Technical University of Denmark

Wind Turbines: Innovative Concepts

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Wind Turbines: Innovative Concepts

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Wind Energy Theme Day for Industry: Control

hi [13] The Nordic Expo,
Herning, September 4th 2013

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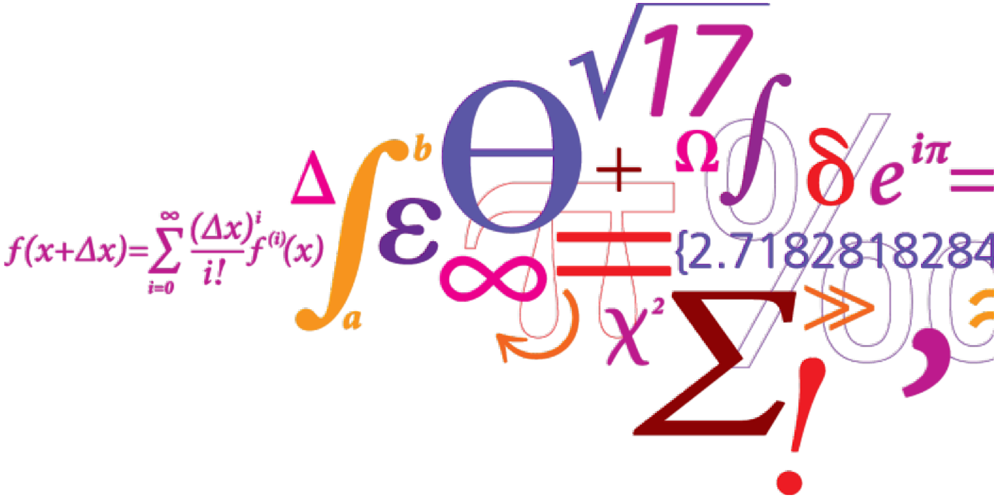
Outline

- Model-based control
  - Basics: State estimation, LQ/MPC control
  - Control Design Model
    - Example: Dynamic Inflow
- Trailing edge flaps
  - The concept
  - Combining trailing edge flaps and IPC
- LiDAR enhanced control
  - Load alleviation
  - Power optimization
- Passive vs. active control
  - Bend-twist couplings
- Floating wind turbines
  - Using an Extended Kalman Filter for state estimation

Model-based Control



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Control Methods applied on Wind Turbines

- **Classic Control Methods**
  - PI Control
  - Interconnected PI Controllers and Bandpass Filters
  - ...
- **Modern Control Methods**
  - Linear Quadratic Control (LQ)
  - Linear Parameter Varying Control (LPV)
  - Robust Control (H_2,H_∞)
  - Model Predictive Control (MPC)
  - Misc. Nonlinear Control Methods
  - ...
- ***Individual Pitch***
  - *Coleman/Multi-blade Coordinate Transformation*
  - *Decoupling of control loops*
  - *...*
- ***Trailing edge flaps***
  - *Decoupling of control loops*
  - *...*
- ***LiDAR***
  - *Feed forward of measure wind*
  - *...*

Model-based Control

Control Theory in Time Discrete Form

State space model

$\boldsymbol{x}(t_{k+1}) = \underline{\boldsymbol{f}}(\boldsymbol{x}(t_k),\boldsymbol{u}(t_k)) + \boldsymbol{w}(t_k)$

$\boldsymbol{y}(t_k) = \boldsymbol{g}(\boldsymbol{x}(t_k),\boldsymbol{u}(t_k)) + \boldsymbol{v}(t_k)$

State estimator

$\boldsymbol{x}(t_k|t_k) = \boldsymbol{x}(t_k|t_{k-1}) + \boldsymbol{L}\cdot[\boldsymbol{y}(t_k) - \boldsymbol{g}(\boldsymbol{x}(t_k|t_{k-1}),\boldsymbol{u}(t_k))]$

$\boldsymbol{x}(t_{k+1}|t_k) = \underline{\boldsymbol{f}}(\boldsymbol{x}(t_k|t_k),\boldsymbol{u}(t_k))$

State space controller

$\boldsymbol{u}(t_k) = \boldsymbol{K}\cdot\boldsymbol{x}(t_k|t_k)$

or

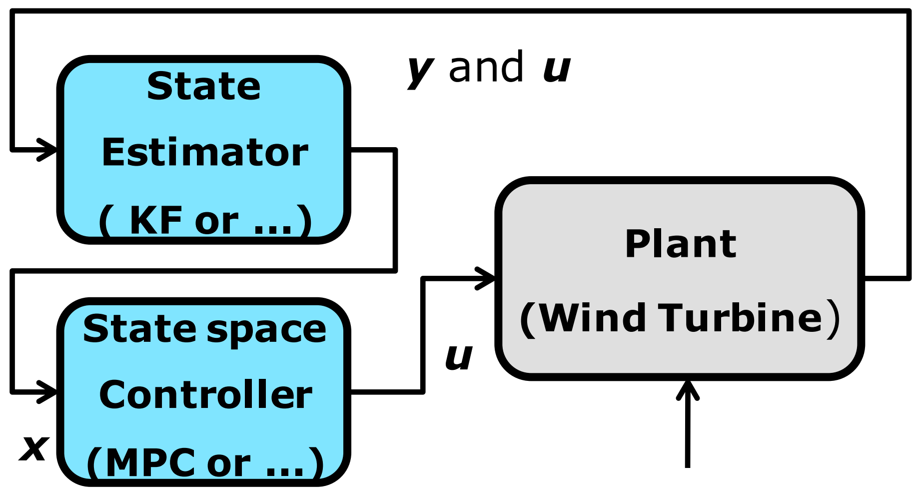
$\boldsymbol{u}(t_k) = \boldsymbol{K}\cdot\boldsymbol{x}(t_k|t_{k-1})$

or

$\boldsymbol{u}(t_k) = \boldsymbol{k}(\boldsymbol{x}(t_k|t_{k-1}))$

or

...



Disturbances: ***w*** and ***v***

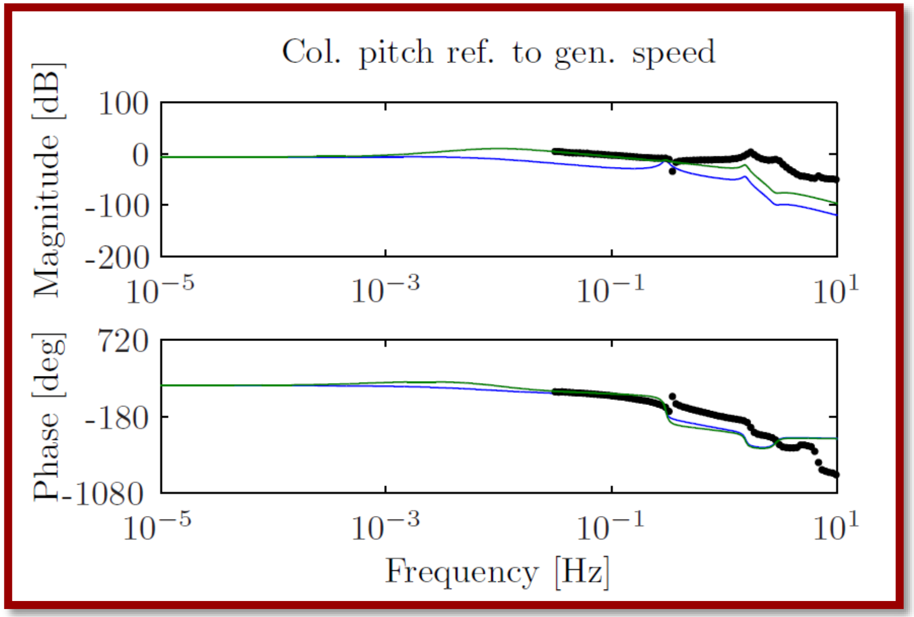
(Turbulent Wind, Wave forces, ...)

