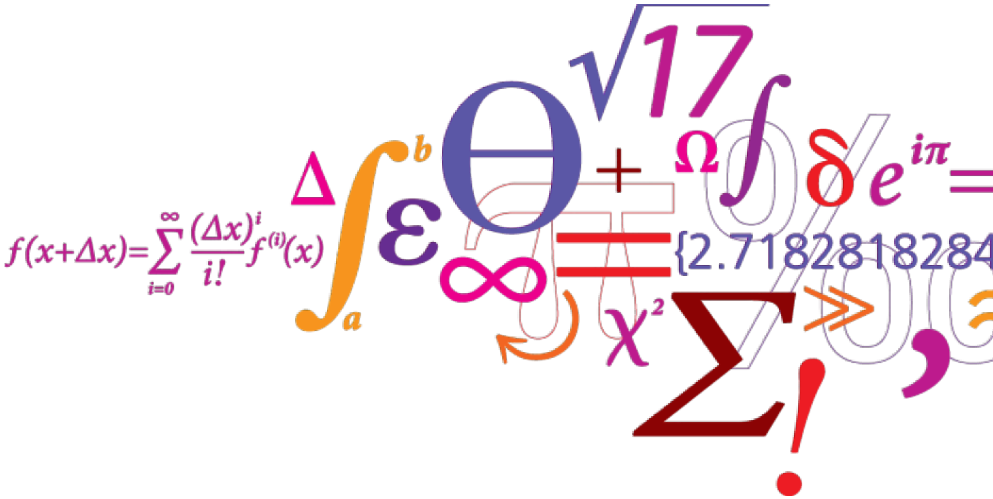
Adaptive Trailing Edge Flaps for Active Load Alleviation

Aerodynamic model, and control integration.

Leonardo, Lars

Project Meeting, 3rd December



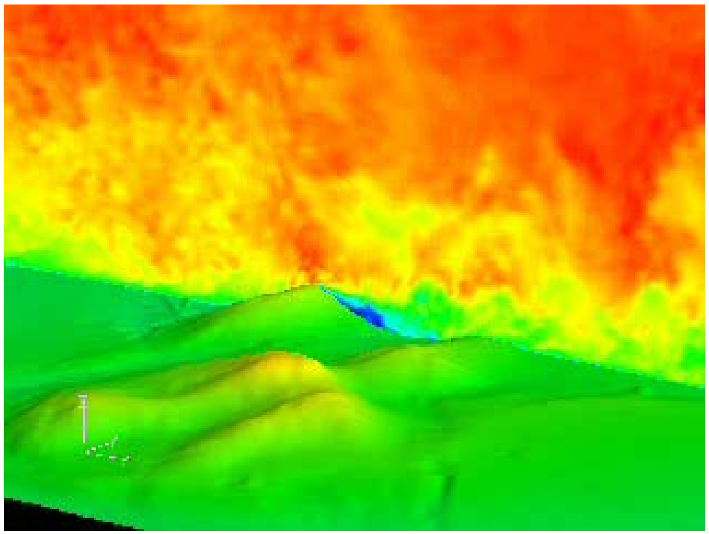
DTU Wind Energy
Department of Wind Energy

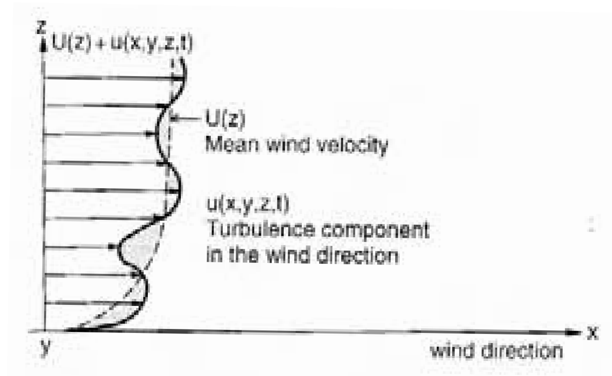
Agenda

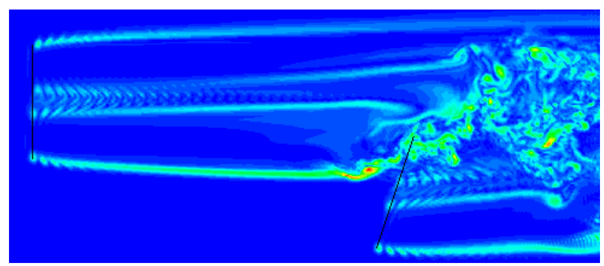
- Why a smart rotor?
- Aerodynamic model for Adaptive Trailing Edge Flaps
- Flap and structural response
- Flap and control
  - SISO System ID and LQ example
  - Potential of integrated model based controller
  - HAWCStab2 Framework for integrated model based control design
- Future work and topics of interest

Why a smart rotor?

