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# A Model Based Control methodology combining Blade Pitch and Adaptive Trailing Edge Flaps in a common framework

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# A Model Based Control methodology combining Blade Pitch and Adaptive Trailing Edge Flaps in a common framework

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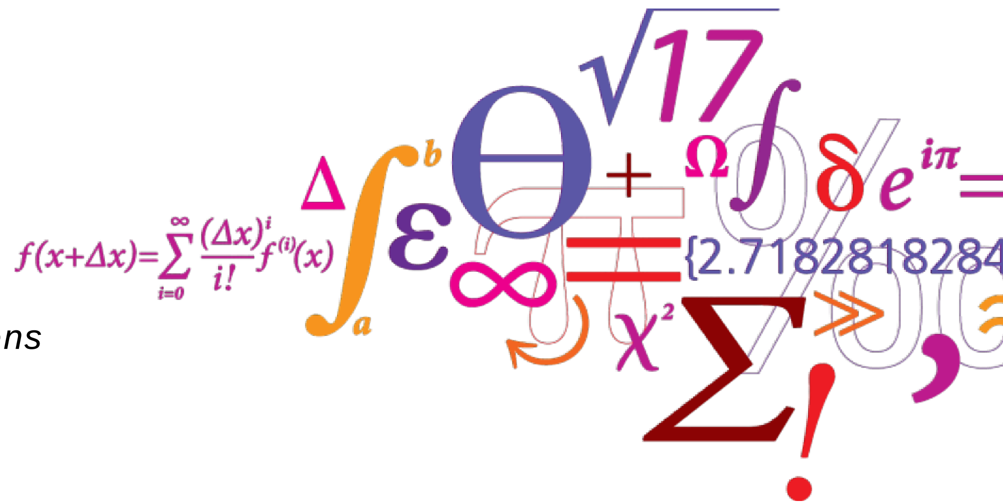


*Aeroelastics: next level challenges and solutions*

**EWEA Wind Energy Conference,**
**Vienna, 4-7 February 2013**

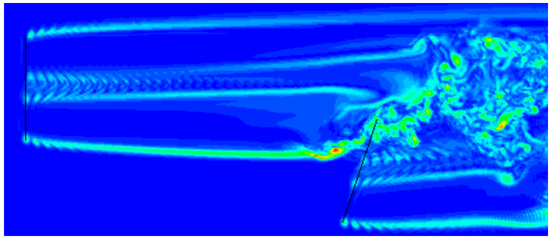
DTU Wind Energy
Department of Wind Energy

# Structure of the presentation

- Introduction
  - Why Smart Rotors? Why a combined control framework?
- Model Based Control Framework
  - Problem formulation
  - Aerodynamic and structural models
  - Verification: compare response on the structure
- Simulation Test Case
- Applications and results
  - Focus on Blade Root Loads Alleviation
- Other applications (preliminary):
  - Increase power capture?
- Conclusion and Future Work

*Introduction*

# Why Smart Rotors?



- Wind turbine operate in non uniform wind field
- What is a 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)
- Literature: simulation and a few experiments
  - Different configurations & conditions
  - Widespread figures (from 5 % to 45 %)
  - All confirm load alleviation
- Active load alleviation
  - Road to up-scaling?
  - Road to decreased Cost of Energy?
  - Next level challenge/solution?

# Why a combined control framework?

- Traditional smart rotor control approach:
  - ‘classic’ power regulation control unmodified
  - Superimposed control for load alleviation
  - Avoid interferences by frequency separation

**Aim of the investigation:**

***Outline a combined control framework, explore its possibility, and its advantages***

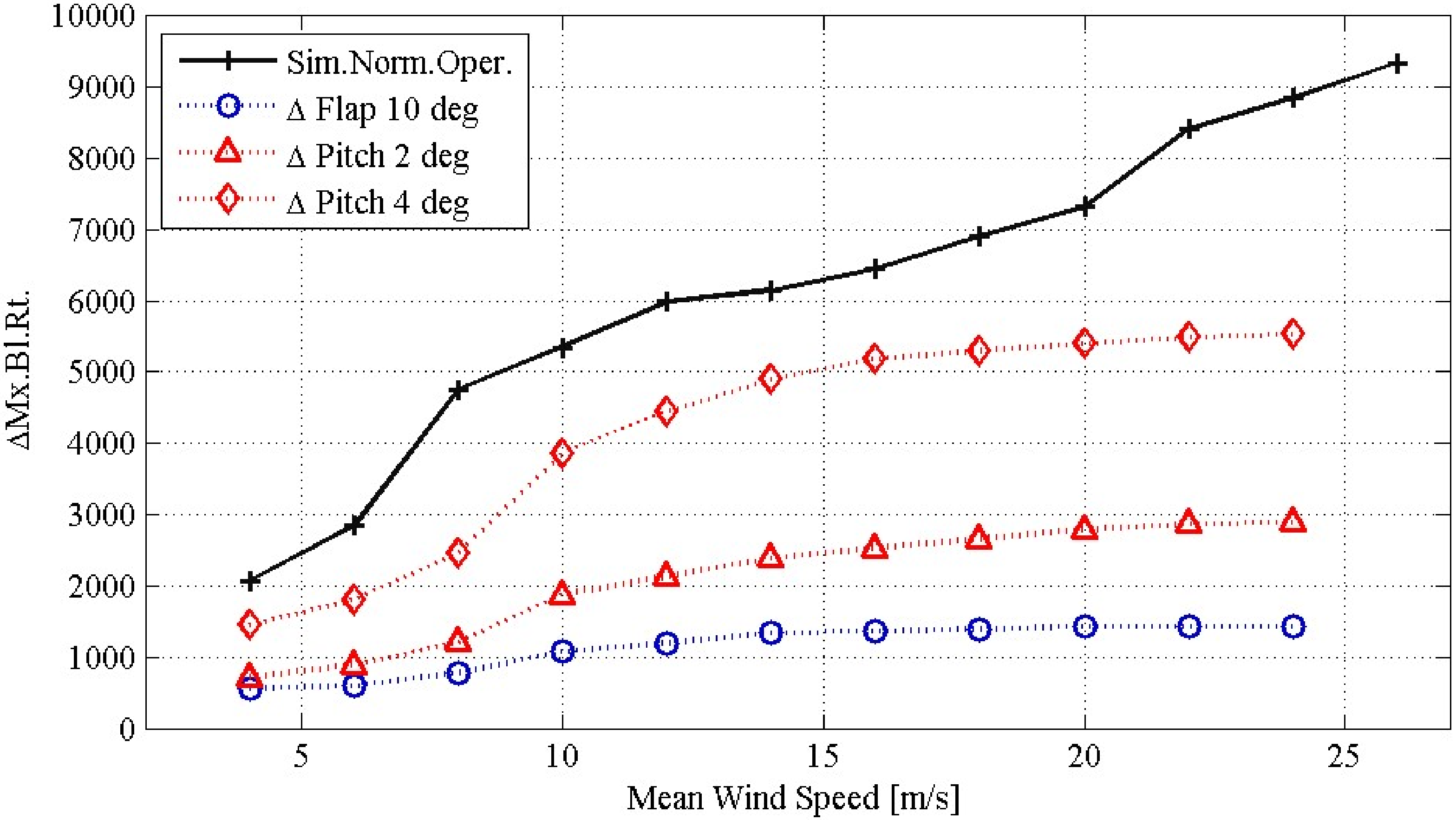
- A single control system integrates generator, pitch, and distributed device control

- <u>Main focus</u>: Application to blade load alleviation
- Other application are possible:
  - Enhanced energy capture below rated conditions (preliminary)
  - Drive train and generator load alleviation
  - ...