Model-based Control
Control Design Model

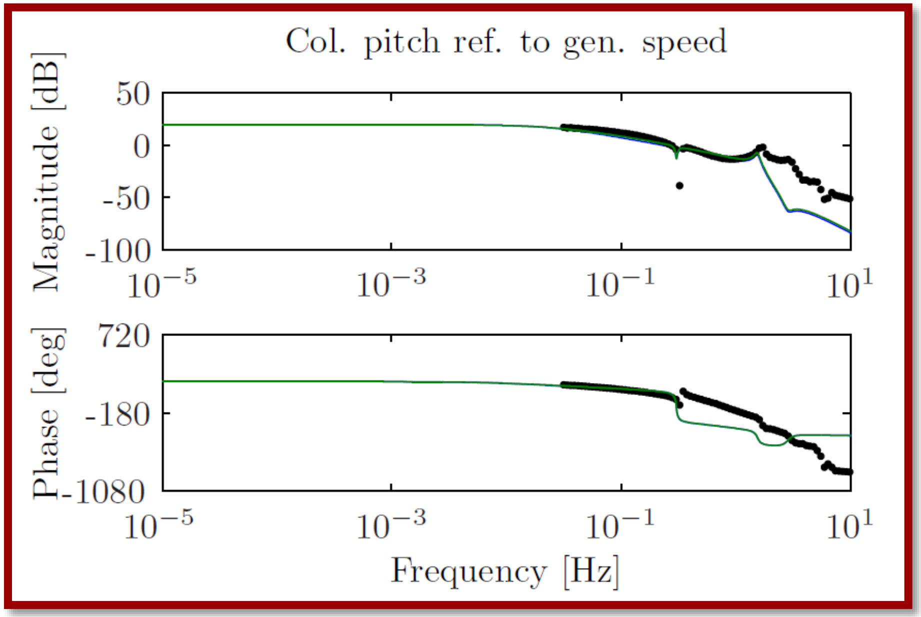
- The control design model is a set of linear/nonlinear ordinary differential equations (in state space form), which are “adequately” describing the system to be controlled.
  - “Adequately” means including phenomena of interest (tower DOFs, blade DOFs etc.) in a frequency range of interest.
- The control design model can be obtained from *first-principles* modeling, system identification (black box), a combination of the two (gray box).
  - A *first-principles* model of a wind turbine can be obtained from aero-elastic software codes such as Bladed, FAST, HAWCStab2 etc.

