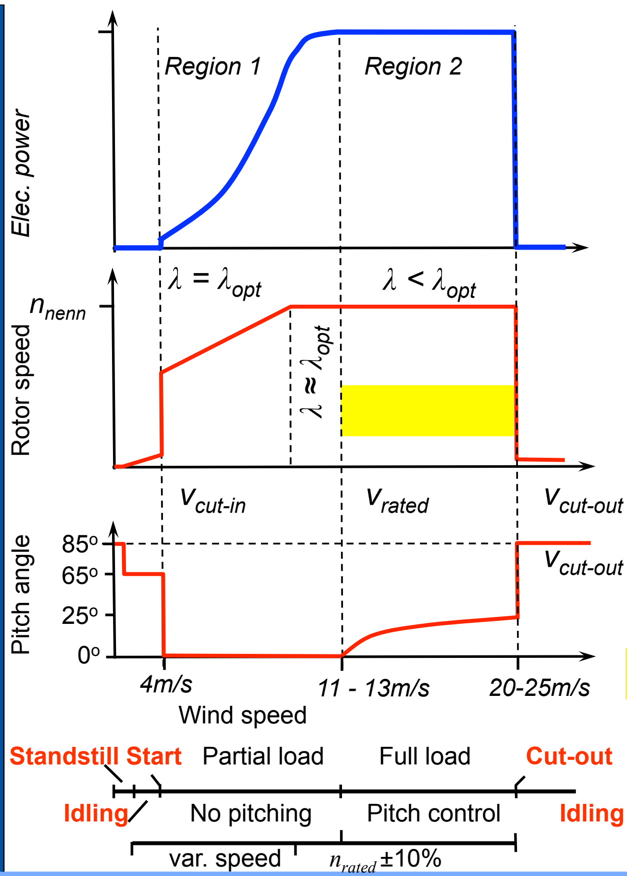
Individual Pitch: 3 Hydraulic cylinders with bladder accumulator

[Fig. Bosch-Rexroth]



Collective: Hydraulic cyl. with piston rod and bladder accumulator [Windmaster 750]

1st Task of pitch system: Power limitation & control



below V_{cut-in} (approx. 3 – 4 m/s) :

- idling, large pitch angle

Region 1: betw. V_{cut-in} and V_{rated} (approx. 11 – 12 m/s) :

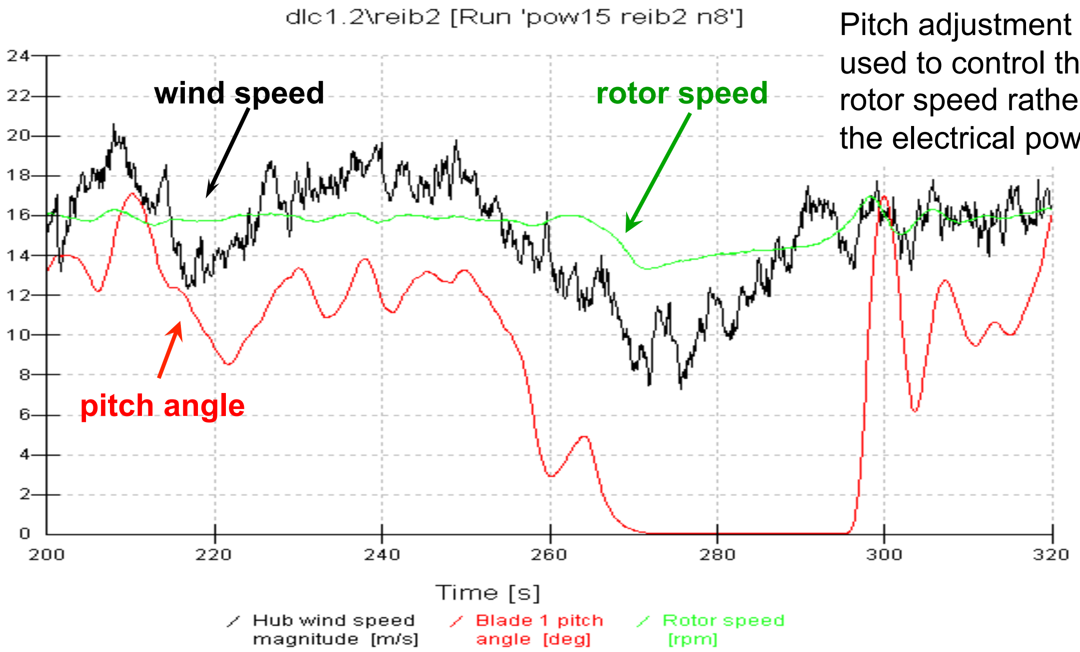
- production at partial load
- pitch angle constant at 0°
- variable speed proportional to wind
- turbine operating at aerodyn. optimum

Region 2: betw. V_{rated} and $V_{cut-out}$ (approx. 20 - 25 m/s) :

- production at full load
- speed on average constant
- pitch angle increases with wind
- dynamic control of speed (fast) and pitch (slower) to reduce power and load variations

above $V_{cut-out}$: idling, large pitch angle

1st Task: Power limitation above rated wind speed by rotor speed control



Remark:
Pitch adjustment is used to control the rotor speed rather than the electrical power

Source: A. Manjock, German. Lloyd Windenergie, “Load Assumptions for the Design of Electro- Mechanic Pitch Systems”, EWEC 2007

2nd Task of pitch system: Safety system

Safety system

- turbine must be or must be brought back to safe operational condition
  „low-level“, fail-safe, autonomous system
  safety loop, i.e. activation by any arbitrary sensor

Function

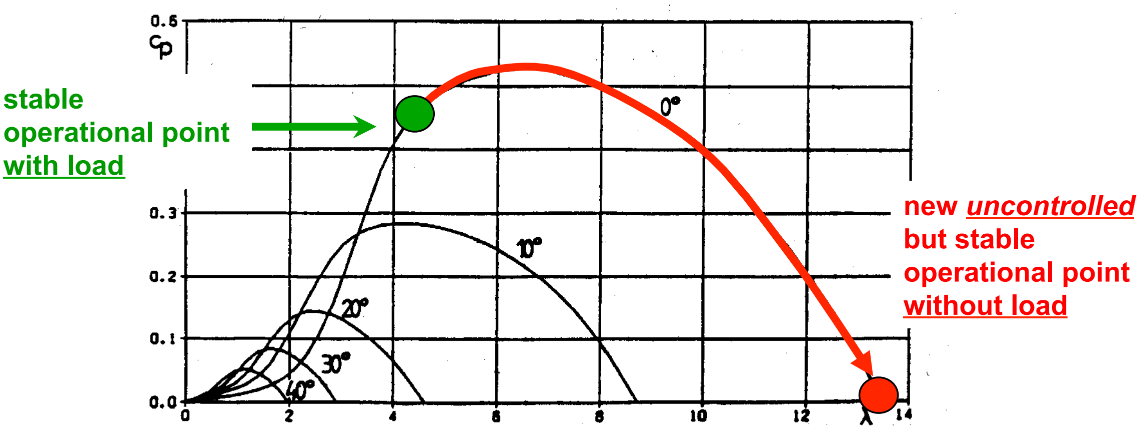
- at least *two independent brake systems*, at least one of this with aerodynamic effect
  => i.e. driven lift and torque must be reduced by
  - pitch adjustment (all big machines, MW-class) or
  - tip brakes (medium size stall turbines) or
  - flaps or similar devices (no longer used)