- Wind turbine (on shore and off shore) operate in non-uniform flow field







- Non-uniform flow filed produces varying loads on blades and structure -> loads amplification and fatigue damage

Why a smart rotor? (2)

Rotor with Adaptive Trailing Edge Flaps

↓

Modify airfoil geometry

↓

Control Aerodynamic Forces

↓

Compensate for variations in wind field

↓

Active Load Alleviation

Smart Rotor

- Combination of sensors, control unit, actuators
- Actively reduces the loads it has to withstand
- Actuators:
    - Blade Pitch
    - Distributed aerodynamic control (Trailing Edge Flaps)

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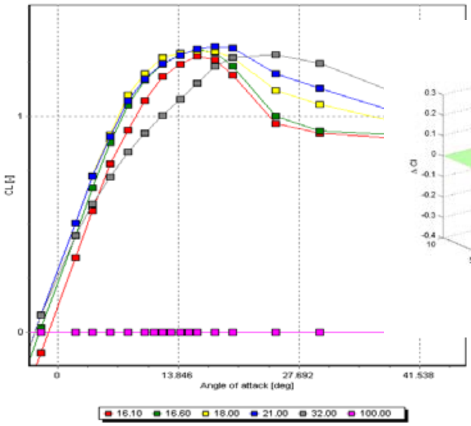
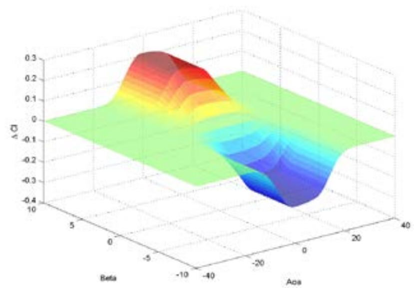
Aerodynamic model for Flaps

- For aeroelastic simulations:
  - – BEM framework: 2D model
  - – Simple and fast: engineering model.
- Model should account for:
  - – ***Steady Effects:***

    Passed as input



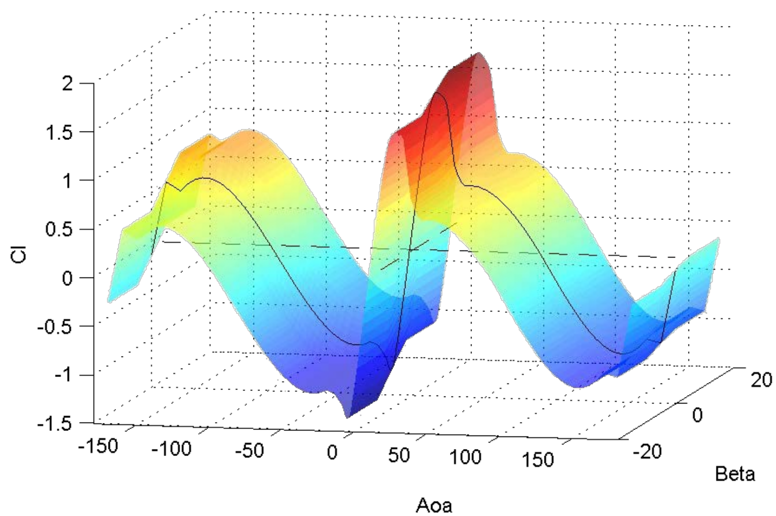


  - – ***Unsteady dynamics:***
- *Attached flow & non circ.*

Thin-airfoil in potential flow (Gaunaa)

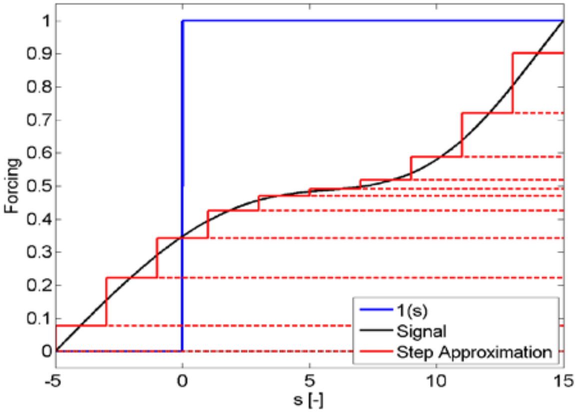
- *Flow separation:*

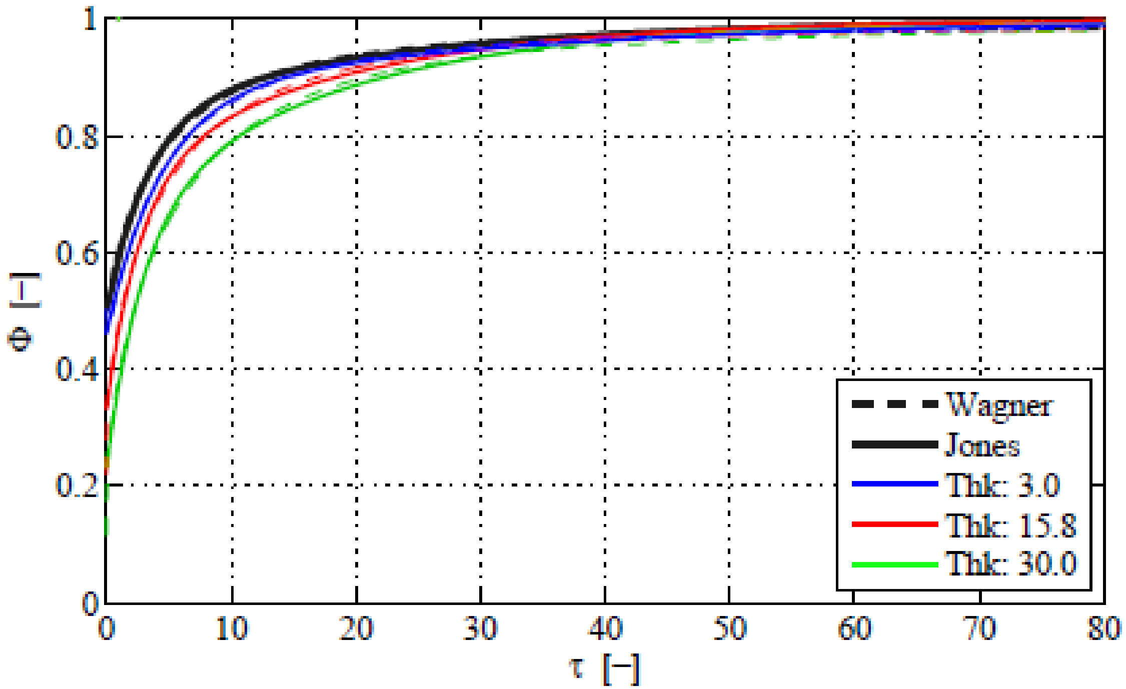
Beddoes-Leishmann type of dynamic stall model (Hansen model for TE stall of a rigid airfoil) Modified for flap contribution