Model-based Control
Control Design Model

- Bode plots – From collective blade pitch to generator speed

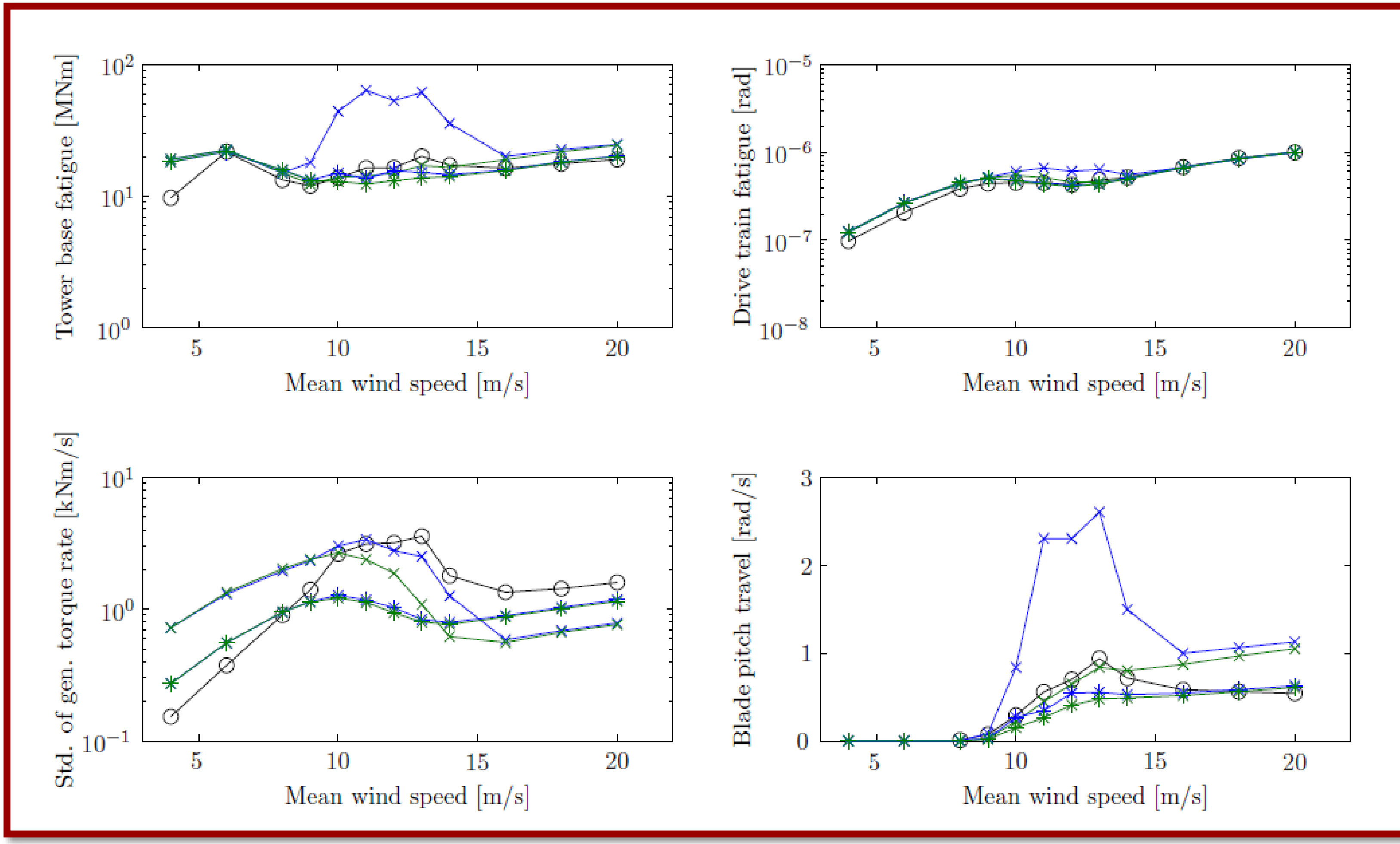


8 m/s

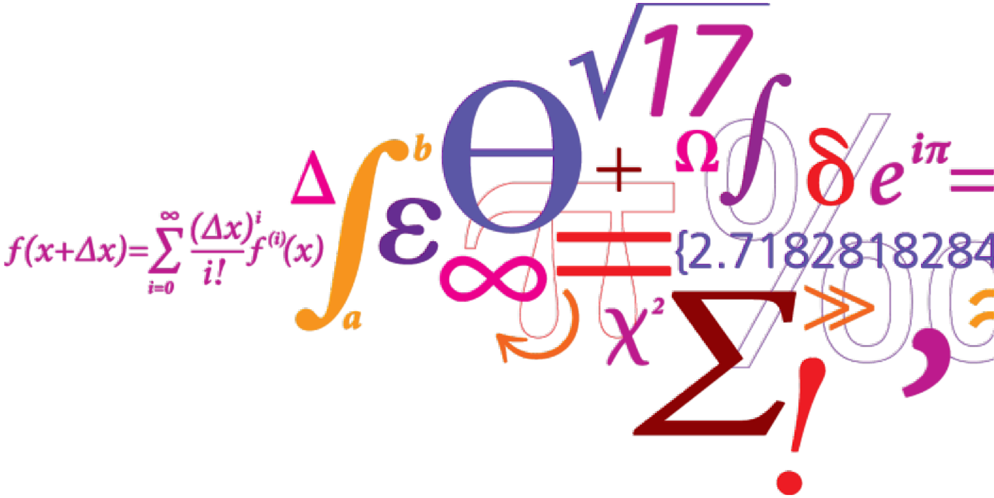


16 m/s

Model-based Control
Dynamic Inflow

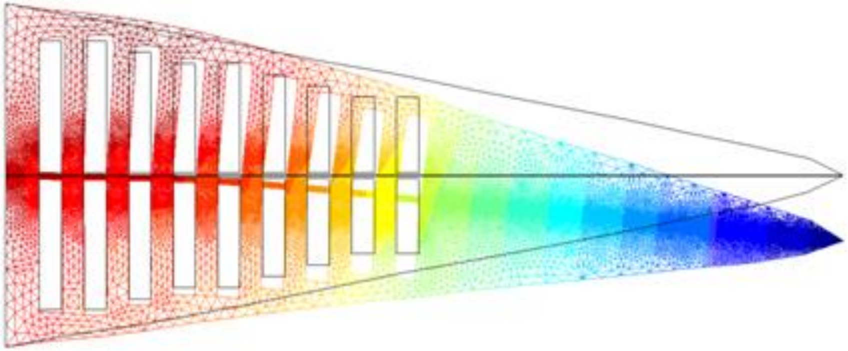


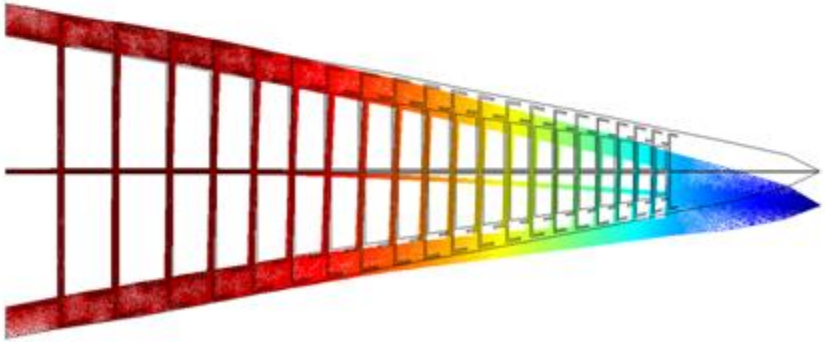
Trailing Edge Flaps

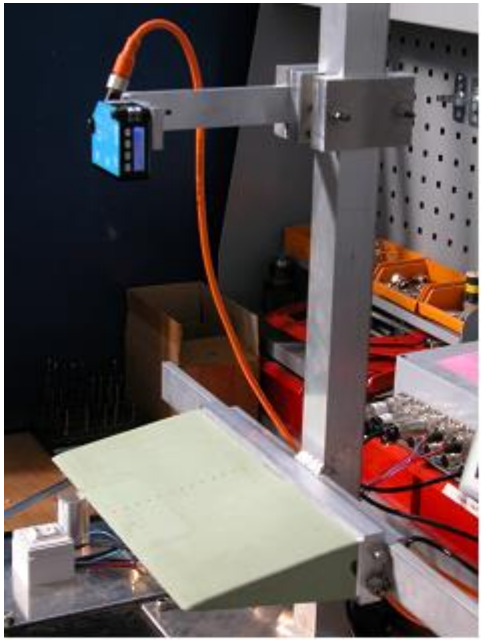


Trailing Edge Flaps
The CRTEF Development

Comsol 2D analyses







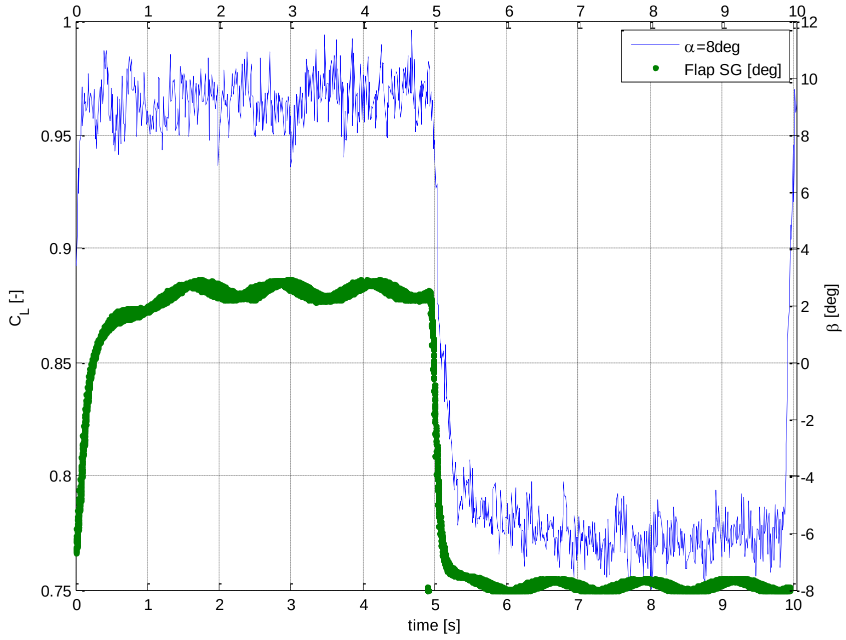
Trailing Edge Flaps

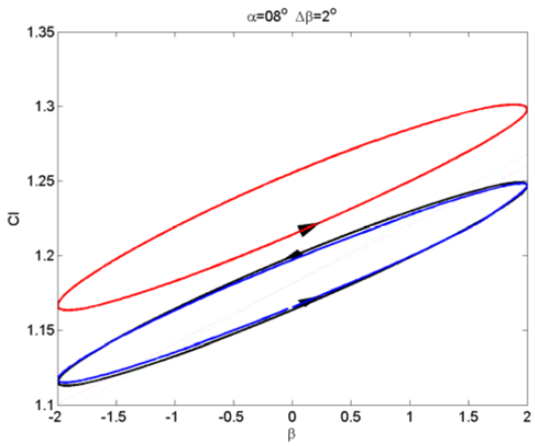
Wind tunnel experiment Dec. 2009

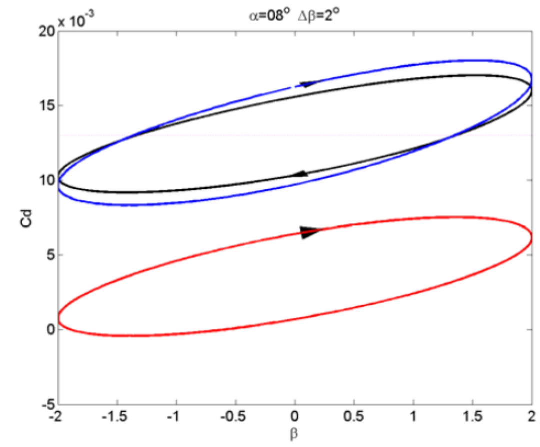
two different inflow sensors

Trailing Edge Flaps