=> collective pitch adjustment: extra mechanical brake needed
or
=> individual pitch adjustment: each blade acts as one brake

Why is *overspeed* dangerous?

uncontrolled load rejection

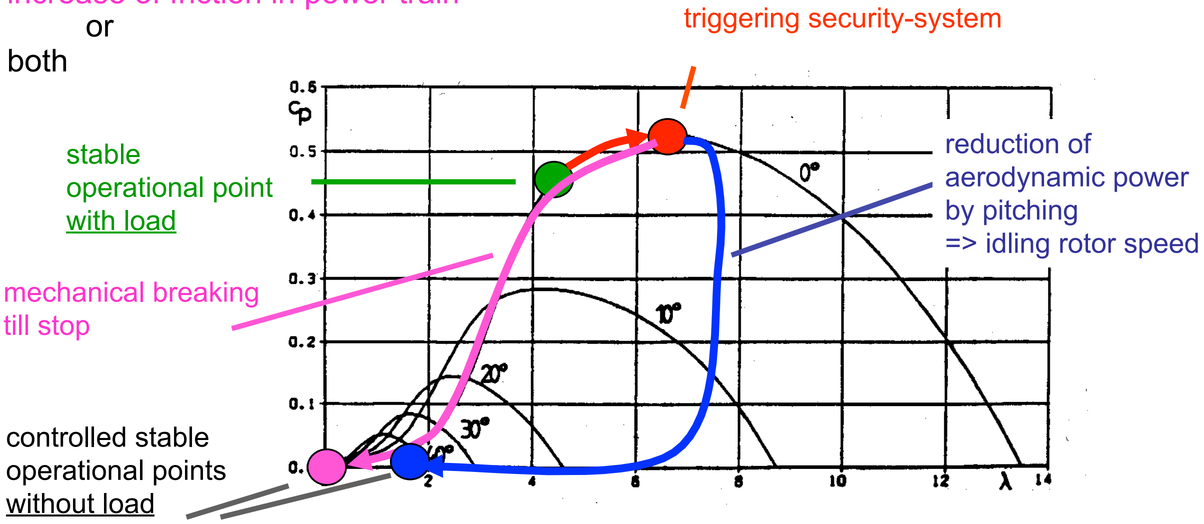
- rotor „seeks“ for operational point with
  aerodynamic power = friction power in power train
- C_p-λ-curve: $\lambda \approx 2\,\lambda_o$ i.e. approx. twice the design tip-speed ratio
- centrifugal forces: approx. four times larger than in rated conditions
- rotor thrust: very large, up to double rated thrust



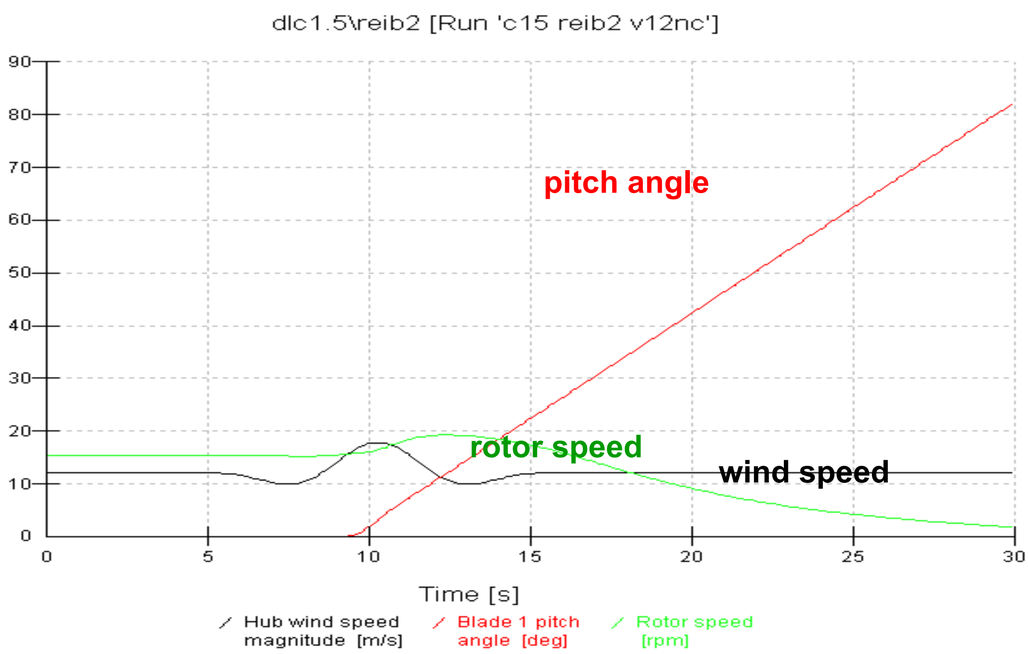
Reduction of over-speed

Counter actions at over-speed :

- reduction of aerodynamic loads
  or
- increase of friction in power train
  or
- both



Example of an emergency stop at over speed and extreme wind gust



Source: A. Manjock, German. Lloyd Windenergie, “Load Assumptions for the Design of Electro- Mechanic Pitch Systems”, EWEC 2007

Safety loop / safety system

Safety system

- turbine must be or must be brought to *safe operational condition*
- „low-level", fail-safe, autonomous system
- security-chain, i.e. activation by an arbitrary sensor

activation of the safety loop (examples)

- Over-speed
- exceeding of the allowable electrical power or torque
- grid failure, grid problem
- short circuit in the electrical system
- extensive vibrations, unbalance
- revolution-speed difference between low-speed shaft and high-speed shaft
- pitch asymmetry
- manual emergency stop, etc.

Requirements of the safety system

- minimum two independent braking systems
- should keep the rotor speed below n_{max}
  - at failure of one braking system
  - at grid failure or load rejection
- (minimum) one braking system able to bring rotor to standstill
- (minimum) one braking system acting on rotor or low-speed shaft
- triggering by grid failure
- triggering and operation independent from control system (PLC)

[GL-Guideline, Chapter 2, Section 1.C.3]

Design principles of the safety system

- *„fail-safe“*
  i.e. in the event of failure, fails in a way that will cause no harm or at least a minimum of harm
- *redundant*
  i.e. at least two indipendent and redundant systens required, eached designed to bring the system back to a safe operational condition
  (Remark: „Fail-safe“ not necessary means redundant!)
- *„Low-level“*
  i.e. robust, as simple as possible, hard wirede, direct impact
- *Autonomous system*
  i.e. watch dog function, triggers once system o.k. signal is interupted
- *Safety loop*
  i.e. triggered by any of many sensors in a connection in series