*Introduction*

# Why a combined control framework?

- “In union there is strength”…
- Load variation in IEC conditions compared to actuator variation



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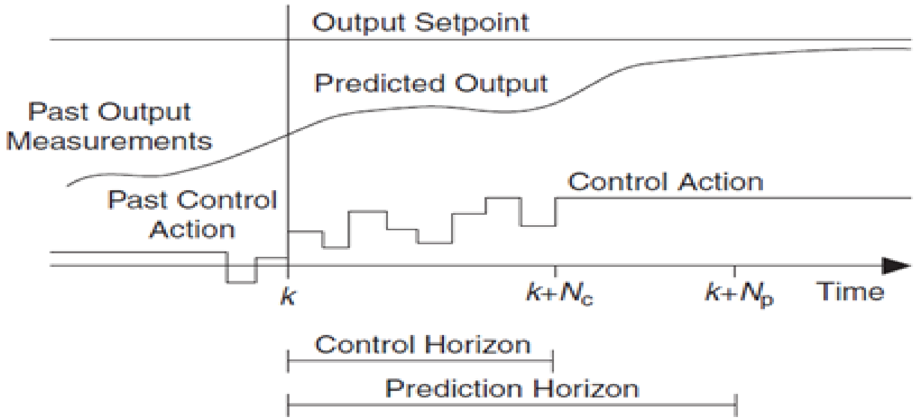
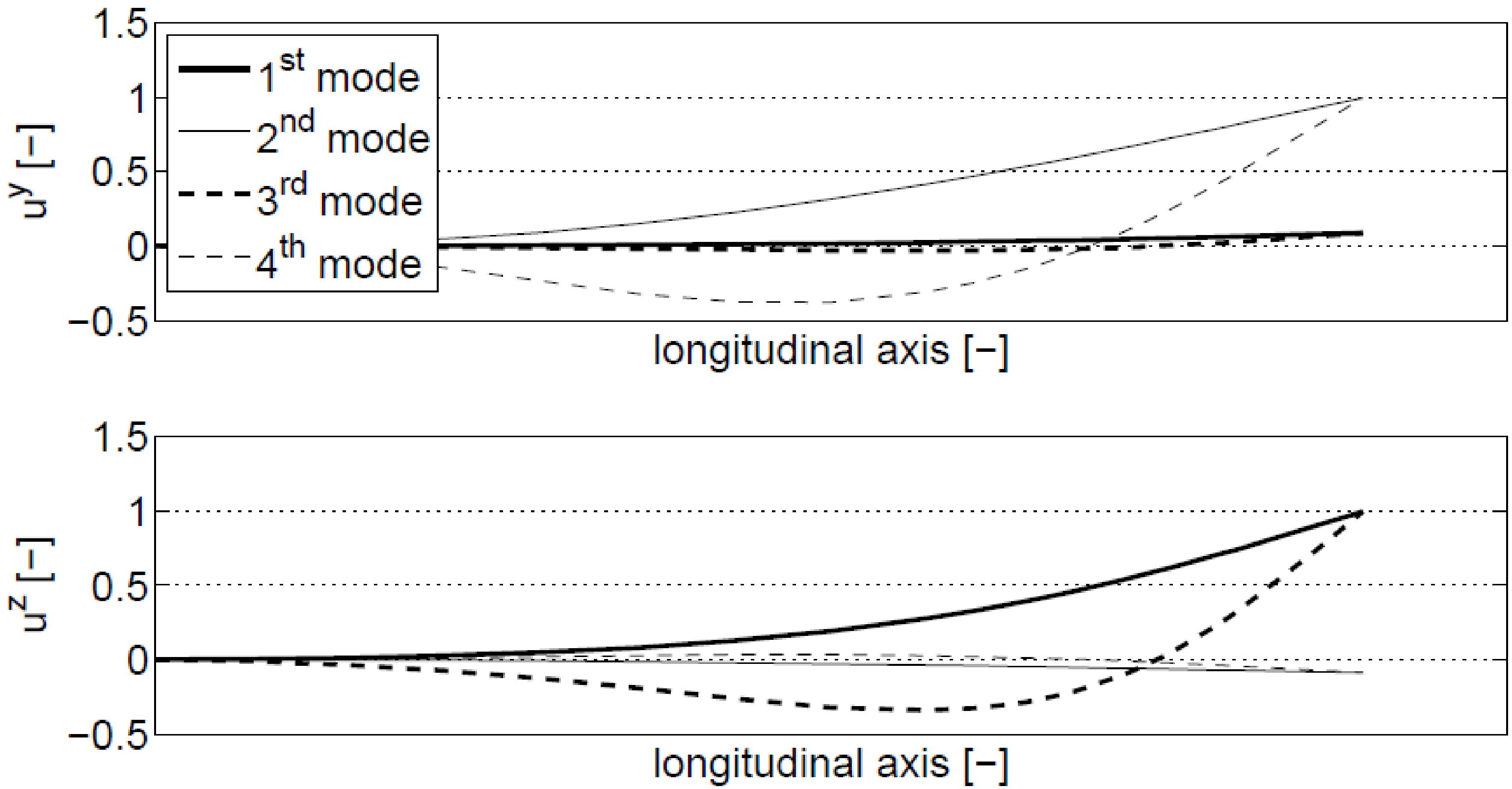
# How: Model Based Control framework

- Formulated as Model Predictive Control problem:
  - ***Optimal control***:
    Minimizes objective function: $$J = f\left(\bar{x}, \bar{u}, \bar{w}\right)$$
    s.t. a set of constraints
  - ***Model Based control:***
    Control design requires a model of the system to control
    - Linear model
    - Capture relevant dynamics ⇔ simple model
    - Aeroelastic problem: model structure & aerodynamics
    - (First principle model)



# Structural model (in MPC)

- Modal shape function approach (simplified model):
  - Superposition of deflection shape functions → Component deflection
  - Deflection shape → Eigenmodes
  - Tower 1 FA + 1SS, Drive Train 1 Torsion
  - Blade: 2 Mx + 2 My



# Aerodynamic model (in MPC)

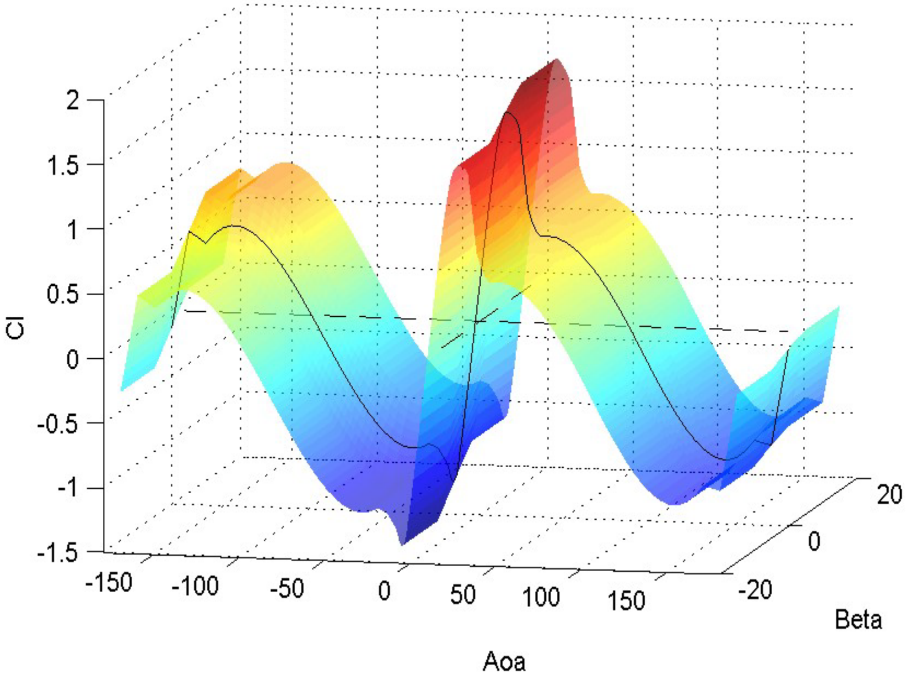
- Linearized BEM-based formulation:
  - Compute a-priori (quasi-steady lookup):
    - Integral aerodynamic forces $C_l(\alpha,\beta)$
    - Induction velocities $a(\theta,\lambda,\beta)$
    - Linearized dependence on flap
  - Dynamic inflow as 1st order filter

*Lift and drag*

- $L = \frac{1}{2}\rho W^2 C_L(\alpha,\beta) \approx \frac{1}{2}\rho W^2 C_L(\alpha,0) + \frac{1}{2}\rho W^2 \frac{\partial C_L(\alpha,0)}{\partial \beta}\beta$
- $D = \frac{1}{2}\rho W^2 C_D(\alpha,\beta) \approx \frac{1}{2}\rho W^2 C_D(\alpha,0) + \frac{1}{2}\rho W^2 \frac{\partial C_D(\alpha,0)}{\partial \beta}\beta$