Comparison of measurements and model



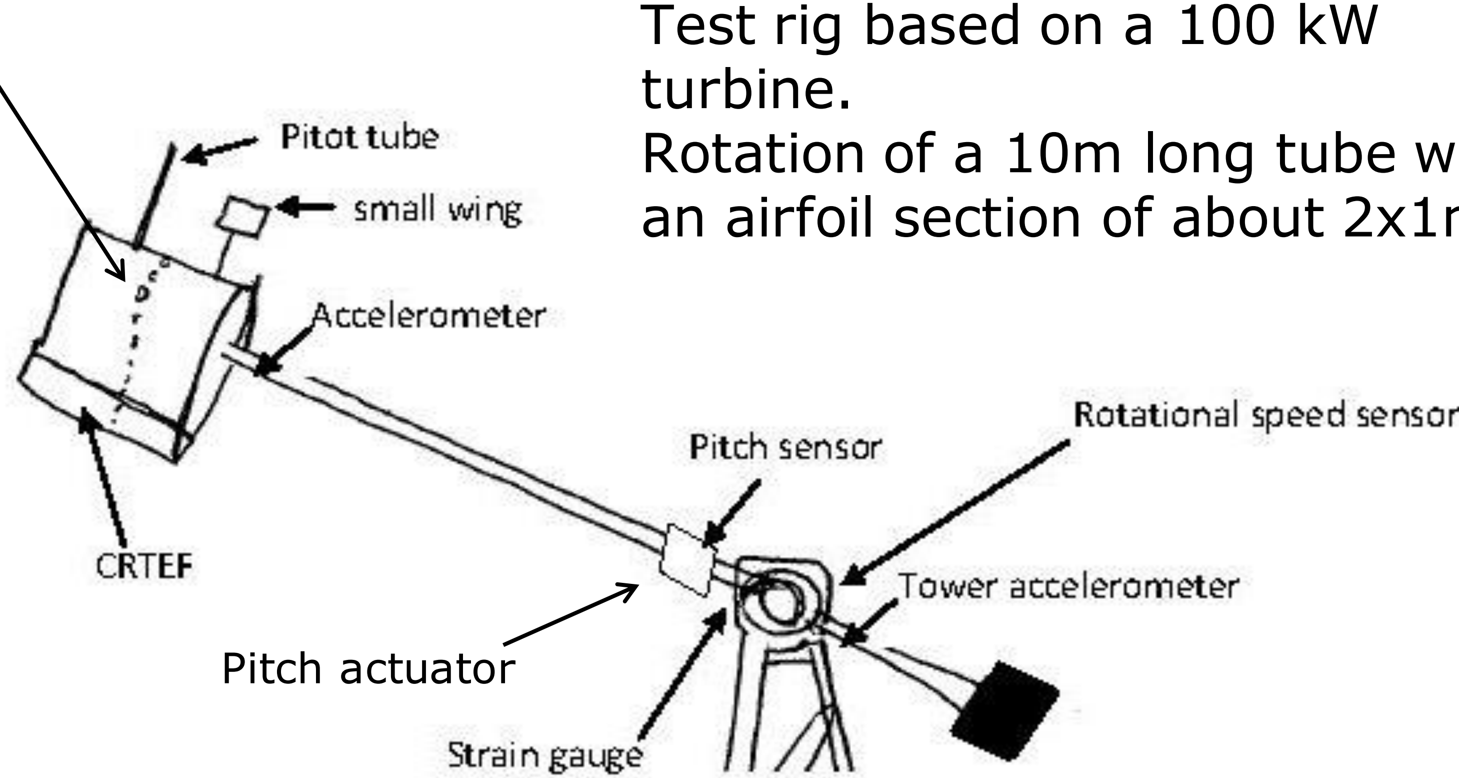




Test rig

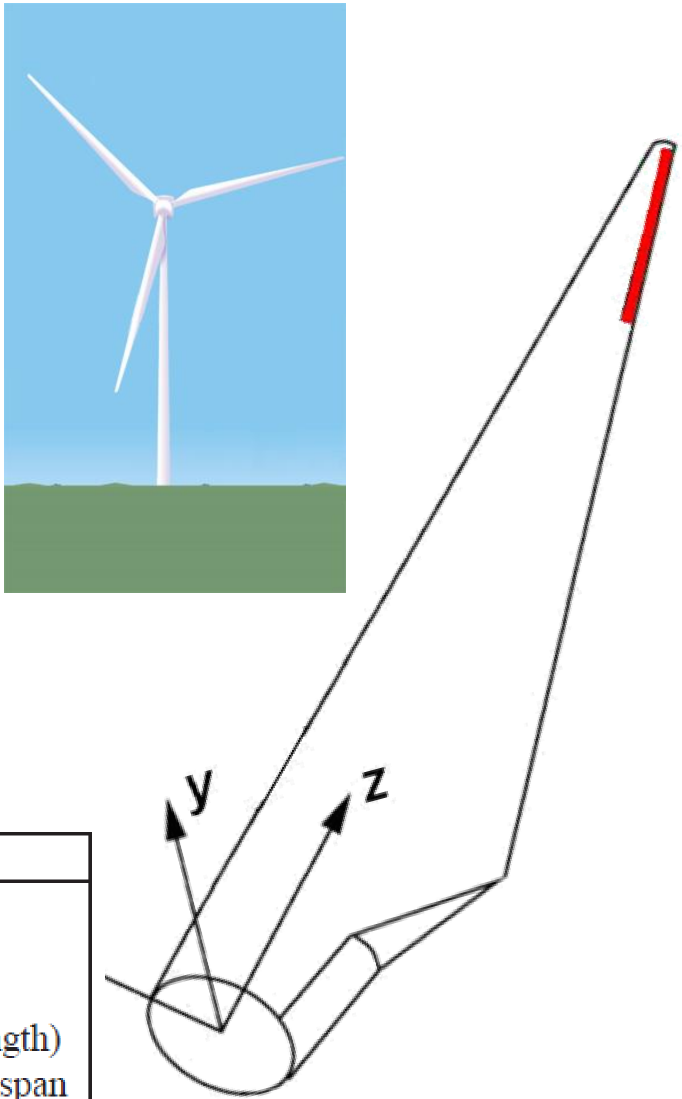
Pressure measurements

Test rig based on a 100 kW turbine.
Rotation of a 10m long tube with an airfoil section of about 2x1m



Trailing Edge Flaps
Simulation Test Case

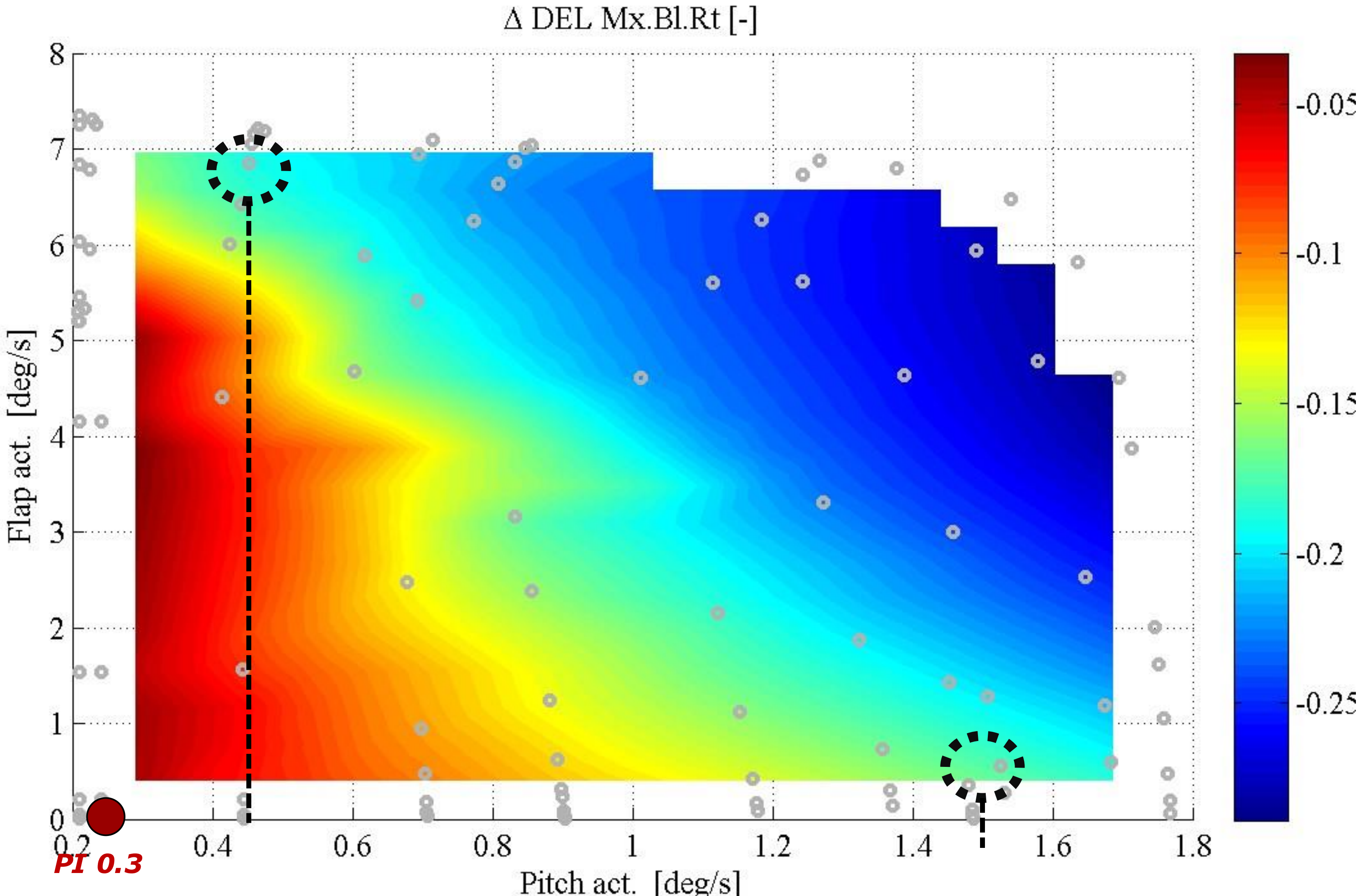
- Reference NREL 5 MW turbine
- Adaptive Trailing Edge Flaps
  - All flaps on one blade moved as one
- Sensors:
  - Shaft sp., Blade root b.mom, Tower top acc.
- Simulations with HAWC2
  - Multibody dynamics, includes torsion
  - Unsteady BEM aerodynamics
- IEC conditions: class A. Iref:0.16 (wsp: 18 m/s)
- Focus on blade load alleviation