Attached flow dynamics

- Lift response: superposition of Step Responses.
  → Indicial Response Function (Wagner):
  - Not dependent on the cause
  - Formulated in exp. terms for integration (Jones)
  - Depends on Airfoil Geometry (Thickness)



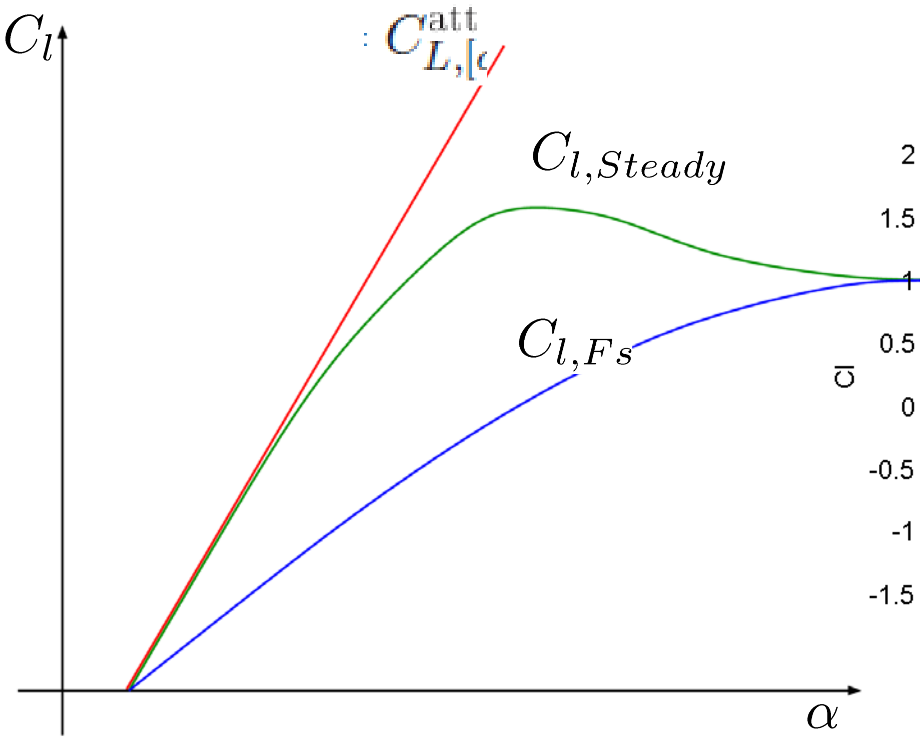


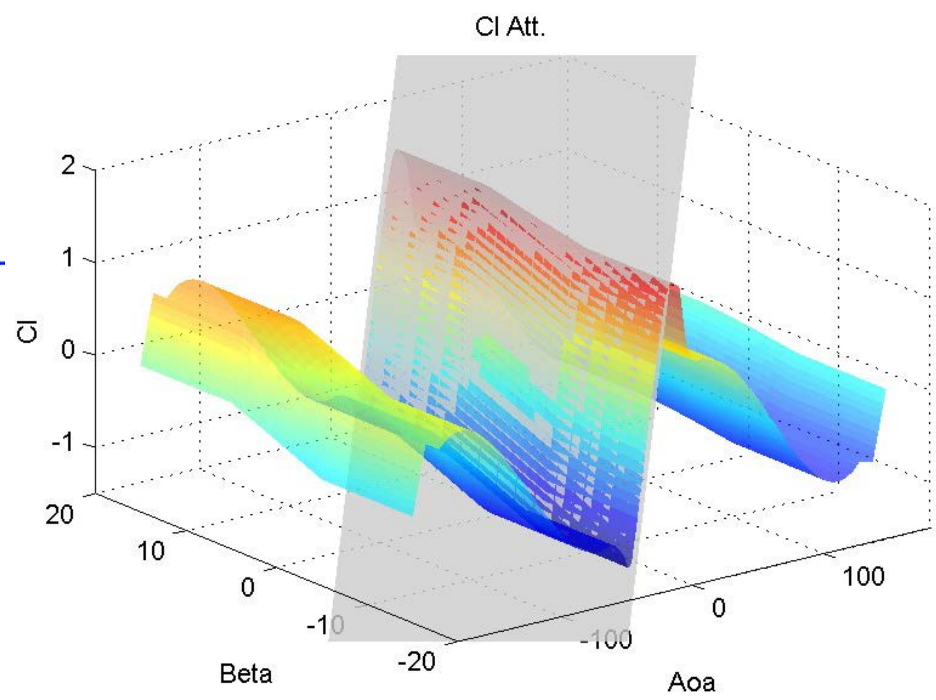
$$\Phi = 1 - \sum_{i=1}^{N_{lag}} A_i \exp^{b_i \tau},$$

Unsteady Aerodynamics: Flow Separation

Potential flow model coupled with Beddoes-Leishmann dynamic stall model:

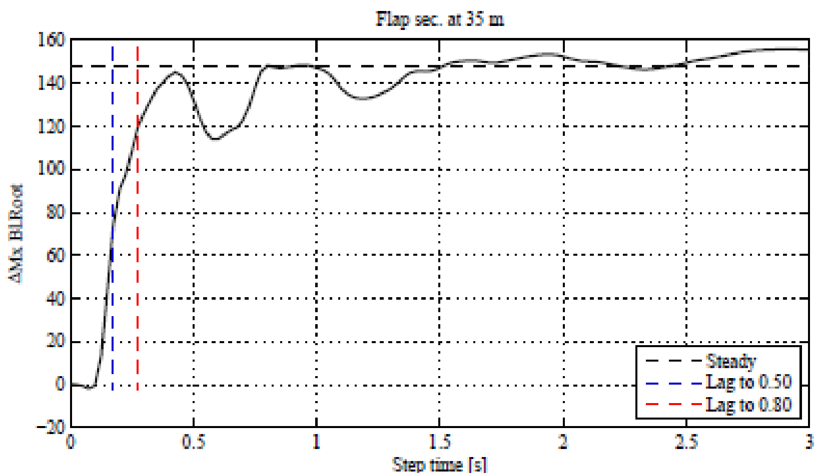
$$C_l^{\text{Circ.Dyn}} = C^{\text{att}}_{l,[\alpha_{\text{eff}};\beta_{\text{eff}}]} f^{dyn} + C^{\text{fs}}_{l,[\alpha_{\text{eff}};\beta_{\text{eff}}]} \left(1 - f^{dyn}\right)$$