*Induction factors normal and tangential to the rotor plane*

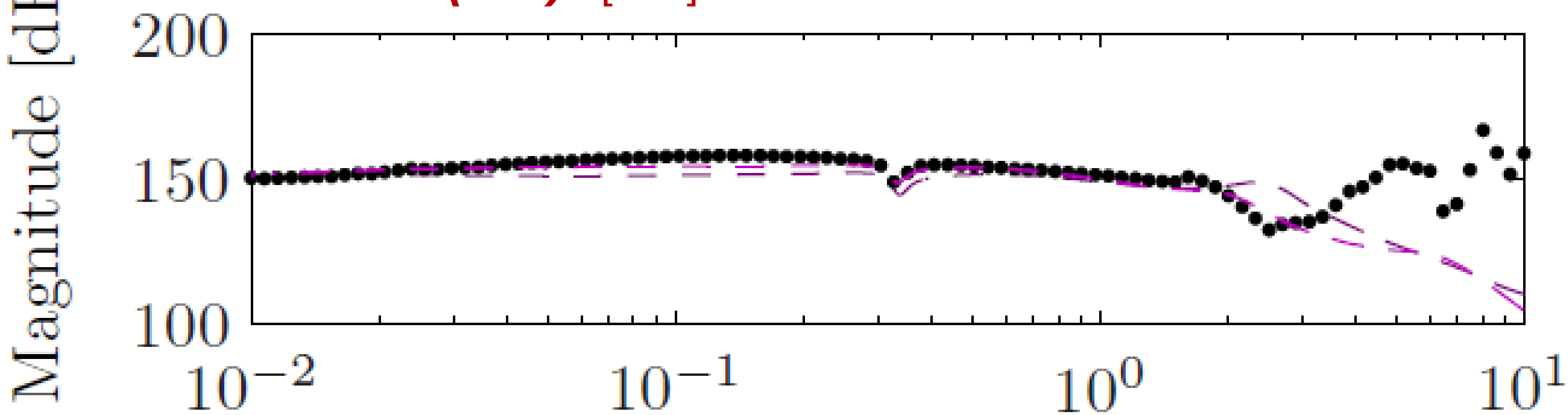
- $a(\theta,\lambda,\beta) \approx a(\theta,\lambda,0) + \frac{\partial a(\theta,\lambda,0)}{\partial \beta}\beta$
- $a'(\theta,\lambda,\beta) \approx a'(\theta,\lambda,0) + \frac{\partial a\prime(\theta,\lambda,0)}{\partial \beta}\beta$



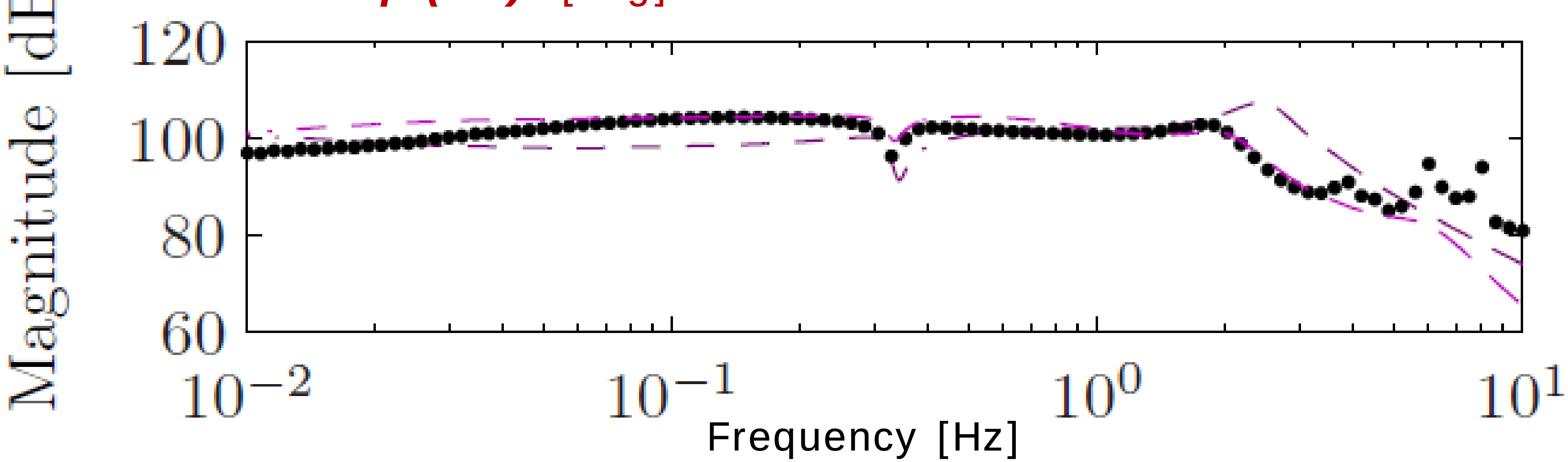
# Verification: Response on blade root

Purple: 2+2 blade modes
Blue: 3+3 blade modes

- ***Pitch (th0):*** [rad]




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



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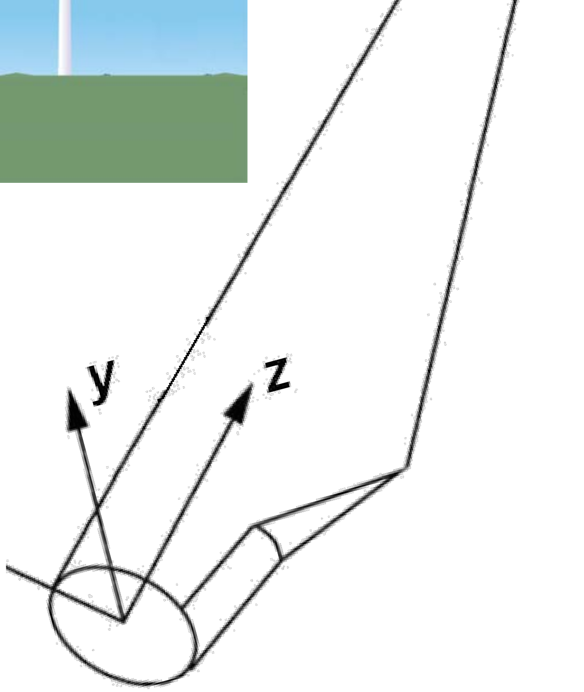
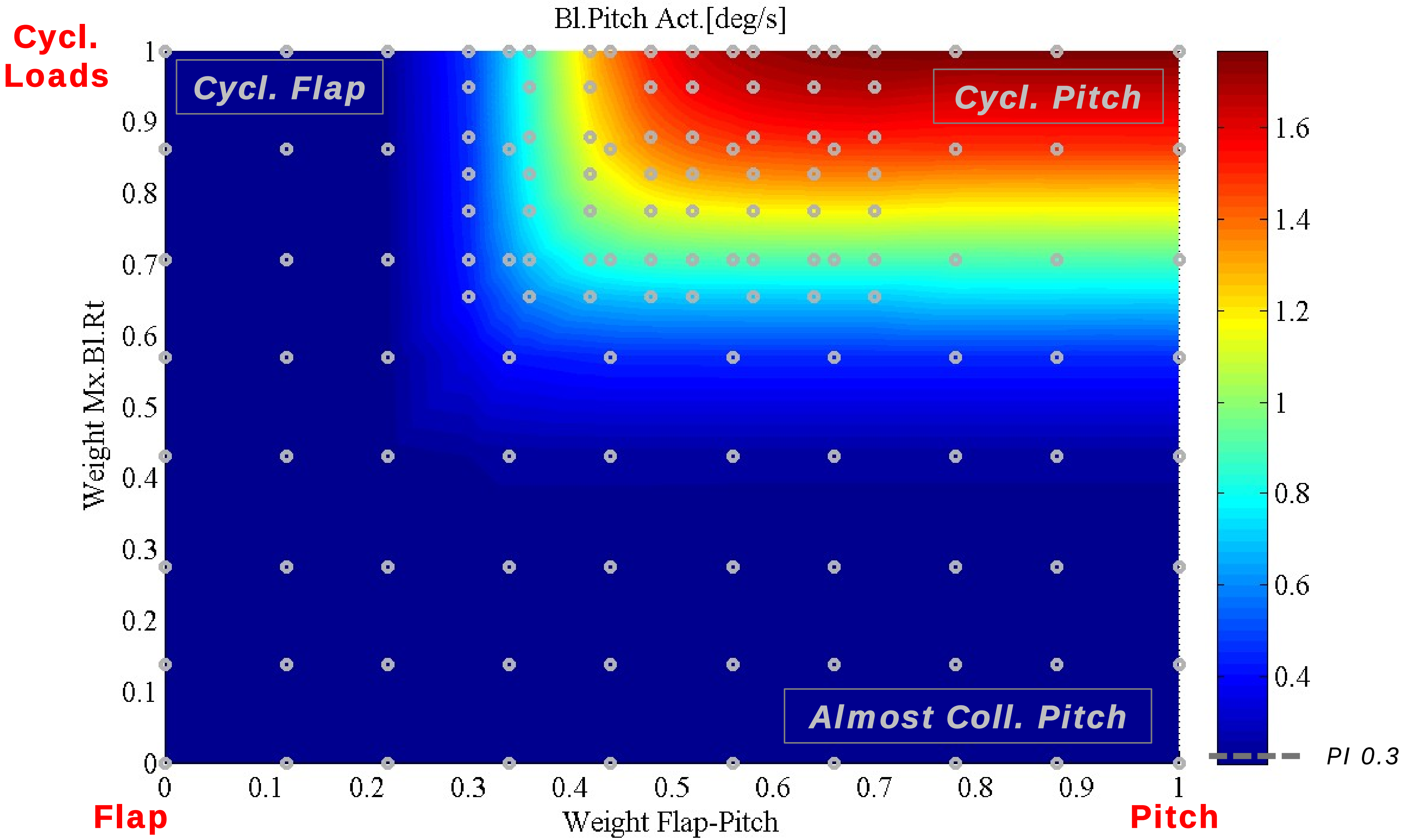
# Simulation Test Case