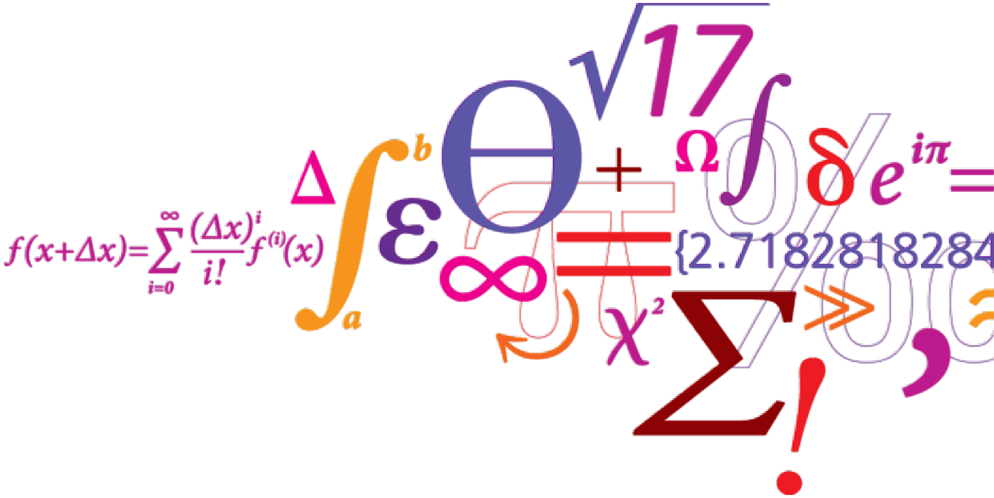
Reference Wind Turbine		*Flap Setup*	
Rat. Power	5 MW	Chordwise ext.	10%
Num.Blades	3	Deflect.limits	$\pm 10^\circ$
Rotor Diam.	126 m	Max. ΔCl	$-0.45 \sim +0.41$
Blade length	61.5 m	Spanwise length	12.3 m (20% blade length)
Rat. Rot.Sp.	1.267 rad/s	Spanwise loc.	from 47.7 m to 60.0 m span
Hub height	90 m	Max.ΔMx.Bl.Rt	approx. $\pm$1100 kNm

Trailing Edge Flaps

Combined IPC and Trailing Edge Flap Control



LiDAR Enhanced Control



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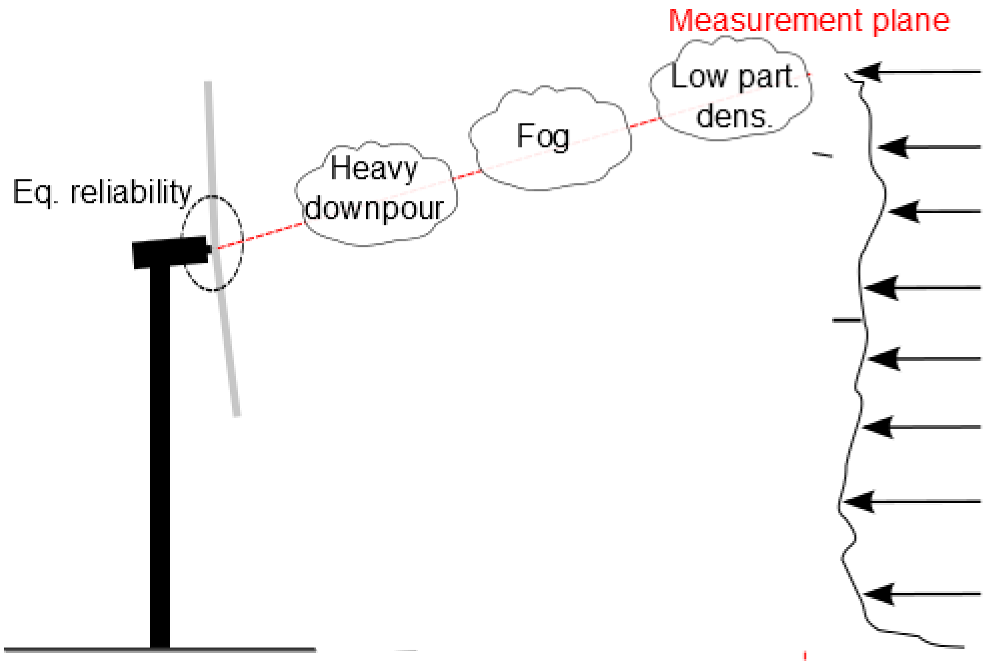
LiDAR Enhanced Control
Types and objectives

- Load alleviation
  - Collective pitch control (CPC)
  - Individual pitch control (IPC)
- Power optimization
  - Tracking optimal operation point
  - Reducing yaw misalignment

- *Nacelle mounted (mounted on top of nacelle)*
- *Spinner/hub mounted*
- *Blade mounted (instead of pitot-tubes)*

LiDAR Enhanced Control
Uncertainties and Limitations

- LiDAR uncertainties
  - Validity of Taylors hypothesis of frozen turbulence
  - Volume average of wind speed measurements
  - Projection error
  - Measurement availability and system reliability



LiDAR Enhanced Control
Collective Pitch Control

- D. Schlipf et al., 2012.
  - Experimental results shows that fatique loads of CART2 turbine can lowered by introducing LiDAR based feed-forward collective pitch control
- E. Bossanyi et al., 2012