Braking systems

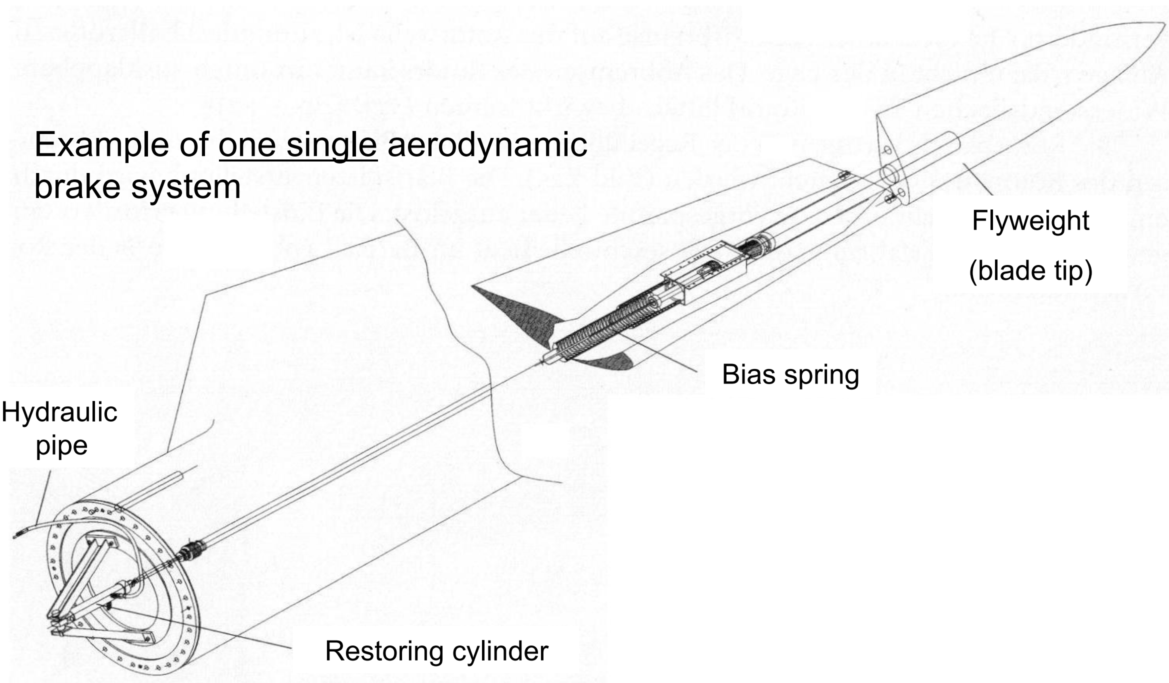
- regulations: primary and secondary braking system
- fail-safe-operation (voltage off ⇒ brake on)
- triggering by safety loop

Stall:
- primary: airbrakes or blade tip brakes (or hydraulic brake at low speed shaft)
- secondary: hydraulic brake at high speed shaft

Typical active-stall turbine:
- primary : collective pitch control
- secondary: hydraulic brake at high speed shaft

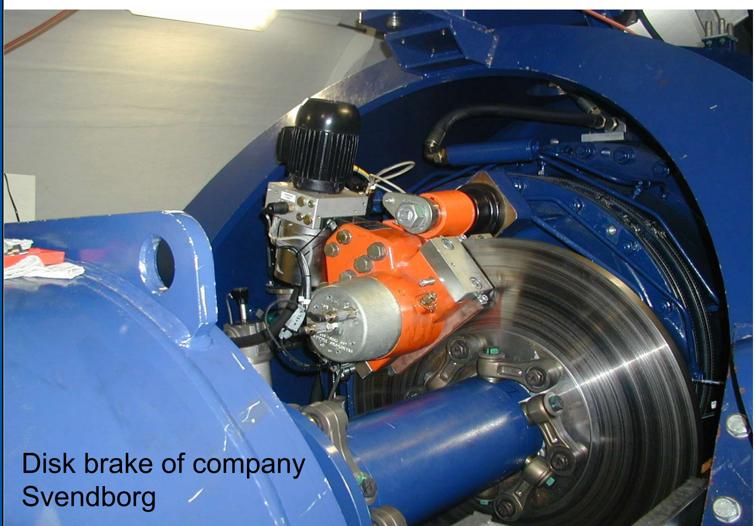
Pitch-controlled turbine (example with electro-mech.pitch system):
- \- primary & secondary: single-blade pitching
  (autonomous battery-equipped for each blade, blades pitched independently)
- \- support: hydraulic brake at high speed shaft

Braking systems: aerodynamic brakes at blade tip (typical for old stall turbines)



[Abb. Hau]

Braking systems: mechanical disk brake at high speed shaft


Disk brake of company Svendborg

Fail-safe Design
- engaged by spring forces
- released by hydraulic actuation

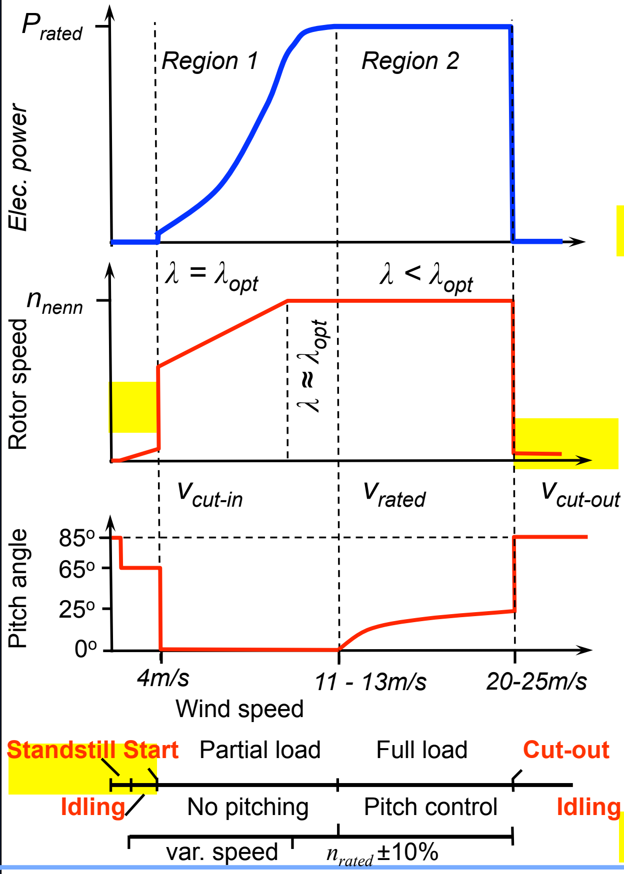
$\Rightarrow$ problem: damge of teeth wheel at stand-still, e.g. after longer duration w/o electric grid

or

Active design
- engaged by hydraulics
- released by springs
- soft brake option (avoid forth and back rotation of rotor directly after drive train coming to a rest)

Modern turbines use the brake mainly as a *parking brake* or auxiliary brake.
Actual braking is secured by individual pitch adjustment.

[Fig.. Gasch]



3rd Task: Manoeuvre (start, stop, idling)

below $V_{cut\text{-}in}$ (approx. 3 – 4 m/s) :
- idling, large pitch angle

Region 1: betw. $V_{cut\text{-}in}$ and V_{rated} (approx. 11 – 12 m/s) :
- production at partial load
- pitch angle constant at 0°
- variable speed proportional to wind
- turbine operating at aerodyn. optimum

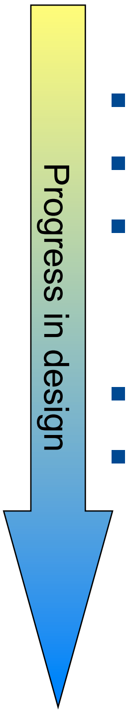
Region 2: betw. V_{rated} and $V_{cut\text{-}out}$ (approx. 20 - 25 m/s) :
- production at full load
- speed on average constant
- pitch angle increases with wind
- dynamic control of speed (fast) and pitch

(slower) to reduce power and load variations

above $V_{cut\text{-}out}$: idling, large pitch angle

Part II: Wind turbine simulation

What‘s the purpose of dynamic simulation?