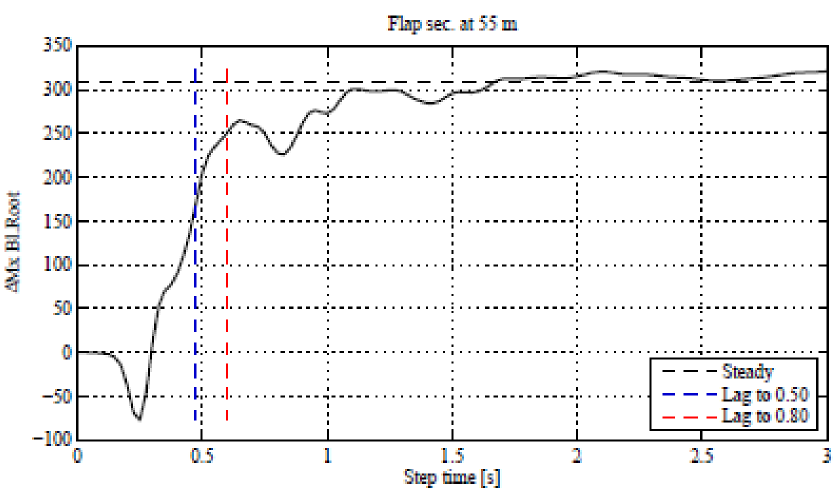


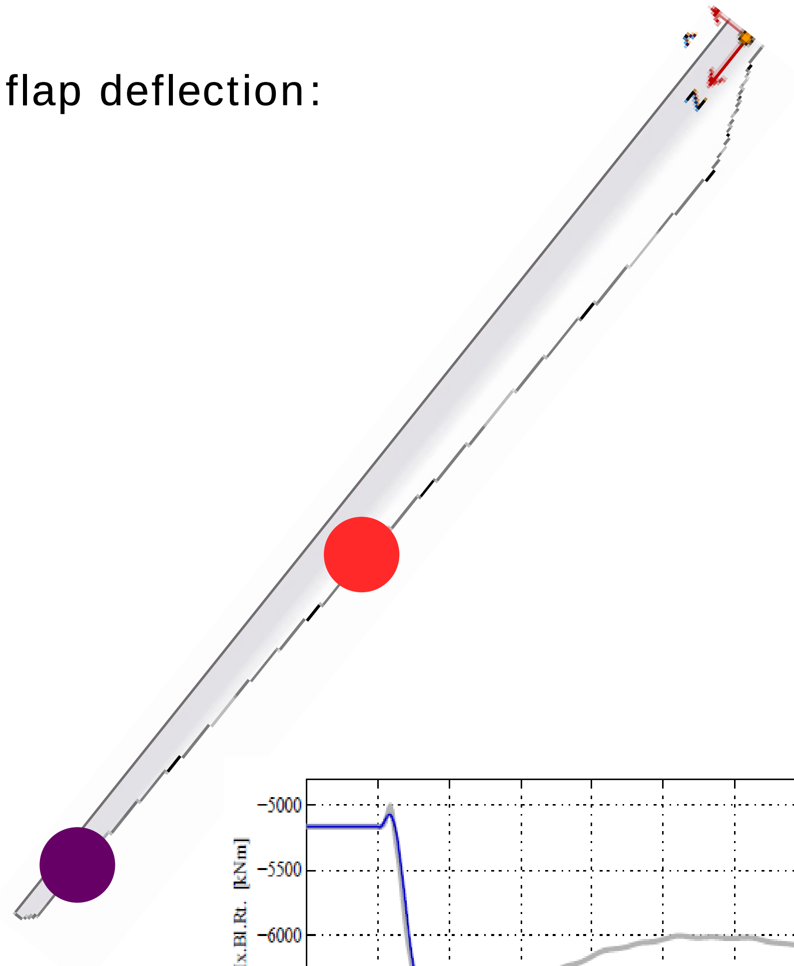


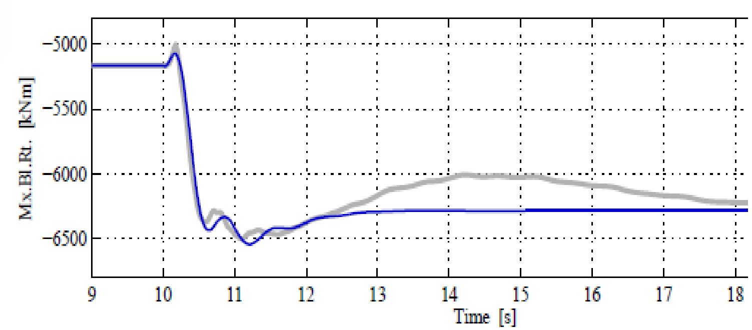
Flap and structural response

- Aerodynamic flap model implemented in HAWC2, aeroelastic model of a rotor with flaps.
- Structural Dynamics in response to flap deflection:









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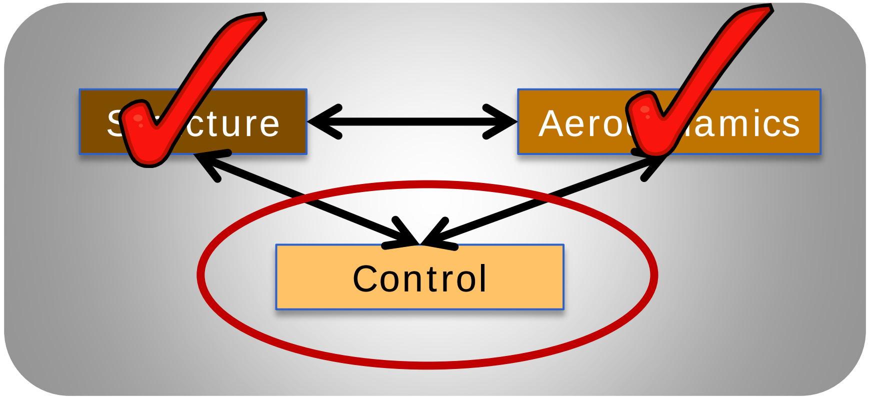
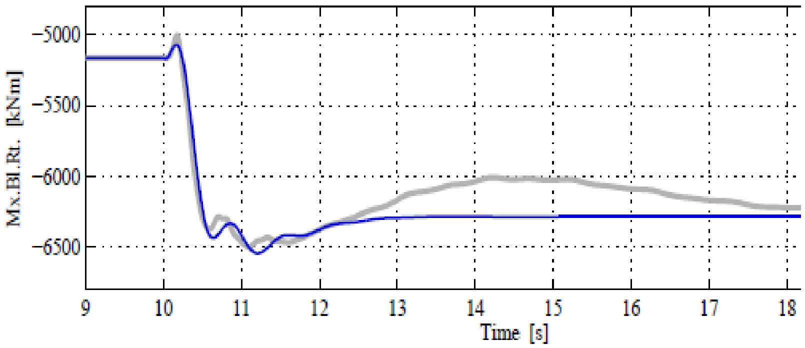
Flap and Control

- Control Algorithm (for flaps)
  - "Brain" of the system
  - Actuates the flap
  - In response to measurements
  - Pursues a control objective: load alleviation, power increase, etc.