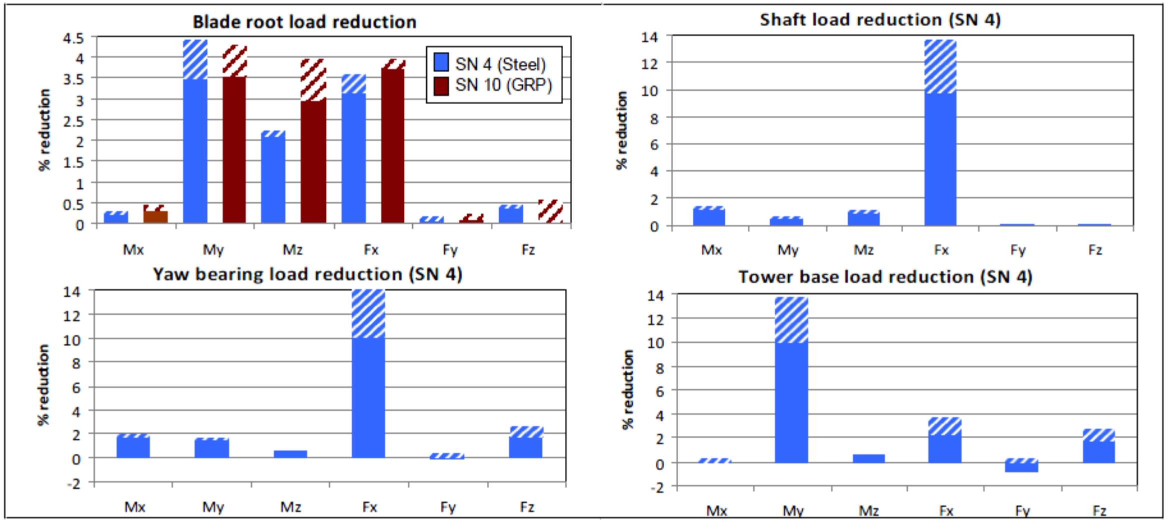
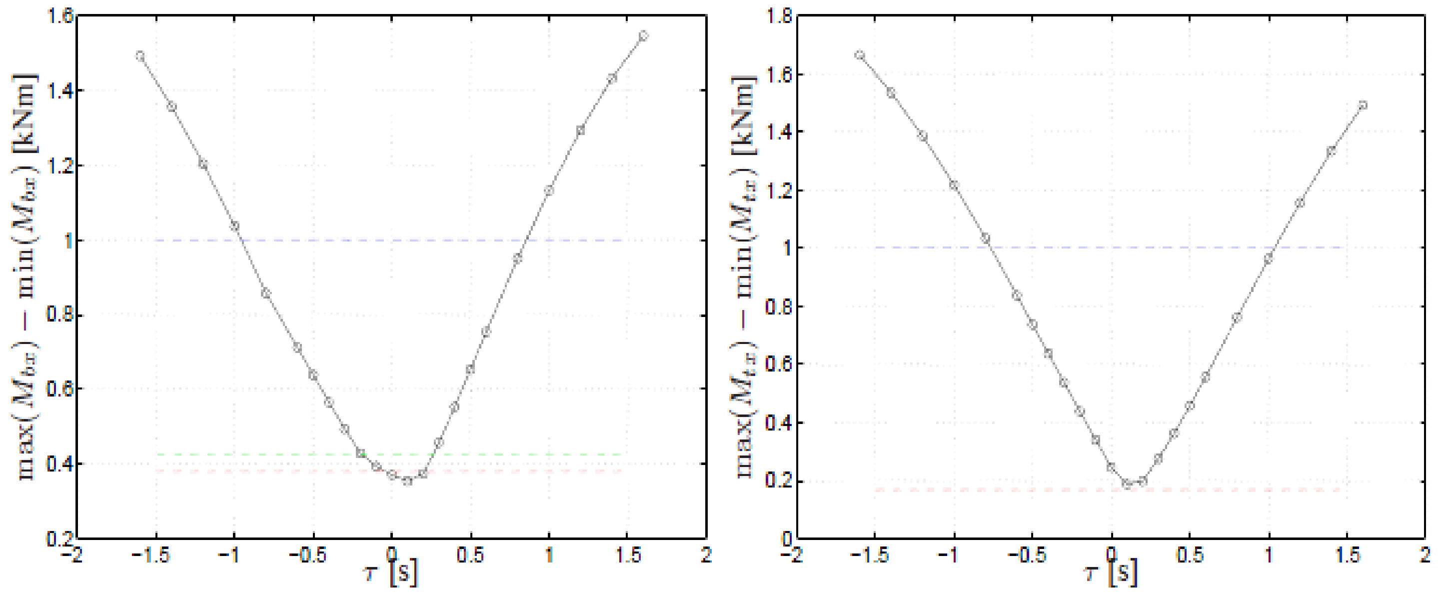


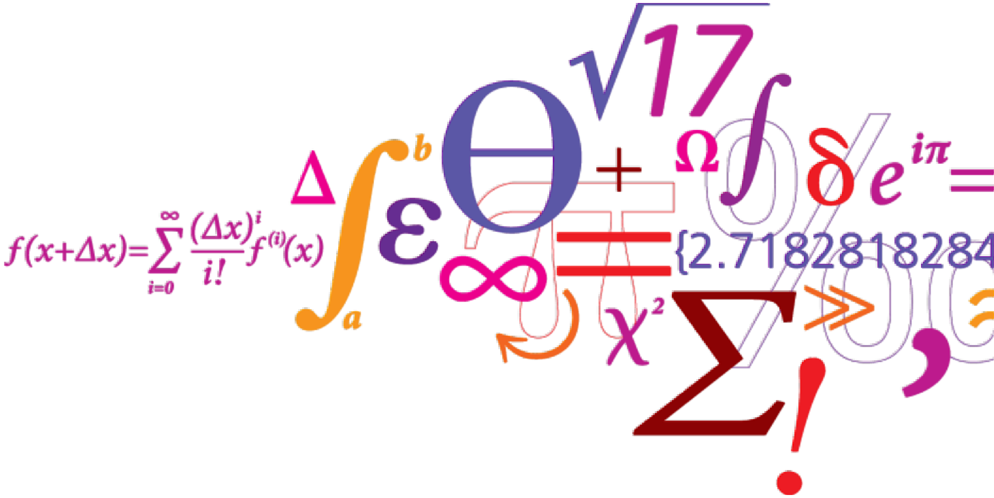
Figure 11: Lifetime fatigue load reductions

LiDAR Enhanced Control
Individual Pitch Control

- K. A. Kragh et al., 2013
  - LiDAR based feed-forward IPC is mainly beneficial in situations with rapid, smal scale variations (e.g. changing wind shear).
  - Very sensitive to uncertainties relating to the inflow estimation



Passive vs. Active Control



Passive vs. Active Control
Overview

- Passive control methods
  - Swept blades
  - Bend-twist couplings

- Active control methods
  - Individual pitch control
  - Trailing edge flap control

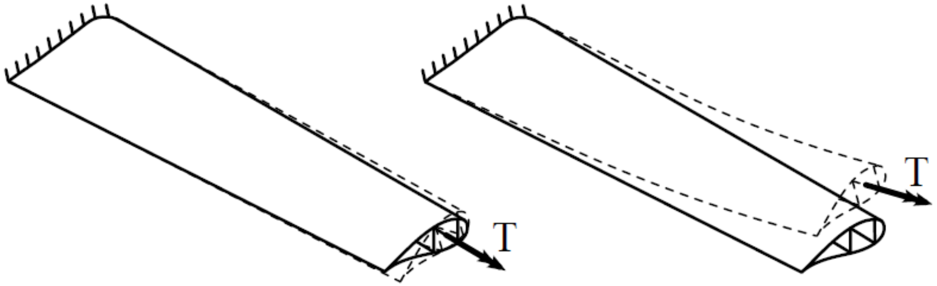


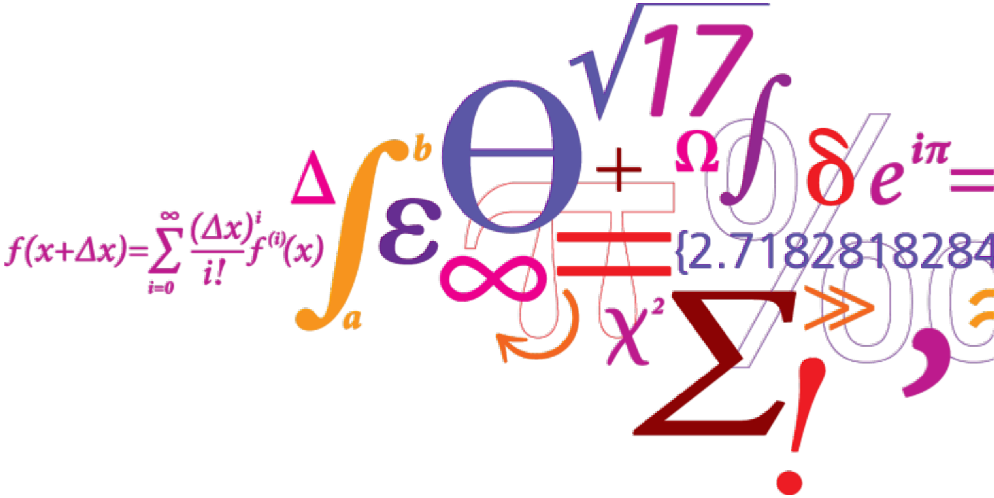
Figure 2.1: Torsion of a traditional design (left) and bend-twist coupled design (right) wind turbine blade sections