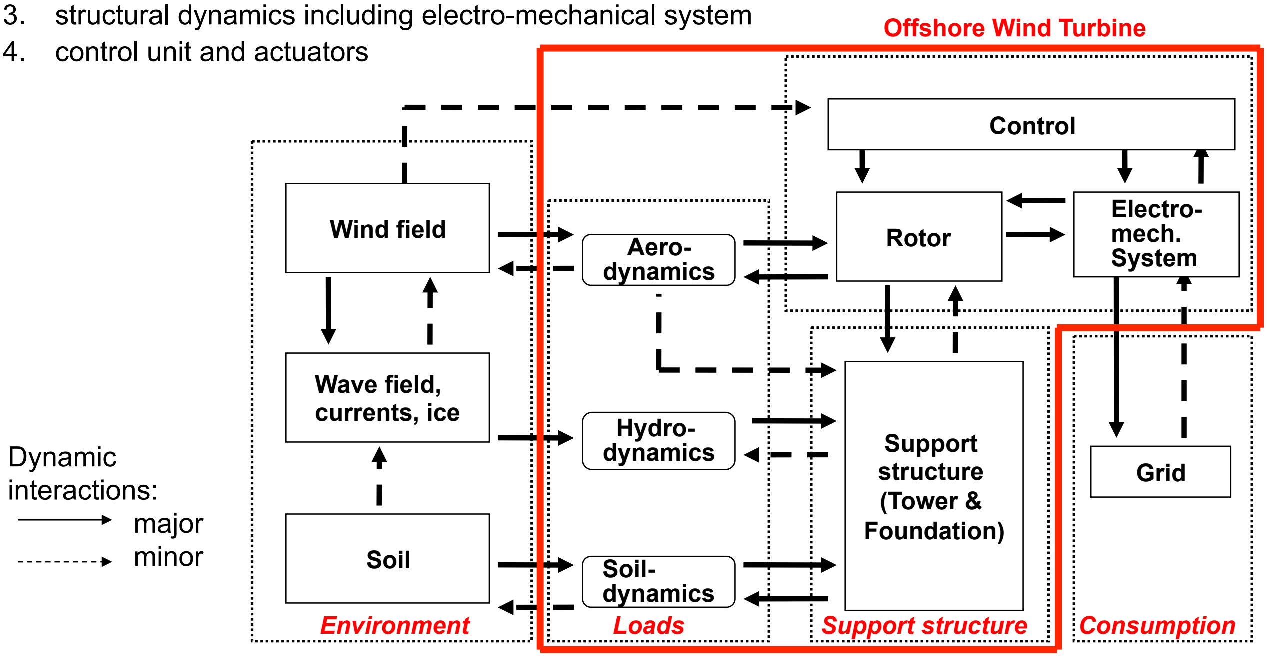


- Parameter studies in the preliminary design phase and optimization
- Loads for design and certification of components
- Analysis and optimization of the WT-performance
  - dynamics
  - control and operation
- Power curves with influence of turbulence and control
- Site- and wind park specific loads
  (wind conditions, wake turbulence)

Integrated system model

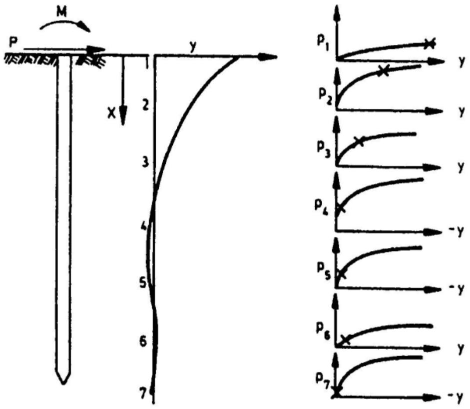
Major modules of a wind turbine simulation tool

1. wind field
2. rotor aerodynamics
3. structural dynamics including electro-mechanical system
4. control unit and actuators

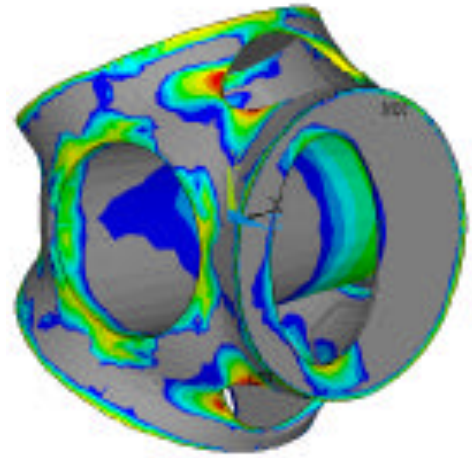


Sub-system model

- Modelling of individual components
- from very crude to very detailed



Simple model of lateral displacements of a monopile foundation with p-y curves



Detailed FE model of a rotor hub for fatigue analysis

[www.mecal.com]

Modelling approaches

Three analysis methods for structural dynamics:

A. Modal
e.g. *FLEX5, BLADED, FAST*

B. Finite Element Method (FEM) or similar methods
e.g. *HawC2*, *ADCoS*, *PHATAS*

C. Multi-Body-System (MBS)
e.g. *SIMPACK, ADAMS/WT*

Approach A: Integrated simulation with modal approach: Flex 5 code (similar to Bladed code)

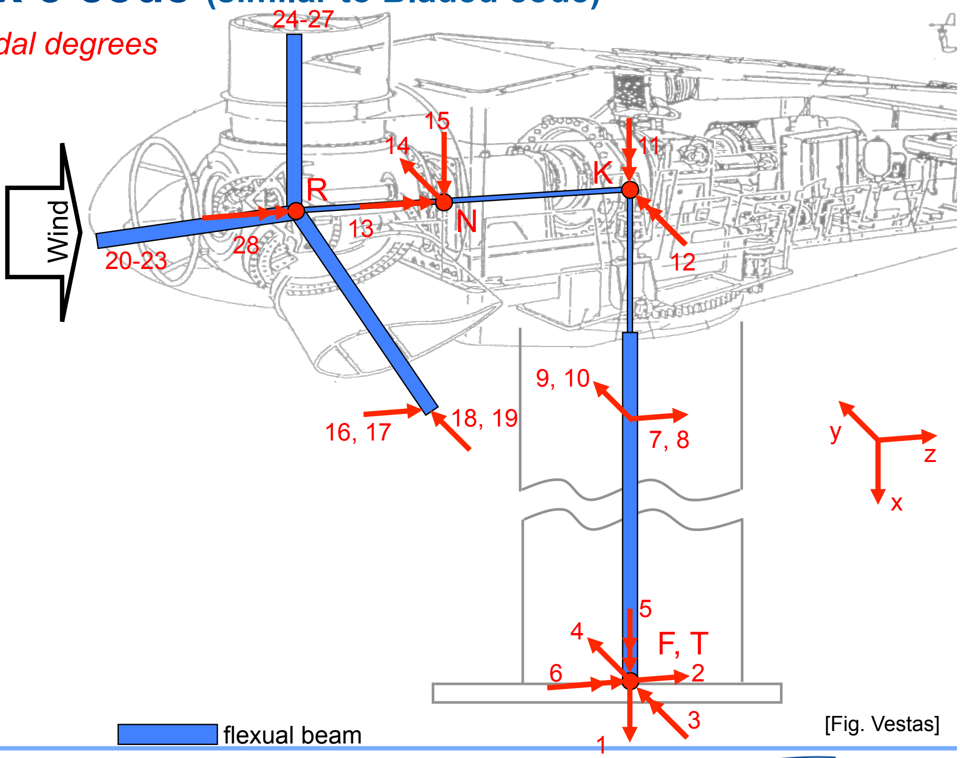
Model with only 28 *modal degrees of freedom* (dof)