- 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

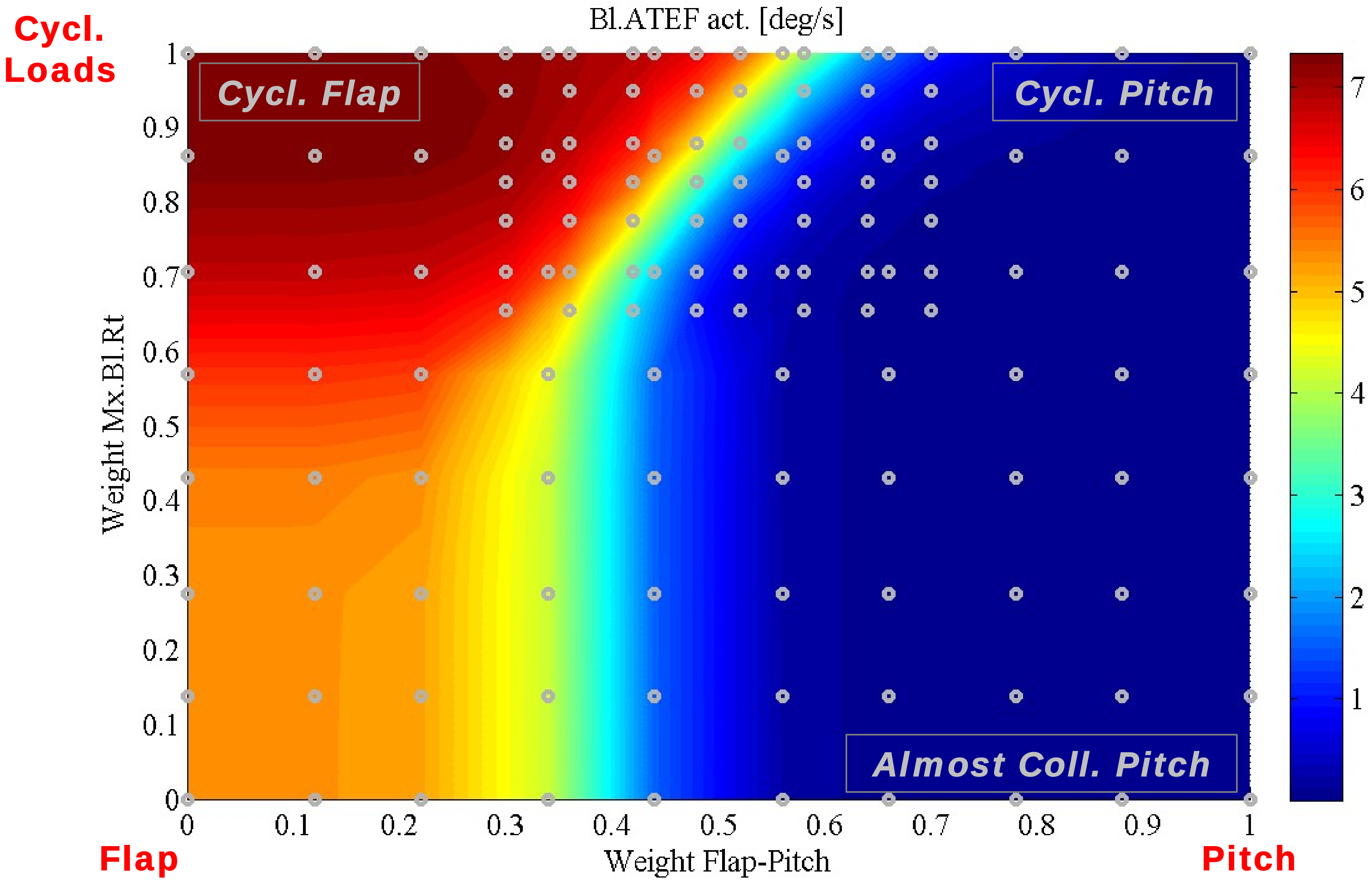



| *Reference Wind Turbine* | | *Flap Setup* | |
|---|---|---|---|
| Rat. Power | 5 MW | Chordwise ext. | 10% |
| Num.Blades | 3 | Deflect.limits | $\pm 10^\circ$ |
| Rotor Diam. | 126 m | Max. $\Delta$Cl | $-0.45 \sim +0.41$ |
| Blade length | 61.5 m | Spanwise length | 12.3 m (20% blade length) |
|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