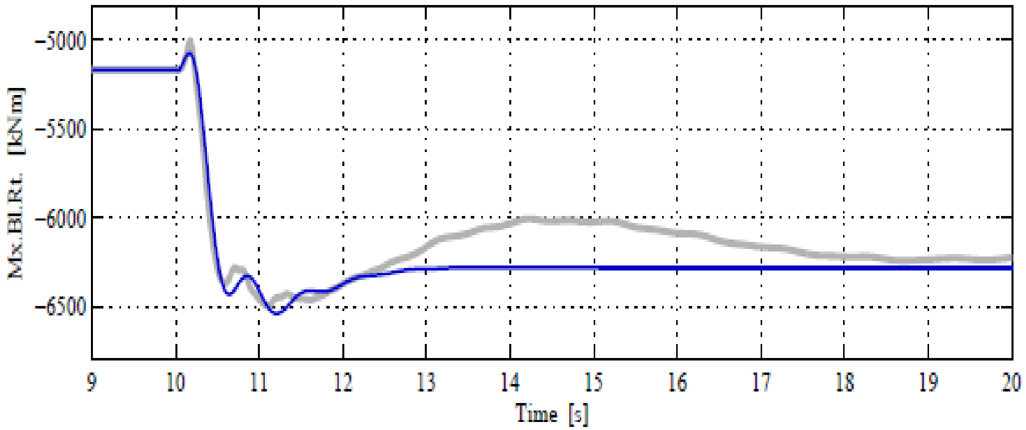


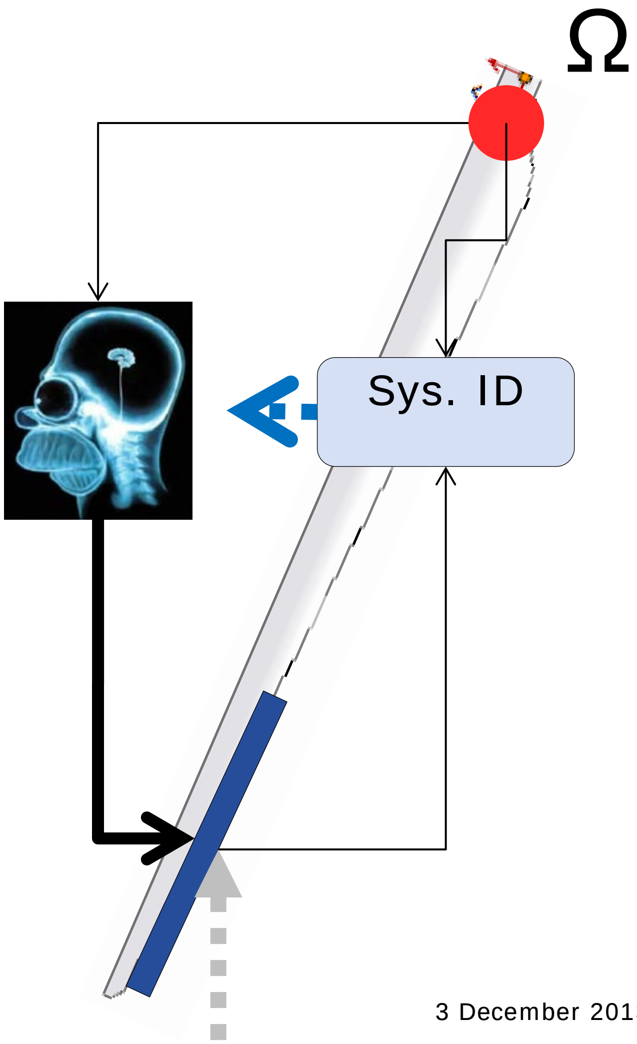
- Model based control algorithm:
  - "knows" the system -> more effective
  - Simplified (linear) model for control design:
    - **System Identification**
    - **First principle modeling**



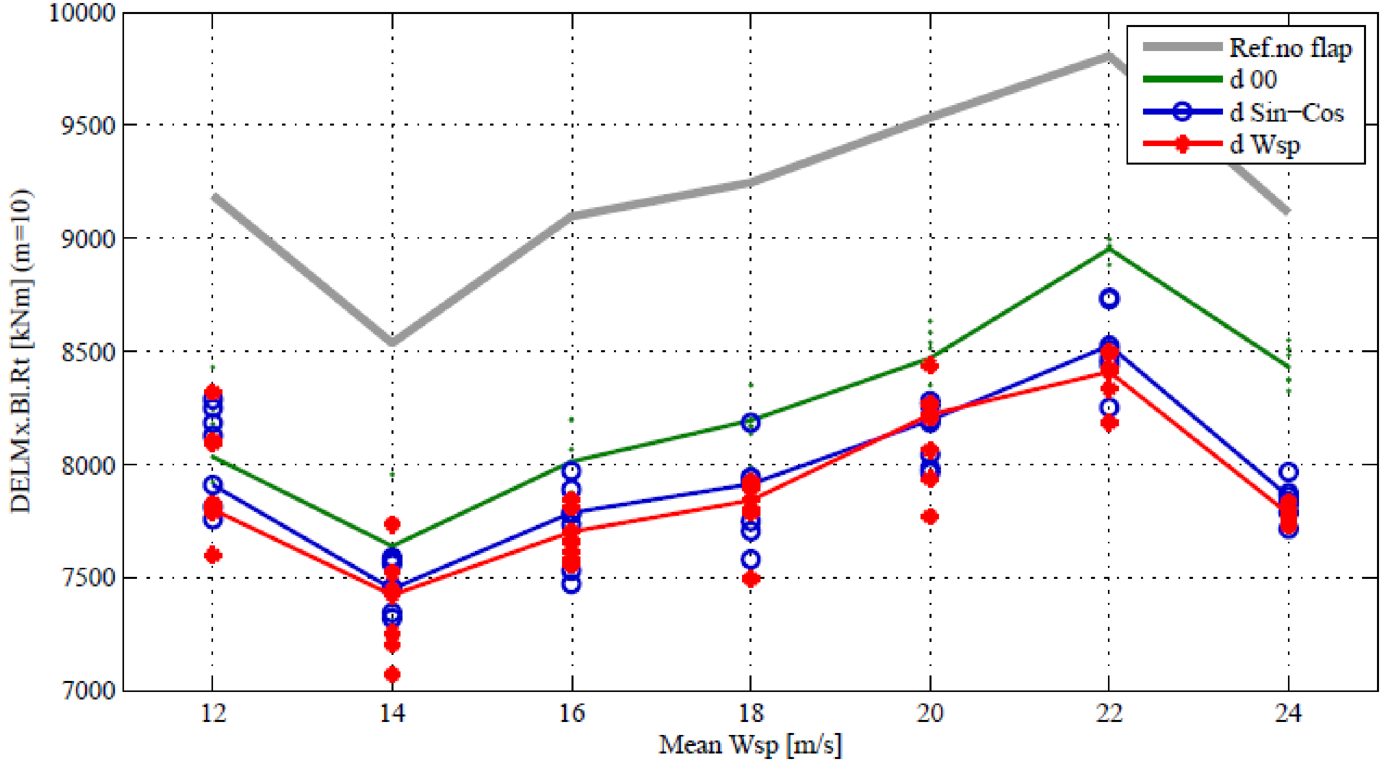
System Identification and LQ control

- Numerical approach: “black-box” relation between input and output
- Isolated blade (simplification)
- Single Input (Bl.Rt.Mx) - Single Output (Flap)
- Additional signals to account for periodic load variation





SISO-LQ: DEL alleviation



Lifetime fatigue DEL alleviation:
(IEC conditions IIb)