Foundation:
6 dof's
3 translational (1, 2, 4)
3 rotational (3, 5, 6)

Rotor blade (each):
4 dof's
2 flapwise (e.g. 16, 17)
2 edgewise (e.g. 18, 19)

Tower:
5 dof's
2 fore-aft (7, 8)
2 lateral (9, 10)
1 torsional (11)

Additionals dof's:
nacelle tilt (12)
rotor rotation (13)
main shaft bending (14, 15)
drive train torsion (28)

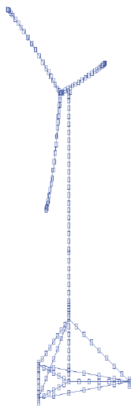


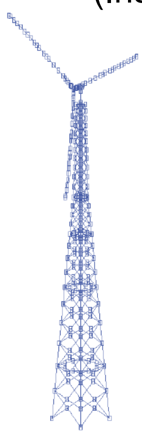
[Fig. Vestas]

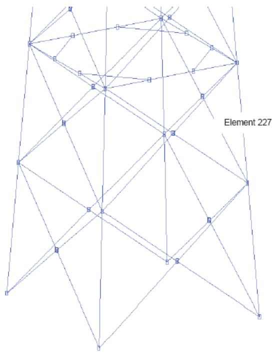
Approach B: Integrated simulation with FE-approach:

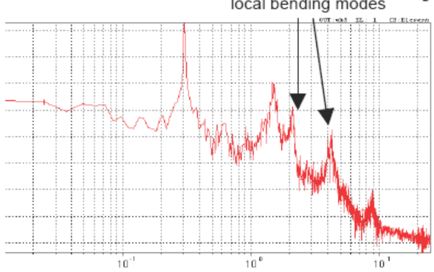
Example: ADCoS from ADC GmbH, Stuttgart

- Equation of motion solved by a non-linear integration method
- Non-linearities e.g. foundation stiffness may be considered
- Offshore-Model by coupling to the offshore code WaveLoads (Institute of Fluid Mechanics from the University of Hannover)









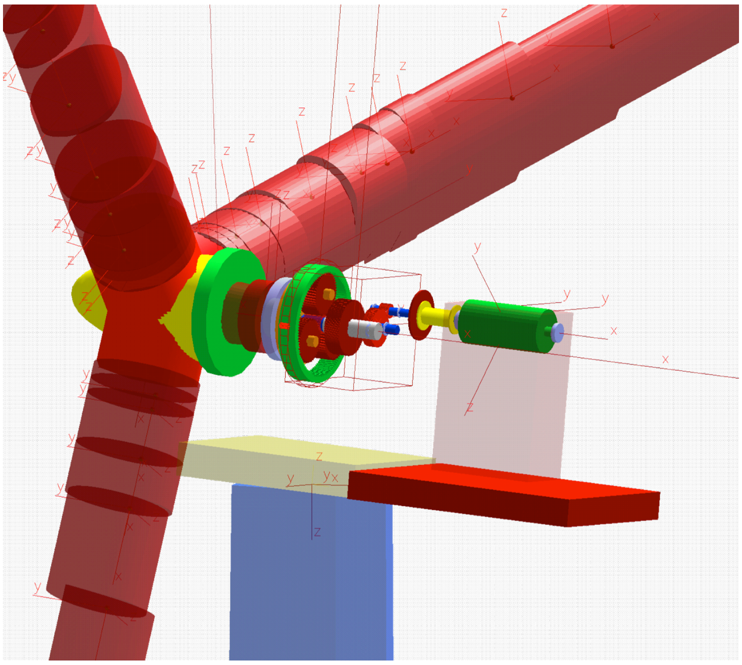
$$[M]\cdot\ddot{u}+[C+G]\cdot\dot{u}+[K+Z+H]\cdot u=R(t)$$

$[M]$	Mass matrix
$[C]$	Damping matrix
$[G]$	Coriolis matrix
$[K]$	Stiffness matrix
$[Z]$	Centrifugal stiffness matrix
$[H]$	Acceleration stiffness matrix
$R(t)$	Vector of external loads
$u, \dot{u}, \ddot{u}$	Displacement-, speed- and acceleration vectors

Approach C: Integrated simulation with multi body approach: SIMPACK

Wind turbine models with flexible level of detail

- Starting from models for parameter studies
- “28DOF models” for aero-elastic simulation
- More accurate models for drive trains etc.



Part III: Experimental Validation & Measurements

CARL VON OSSIETZKY universität OLDENBURG

What's the purpose of measurement?

Important Measurements

- Natural Frequencies
- Loads
- Operational Data

=> *Verification of Design*

- Power Curve
- Noise
- Grid Code Compatibility

=> Required for certification

=> Important for *marketing*

Offshore prototype
of REpower 6M at Ellhöft

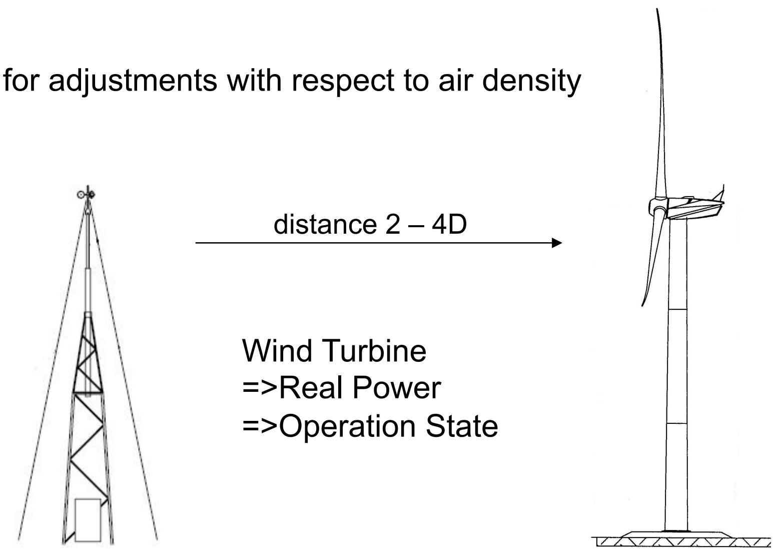
Repower 6M
[Fig. ForWind]