# Blade Root Loads Alleviation

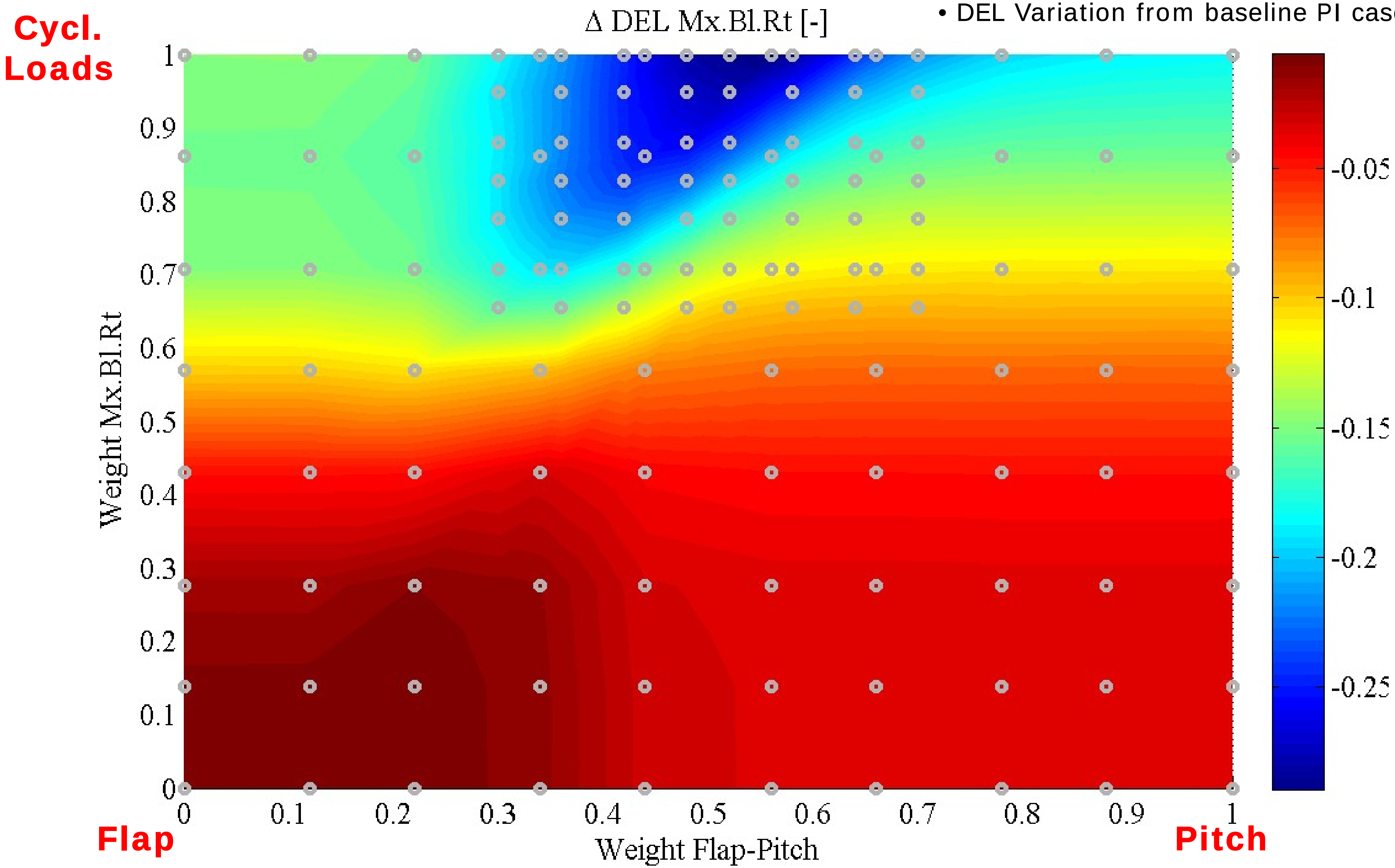


# Blade Root Loads Alleviation



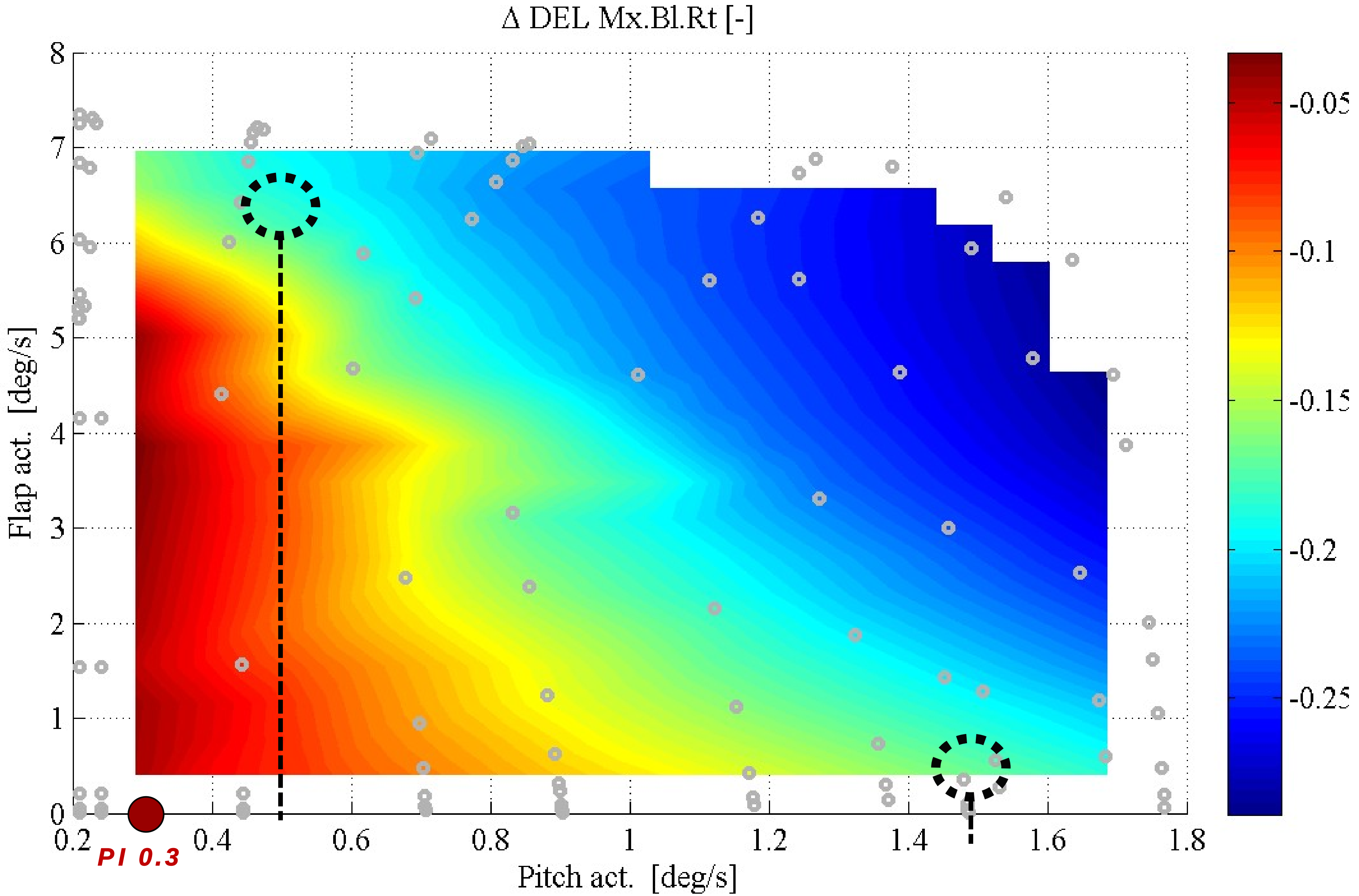
# Blade Root Loads Alleviation

• DEL Variation from baseline PI case



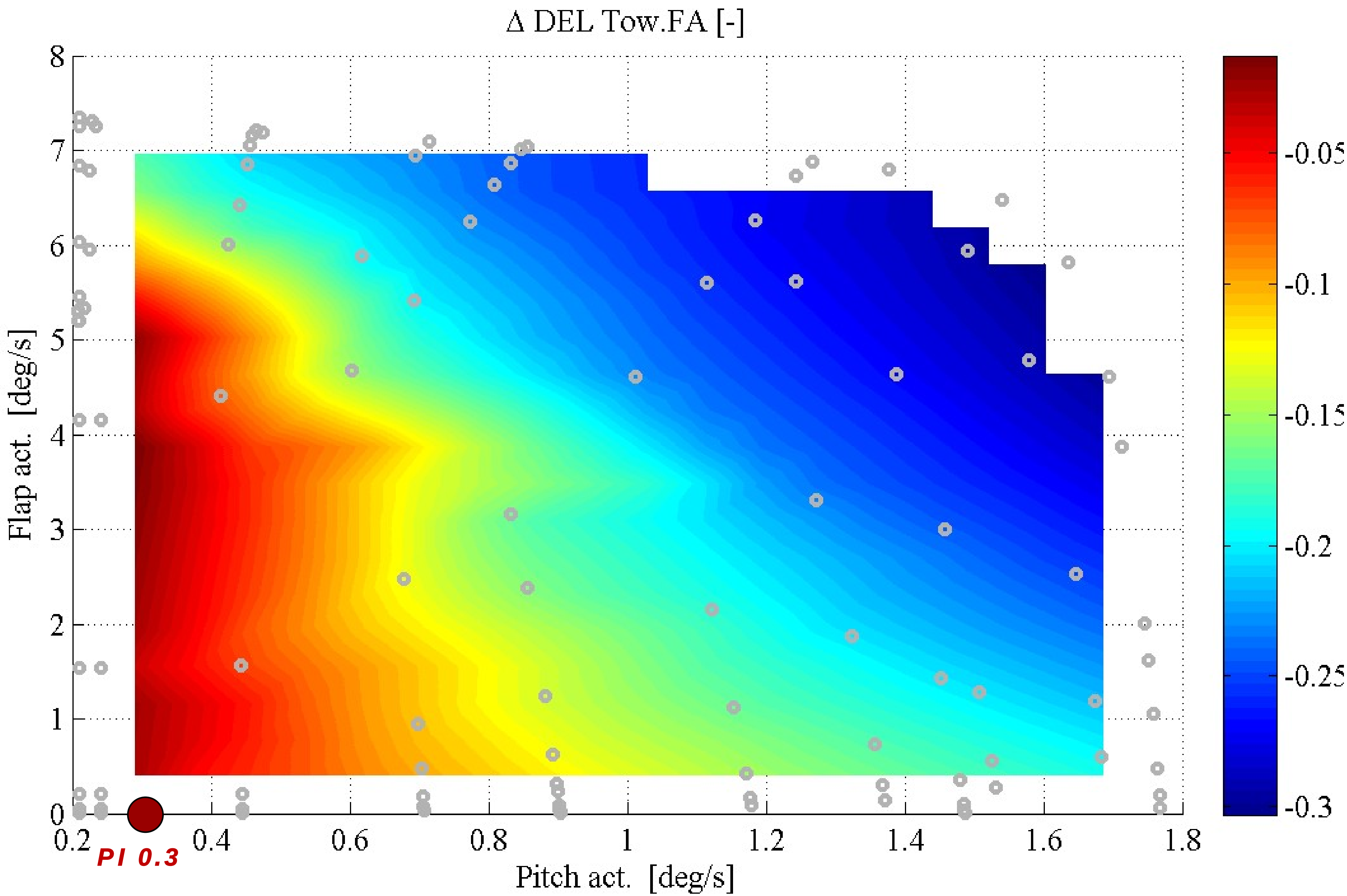
*Application and results*

# Blade Root Loads: “cost-benefit”



*Application and results*

# Effects on tower



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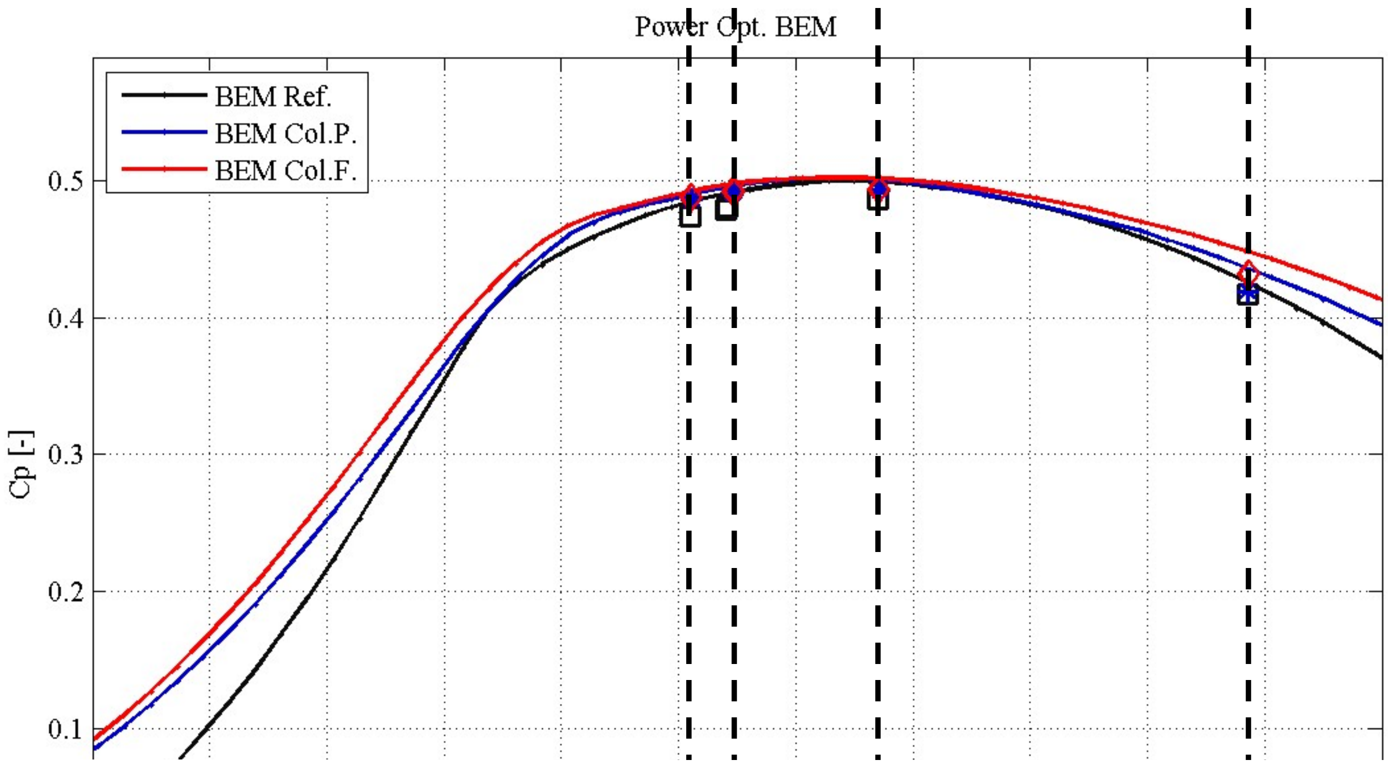
# Increase power capture below rated

- Below rated: load alleviation not convenient
- Use Adaptive Trailing Edge Flaps to increase power capture?
- Simple BEM analysis (ideal rigid rotor):




- No gain at optimal Cp-Lambda

Quick-check with std. controller:

- Sub-optimal operational pts
- Tower frq.

- Variations around an operational point

IEC class II:

| | | Ref. | Col.P. | Col.F. | CPC | CPF |
|---|---|---|---|---|---|---|
| AEP | [GWh] | 19.77 | 19.98 | 20.00 | 20.01 | 20.03 |