Passive vs. Active Control

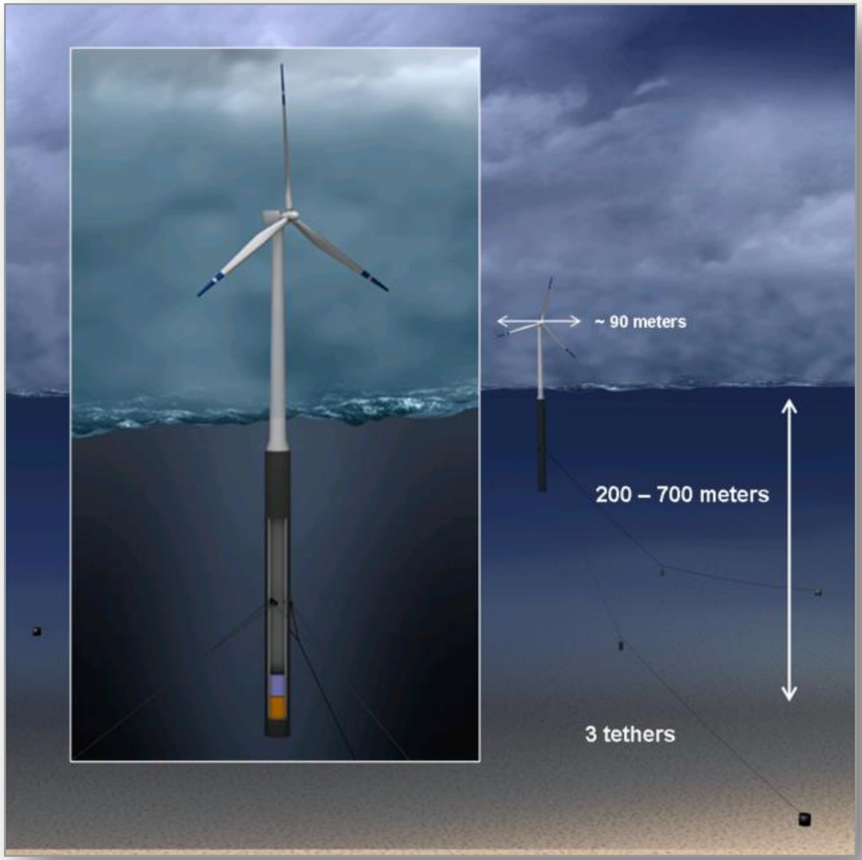
Issues

- Many aero-elastic tools needs further development to handle complex beam models.
- Can the blades be fabricated such that they behave as predicted by the aero-elastic tools.
- Further development of control methods is needed.
- Developed control methods should be adopted by industry.

Floating Wind Turbines



Floating Wind Turbines
The Hywind Concept



Floating Wind Turbines
Simulations of the Hywind Concept (I)

Wind turbine states

- 1 or 2 tower fore-aft DOF
- 1 or 2 tower side-side DOF
- 2 blade edge-wise DOF pr. blade
- 2 blade flap-wise DOF pr. Blade
- 1 induced wind speed state pr. blade

- ***Disturbance states***

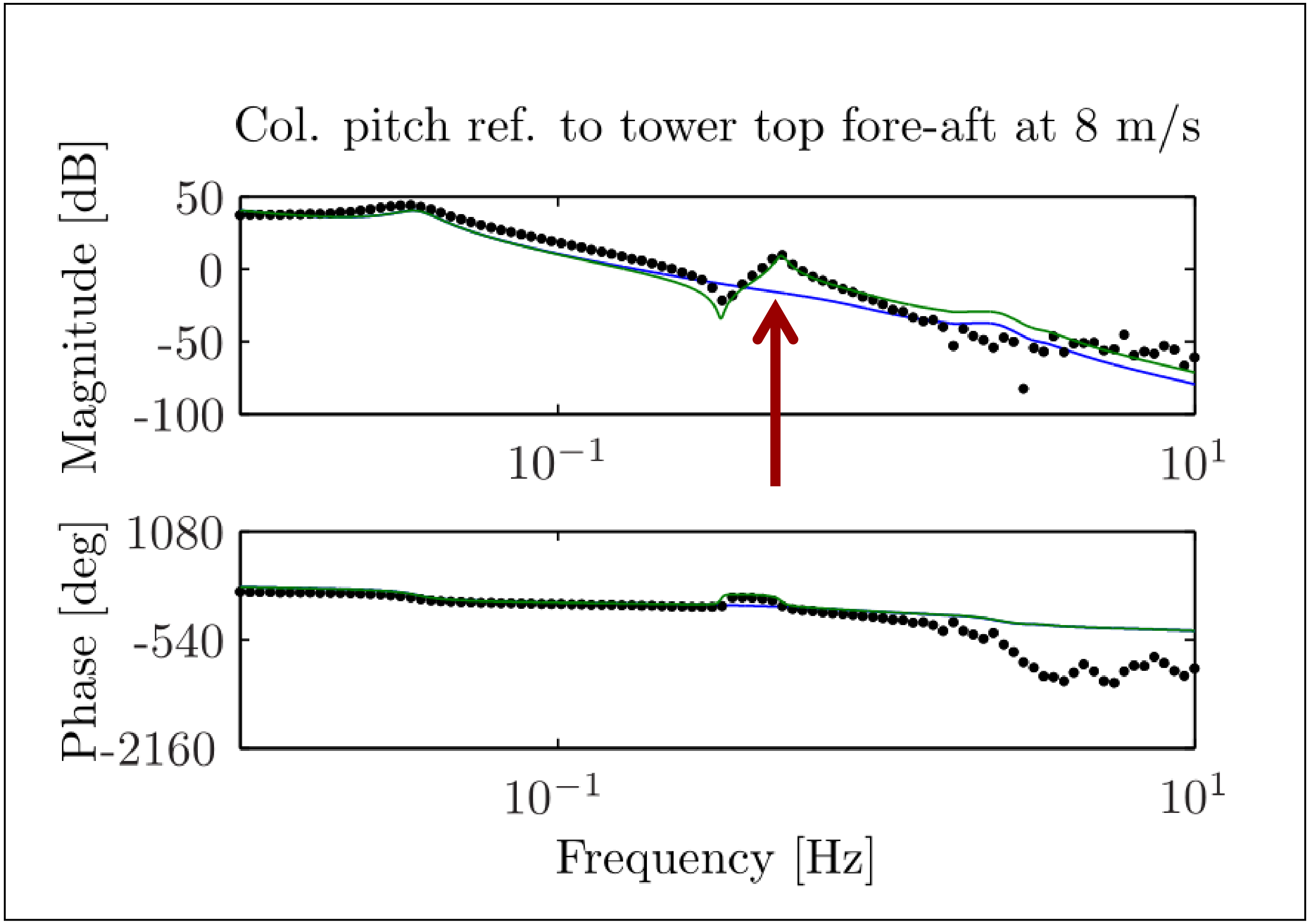
- 1 wind speed (2nd order) pr. blade
- 1 fore-aft hydrodynamic force (2nd order)
- 1 side-side hydrodynamic force (2nd order)