Measurement of power curve acc. to IEC 61400-12

Equipment at hub height (Distance 2 - 4 D, optimum: 2.5 D)

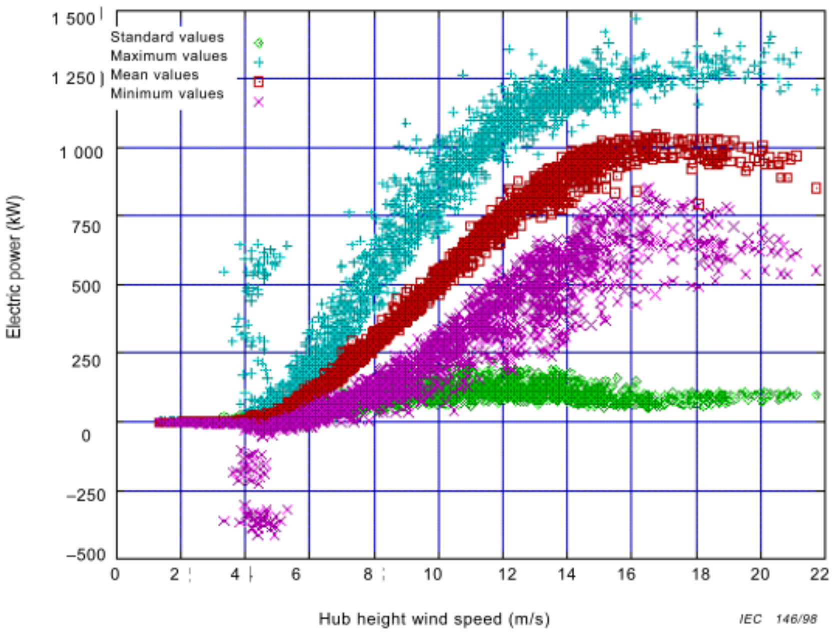
- Wind Speed
- Wind Direction
- Temperature
- Air Pressure
- Condensation

} for adjustments with respect to air density



[Fig.: REpower Produkt CD]

Scatter plot: Min-, Max-, Mean-, Std- values



Load measurement due to IEC 61400-13

Equipment at hub height
(equal to measurement of power curve)

Wind Turbine

- Rotor
  Bending: Flap- and edgewise direction
  Pitch angle
- Nacelle
  Rotor Shaft: bending (x, y) and torsion
  Rotor Position, Rotational speed, Azimuth position
  Wind speed
- Tower top
  Acceleration (x, y) or bending, Torsion
- Tower bottom
  Bending (x, y), Torsion
  Power, Operational state

[Repower 6M
Fig.: ForWind -WeSyS]

Measurement load cases (MLCs) acc. to IEC 61400-13

Measurement load cases during steady-state operation:

- 1.1 Power production
- 1.2 Power production plus occurrence of fault
- 1.3 Parked, idling

Measurement of transient load cases

- 2.1 Start-up
- 2.2 Normal shut-down
- 2.3 Emergency shut-down
- 2.4 Grid failure
- 2.5 Overspeed activation of the protection system

Note: Extreme wind loading (e.g. 50 years gust) cannot be measured, in practise!

Storage of 10 min measurements in „capture"-matrix

Minimum number of Datasets required

Measurements close to shut-down wind speed are time consuming due to the low frequency of occurrence

Turbulence Intensity [%]

Produktionsbetrieb bei Nennleistung Windgeschwindigkeits-Klassenbreite 1 m/s Turbulenz-Klassenbreite 2%																			
Zeitreihenlänge	Anzahl der 10-min Aufzeichnungen																		
Windgeschwindigkeit in m/s -> I in %	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	23
<3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-5	2	10	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5-7	5	23	9	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-9	8	30	28	23	16	5	3	1	3	1	0	0	0	0	1	0	0	0	0
9-11	13	45	62	51	45	45	21	15	10	7	8	1	6	2	6	4	0	0	0
11-13	14	74	121	170	125	88	75	52	48	43	18	18	29	29	25	10	2	2	0
13-15	15	89	116	191	200	146	103	77	86	64	46	49	51	50	23	6	2	0	0
15-17	17	70	101	160	147	108	109	65	51	61	49	57	39	18	11	6	2	0	0
17-19	9	29	53	57	48	49	36	29	22	30	34	31	32	8	4	0	0	0	0
19-21	5	16	21	13	15	16	10	9	2	8	9	6	4	2	0	0	0	0	0
21-23	4	1	1	10	6	3	6	1	0	4	1	0	0	0	0	0	0	0	0
23-25	0	1	4	3	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
25-27	1	3	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
27-29	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>29	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Anzahl der Turbulenzklassen mit mehr als 3 Zeitreihen	9	10	9	10	8	8	8	6	6	7	6	5	6	4	5	4	0	0	0
Gesamtanzahl	95	393	520	695	613	468	363	256	228	226	171	167	167	113	75	30	6	2	0

Erfassungsmatrix Normalbetrieb   Windgeschwindigkeiten: Medianwerte der Klasse

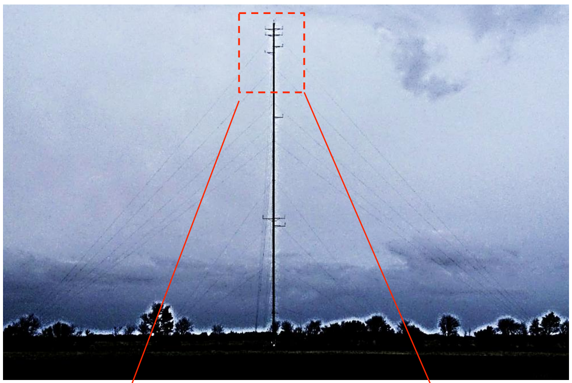
Mean Wind Speed

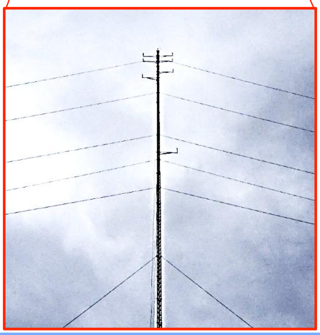
[Fig. Gasch]

Standard measurement system & campaign

1st class anemometer and atmospheric pressure

view from 100m





[Repower metmast
Fig.: ForWind -WeSyS]

temperature sensor and wind vane

data acquisition system

Measurement equipment mounted on the met mast

cup anemometers: 1st class type (Thies, Risø) at different heights:

- 102m (hub height)
- 74m (middle of rotor blade)
- 44m (tip of rotor blade)

air temperature sensors: 102m, 10m

atmospheric pressure: 101 m

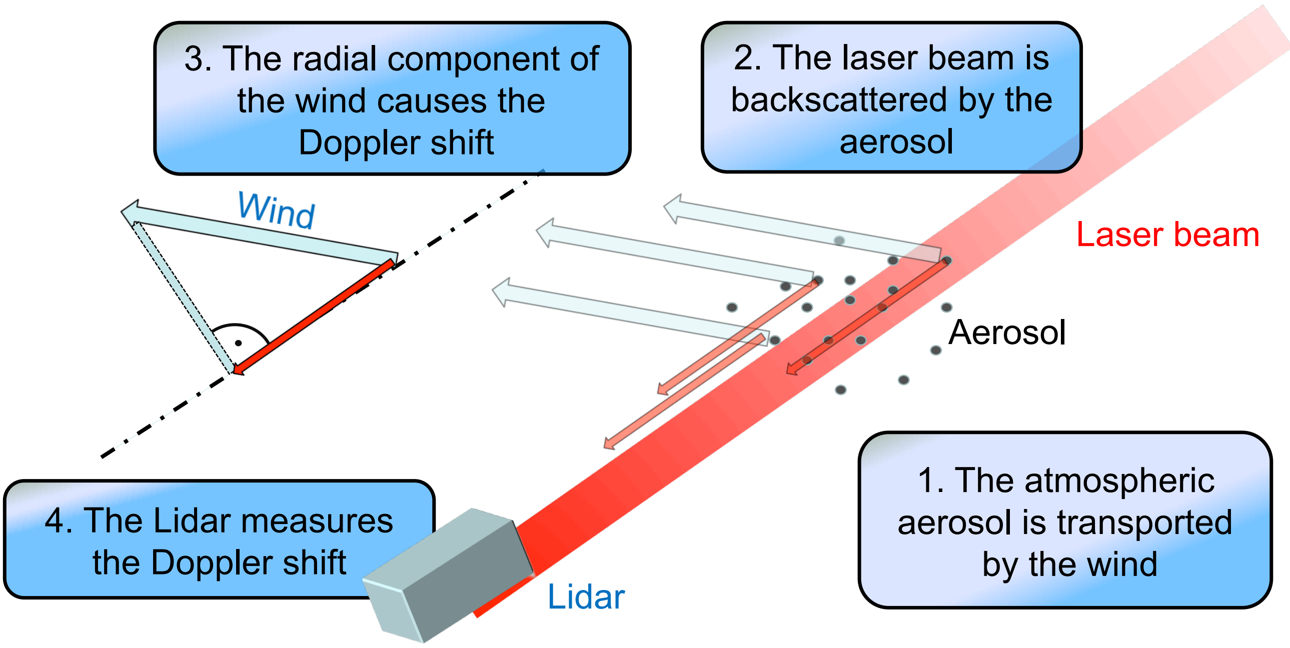
Wind vanes at different heights:

- 100m
- 73m
- 43m

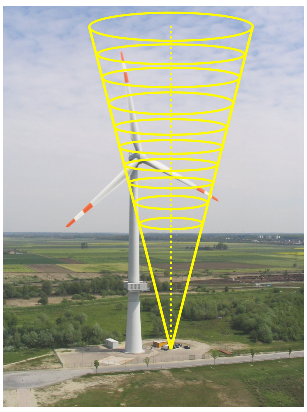
rain sensor: 10m

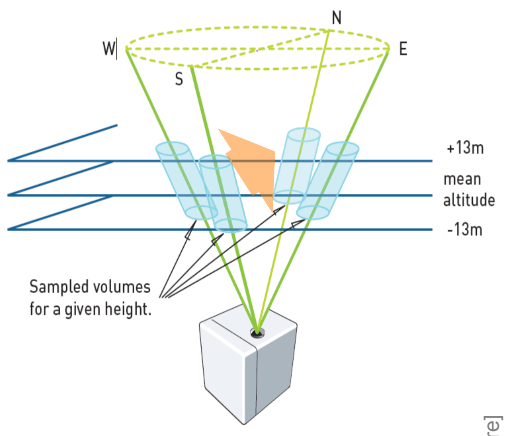
[Fig. Thies Klima, Risø]

LiDAR (Ligth Detecting and Ranging)



LIDAR: A quantum leap in wind measurement technology





- no need for expensive met masts
- larger measurements height
- high temporal and spatial resolution
- no offshore met platform (e.g. FINO 1)
- “smart” applications e.g. gust prediction, control

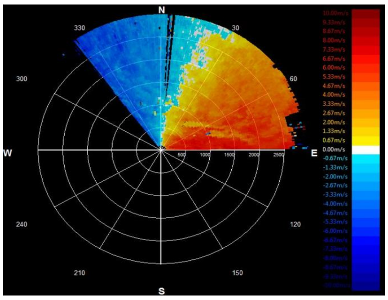
- wind profiler
  2D-wind vector derived from circumferential scan

[Abb. DLR, Leosphere]

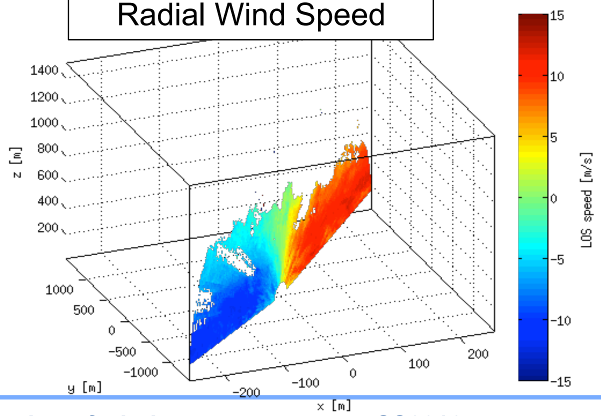
Lidars, not only profilers
Scanning lidars

- Wind field measurements
- Flexible trajectories
- Vortex detection
- Hard targets, clouds, atmospheric boundary layer

Fixed elevation (PPI), Radial Wind Speed



Fixed azimuth (RHI) Radial Wind Speed



RHI, CNR

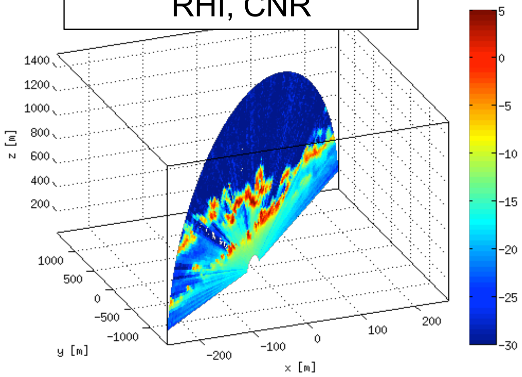
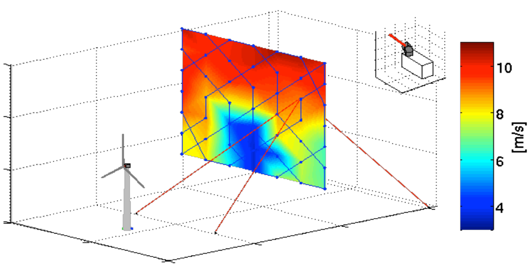
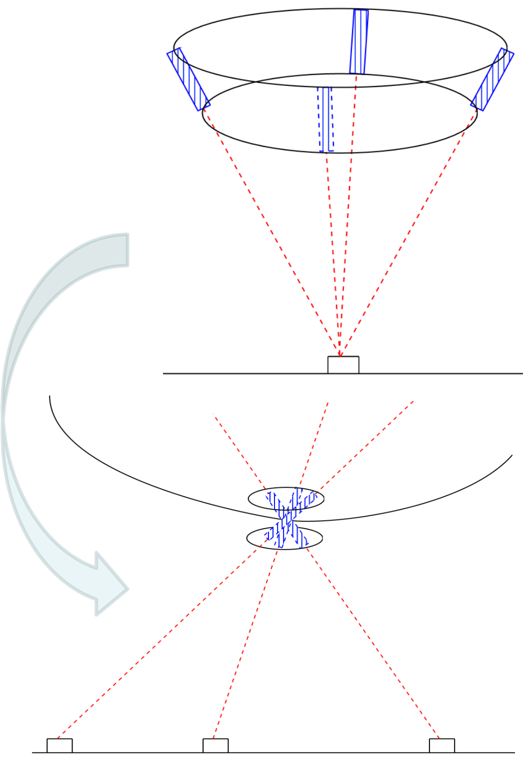


Fig.: ForWind – Uni Oldenburg.