| Δ AEP | [pct] | – | +1.08 | +1.15 | +1.24 | +1.34 |

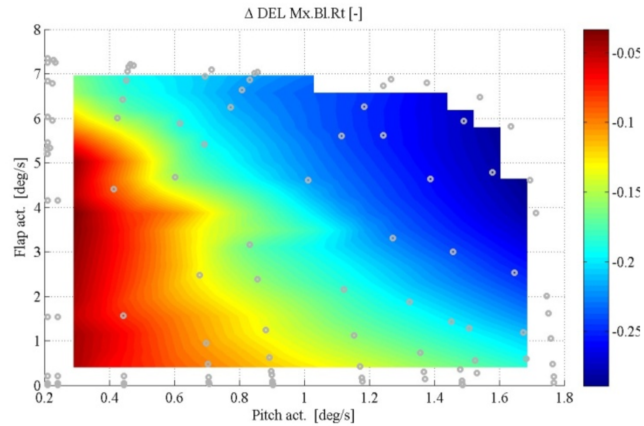
# Conclusion

- "In union there is strength" applies to Smart Rotors
- MPC framework:

  → Positive collaboration of pitch and flap actuators

- Advantages of combined actions: load alleviation
  - Increase alleviation potential: [15 %; 18 %] ➔ 30%
  - Spare pitch, take over with flap (or viceversa): 16 % + fl → 1/3
  - Alleviation on other parts of the structure

- Possibly enable other applications (future work)
  - Distributed actuators and sensors
  - Enhance power capture
  - Reducing loads in DT and speed variation
  - ...



# Thank you…

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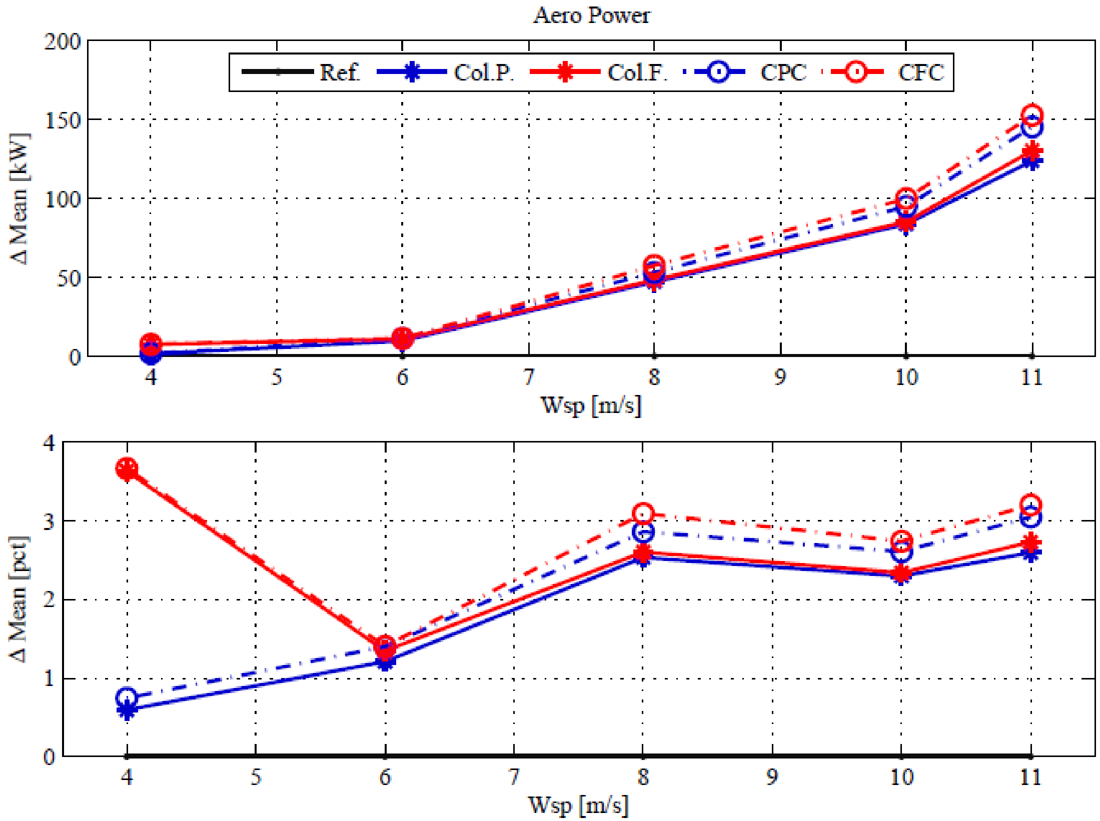
# Bonus slides…

# Increase power: cyclic

- Simplified analysis: optimize power from cyclic flow variations
- Stiff rotor in deterministic (no turbulence) wind field

Results need to be confirmed in “realistic” conditions!