Sensors used by the EKF

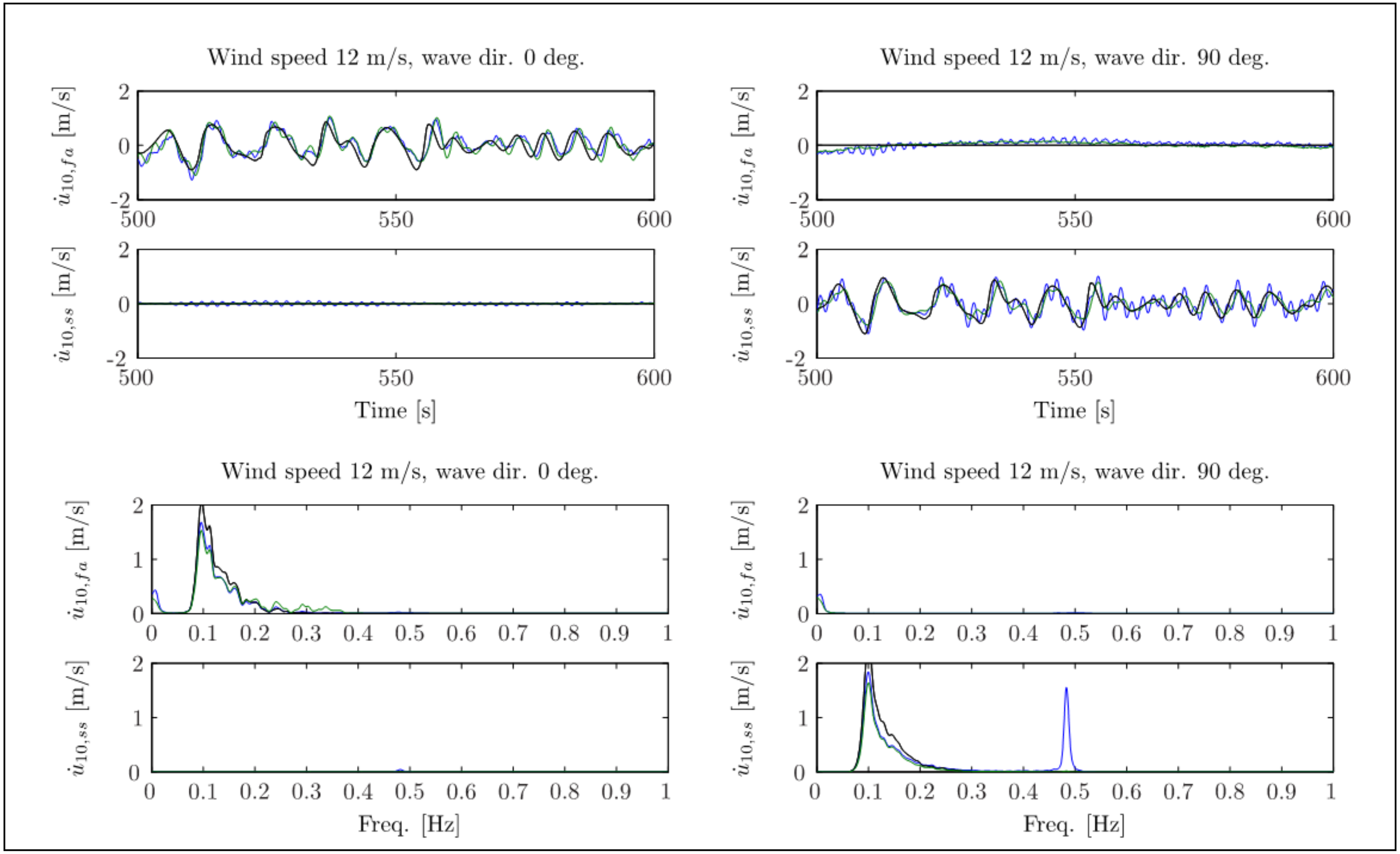
- Pitch angles of each blade
- Electro magnetic generator torque
- Generator power
- Generator speed
- Rotor speed
- Tower top fore-aft acceleration
- Tower top side-side acceleration
- Flap-wise blade root bending moment at each blade
- Edge-wise blade root bending moment at each blade

Floating Wind Turbines

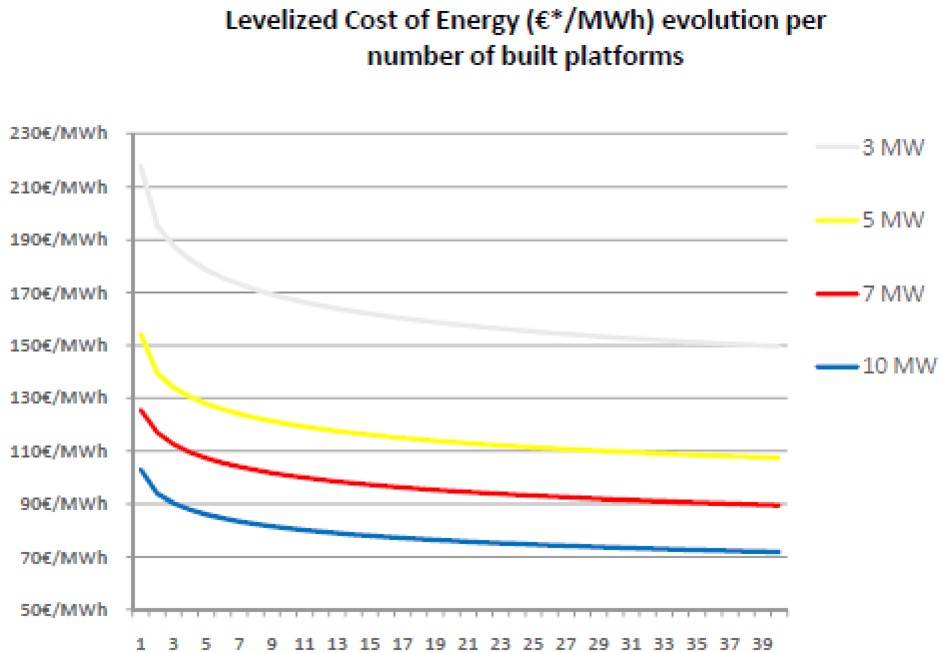
Simulations of the Hywind Concept (II)



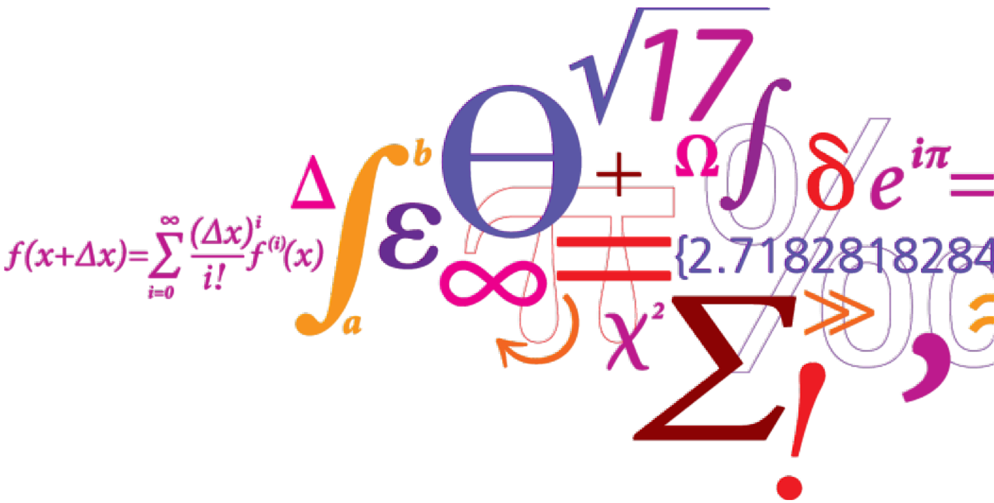
Floating Wind Turbines
Simulations of the Hywind Concept (III)



Floating Wind Turbines
The WindFloat Concept



Industrial/academic Cooperation



Industrial/academic Cooperation

- Foundations for offshore wind turbines (incl. floating concepts)
- Trailing edge flaps
- LiDARs
- Pitch gears
- Drive train gears
- Aerodynamic blade design
- Structural blade design

- Materials research both composites and alloys/metals
- Wind Recourse Assessments

- Measurement campaigns for wind turbines

- High altitude wind energy converters (Kites and lighter than air devices)

Conclusions

- Good mathematical models of systems and components are required both for control design purposes but also for evaluation of performance/behavior.
- Many innovative concepts have been and will be tested and developed, some will mature for commercial success and some will be forgotten, only to be presented as innovations a decade later.
- Cost-of-energy (COE) is ultimately the main driver determining whether or not an innovation will reach a commercial state.
- Academic cooperation is good way to test some of the innovative ideas before spending to much time and money on the idea.

Thank you for your attention!