- d00: -10.2 %
- d Sin-Cos: -13.8 %
- d Wsp: -14.5 %

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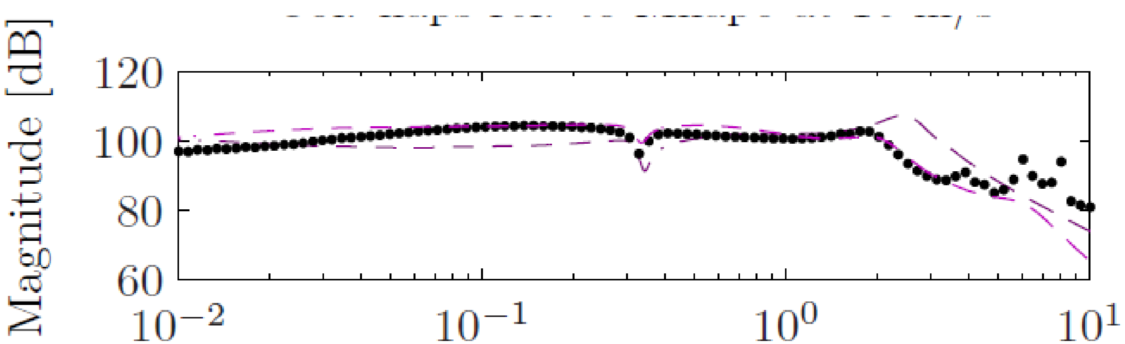
Integrated Model Based Control

Framework for ***linear control design models***:

- Tool to derive linear model describing the whole system behavior
- From First principle modeling

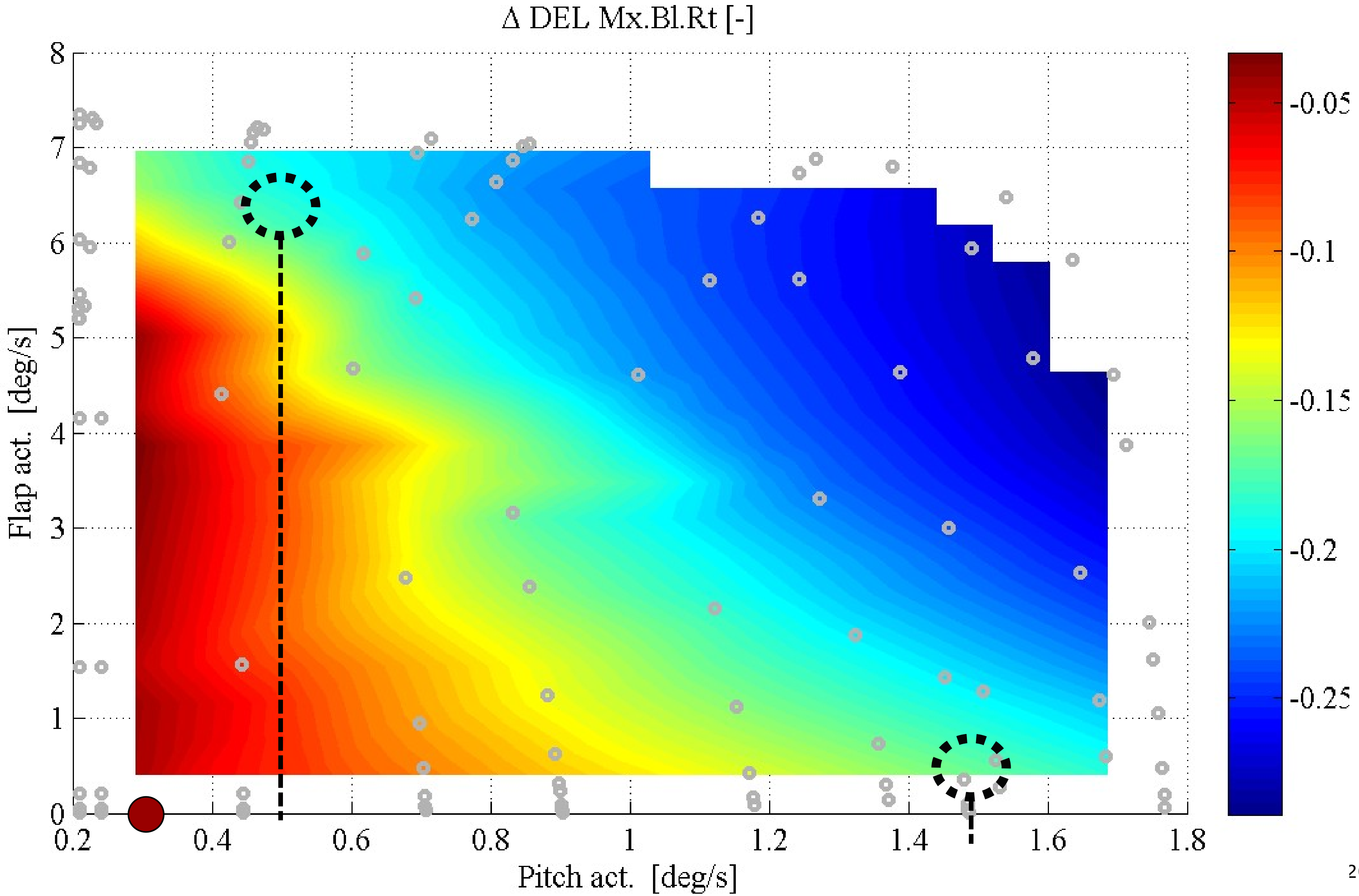
- **<u>Potential:</u>** Integrated controller design:
  - Measurements from all available sensors
  - Controls all available actuators: Individual Pitch, Flaps
  - Multiple control objectives: Power limitation, load alleviation on blade, load alleviation on other components (tower), (power enhancement?)