Cyclic trajectories for power increase load variation

IEC class II:

| | | Ref. | Col.P. | Col.F. | CPC | CPF |
|---|---|---|---|---|---|---|
| AEP | [GWh] | 19.77 | 19.98 | 20.00 | 20.01 | 20.03 |
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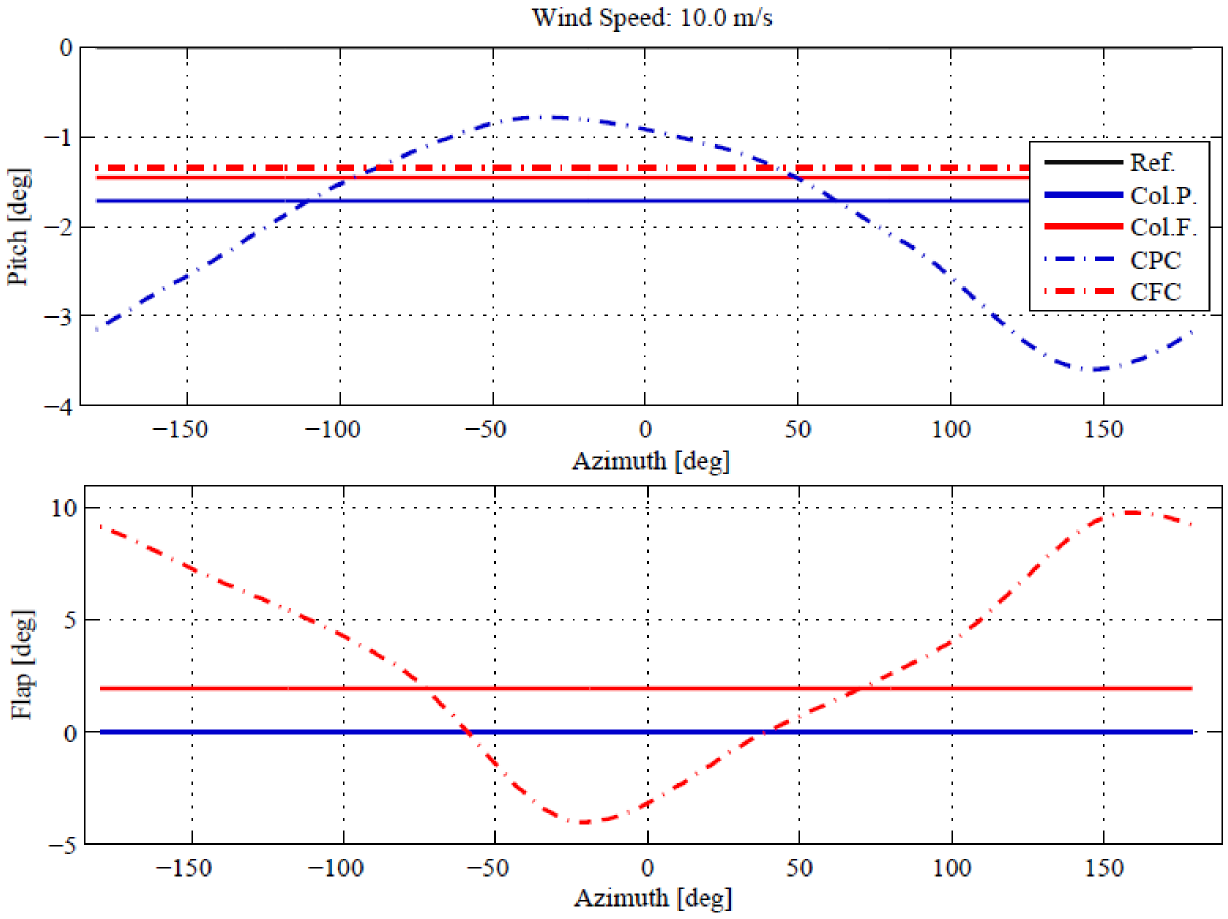
# Increase power capture: cyclic trajectories

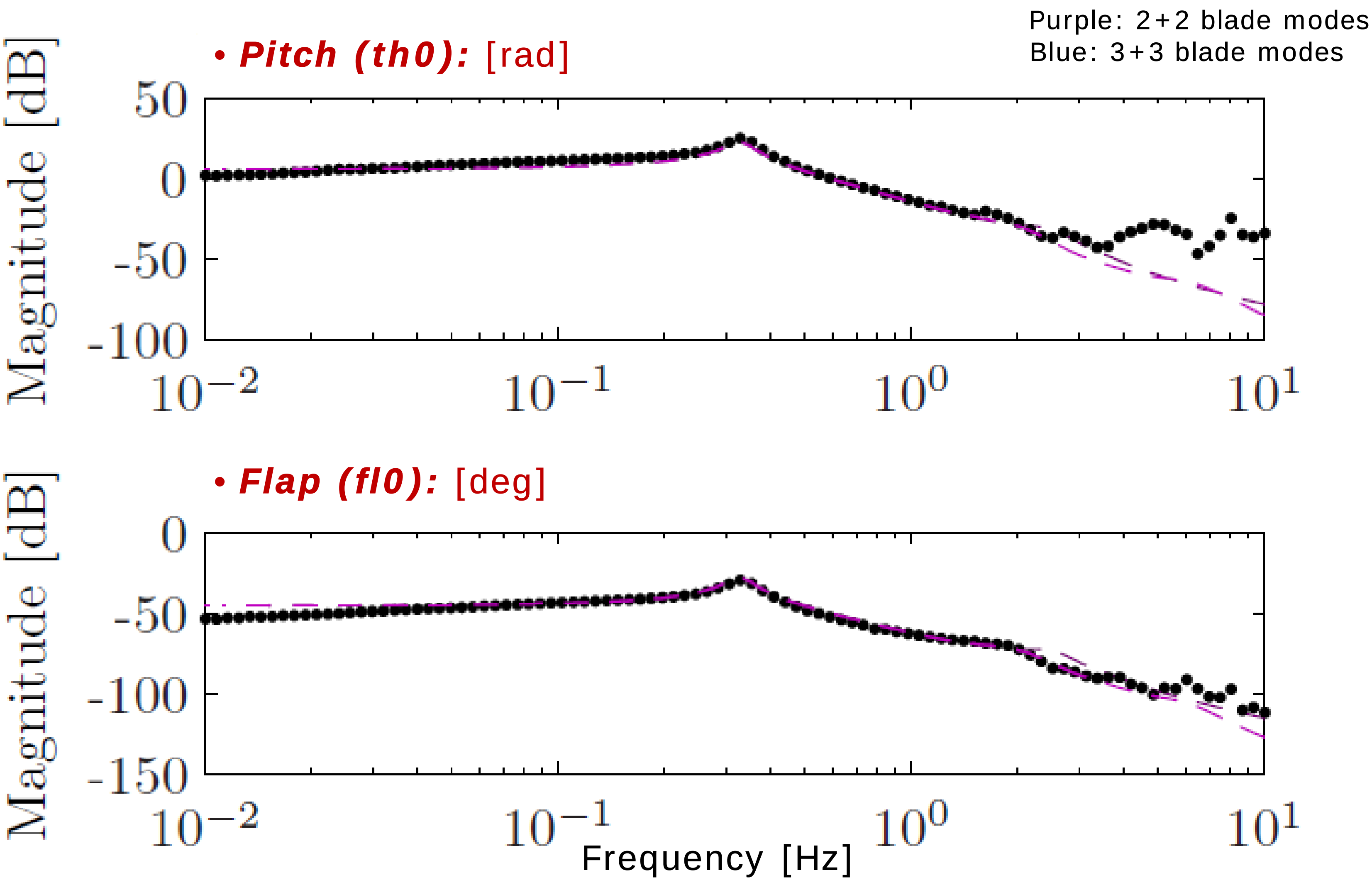
- Cyclic control action for increased power capture increases blade load variation