Lidars, not only profilers
Multi lidar

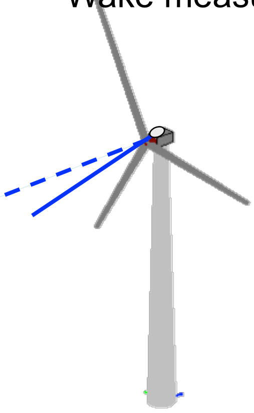
- Retrieval of the 3D wind vector
- Reduced probe volume
- Higher sample rate



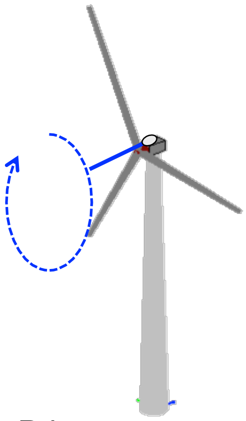


Lidars, not only profilers
Nacelle based lidars

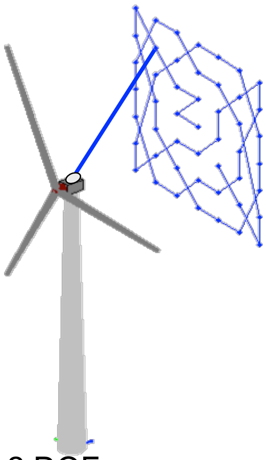
- Wind turbine control (pitch and yaw)
- Power/loads assessment (particular advantages for offshore application)
- Wake measurements



2 alternating beams
(pulsed,cw)



Prism scanner,
spinner based
(pulsed,cw)



2 DOF scanner,
(pulsed)

Lidars, not only onshore
Floating wind profilers

- Easy deployable
  (compared to a mast)
- Power supply issue
  (small wind turbines, photovoltaic panels
  battery, generator)
- See-state compensation
  (relative speed, beam inclination, wave height)

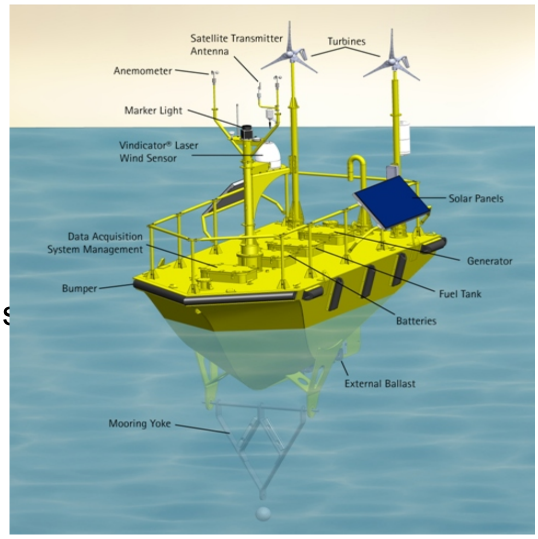
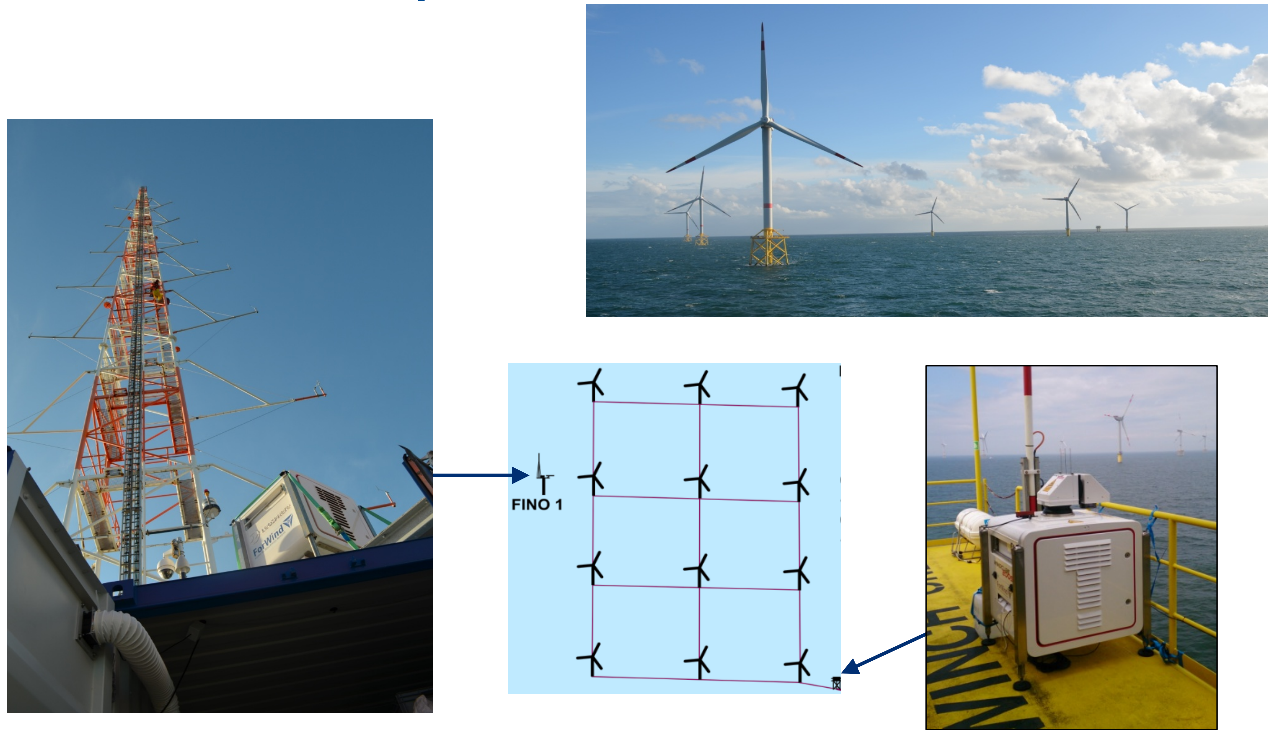


Fig.,AXYS, WindSentinel.

Fig.3E, Flidar .

Fig.,Zephir LTD, SeaZephir©

Measurement campaign with long-range Lidar windscanner at alpha ventus



Literature

[Hau] Erich Hau, Windkraftanlagen. Grundlagen, Technik, Einsatz, Wirtschaftlichkeit. 3. Aufl., 2003, Springer-Verlag; ISBN: 3540574301. Chap. 6.3 and 6.5

[Burton] T. Burton, et al., Wind Energy Handbook, 2001, Wiley

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