- Potential for load alleviation verified in a preliminary study on NREL 5MW:
  - Simplified modeling approach
  - Confirmed the potential for load alleviation
  - Allows for work load distribution between actuators



- ***Flap (fl0):*** [deg]

Integrated controller potential



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Next steps: HAWCStab2 and Flap ctrl

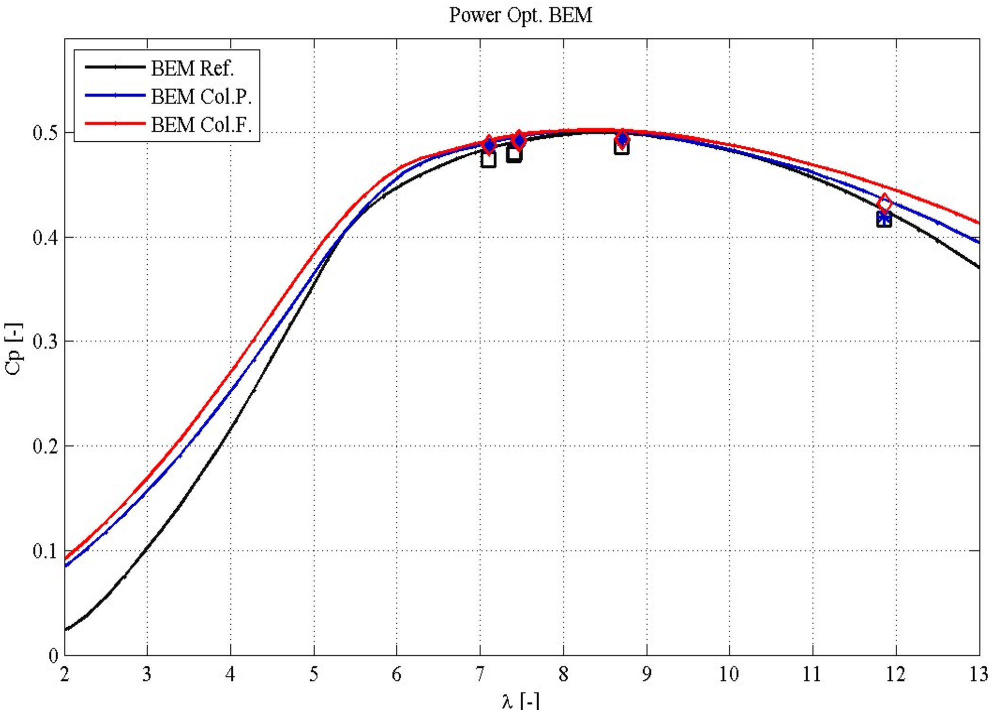
- Linear control design models framework from HAWCStab2
- Implementation of simplified linear flap aerodynamic model:
  - Quasi-Steady aerodynamic effects from flap deflection
  - Flap doesn't affect flow separation (stall).
  - Frozen wake assumption with no flap effects.
- Validation and limits of simplified flap model:
  - Comparison with time marching response (step, bode)
  - ...eventually expand the model
- Model reduction method:
  - HAWCStab2 linear model → Control design model
- Design and testing of an integrated pitch-flap controller
  - Single flap section per blade, Multiple flap sections
  - Integration with inflow measurements
  - Load alleviation on different components
  - ...

Next Steps & Topics of interest

- Integrated model based control design:
  - HAWCStab2 Framework for ***linear control design models***

- Incorporate ***inflow measurement*** in advanced controllers:
  - Control formulation (measured disturbance?)
  - Effect of bound circulation? (model for simulations)
  - Pressure difference sensors on the airfoil?

- Control below rated for optimal power tracking?



Thank you…

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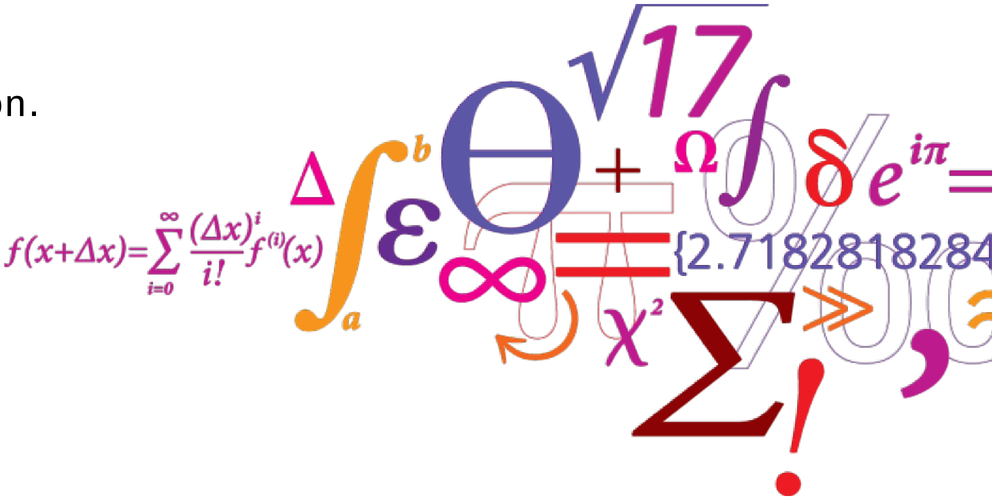

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