- As lambda increases, better Cp is in the direction of lower Ct

→ Amplifies load variation

# Verification: Response on tower bottom



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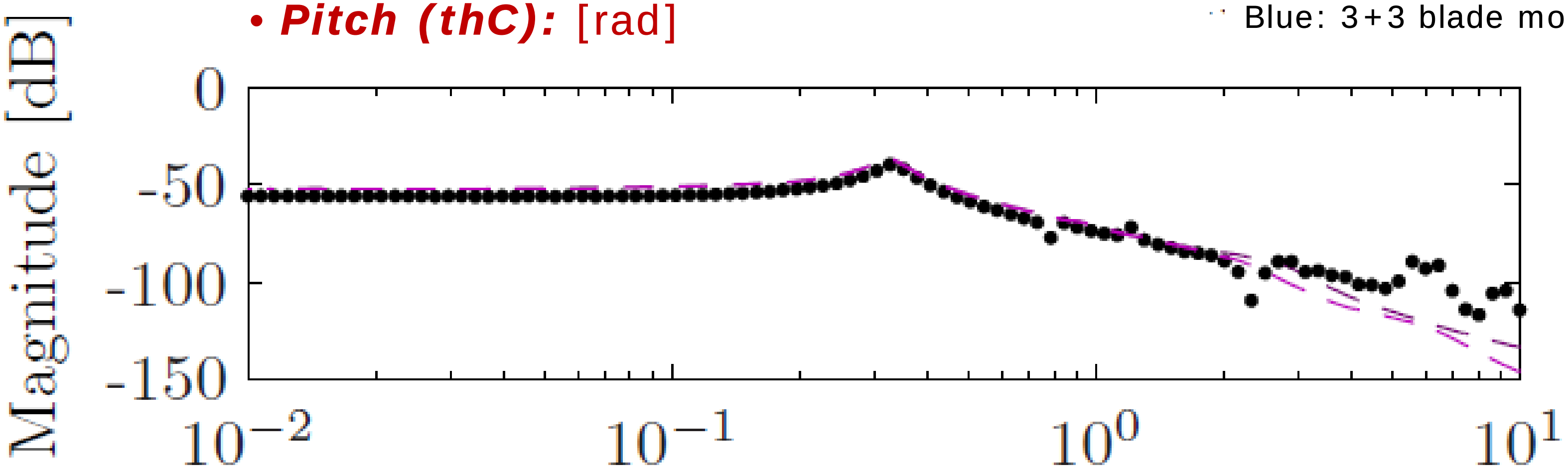
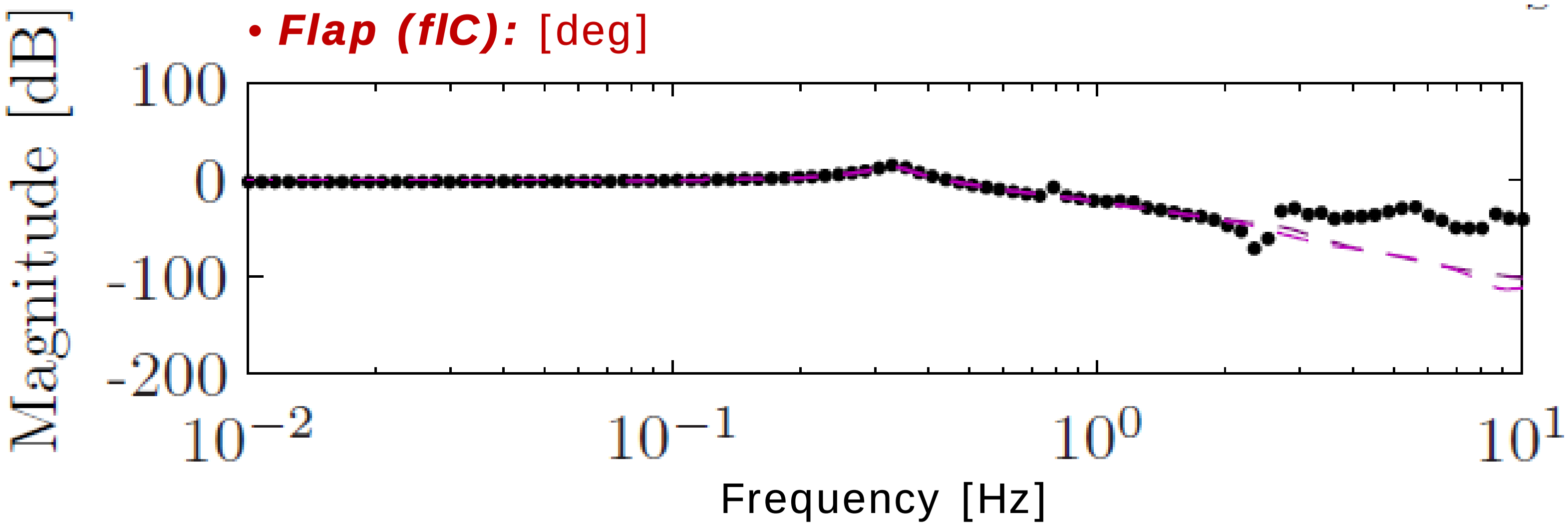
- ***Pitch (thC):*** [rad]

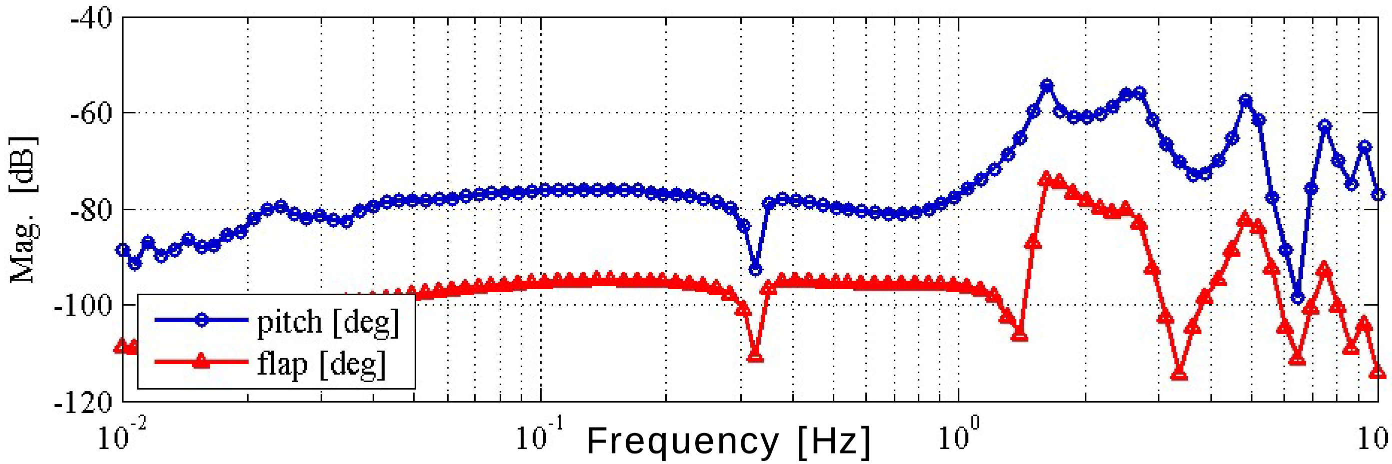



- ***Flap (flC):*** [deg]

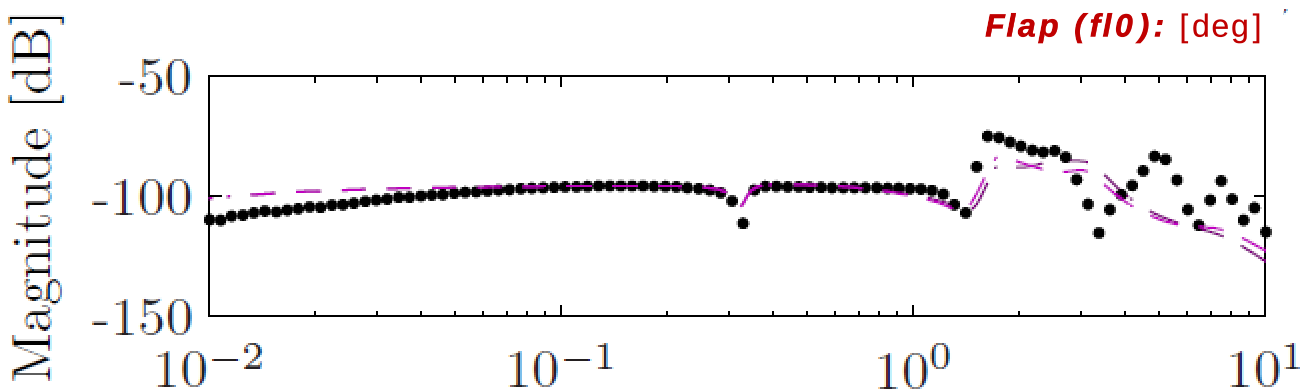


# Drive train load alleviation (preliminary)

- Collective flap and pitch both have an effect on aero torque and shaft torsion




- Also modeled in the MPC framework:




- Use flap to help in reduction of torque fluctuations → reduce DT requirements