Influence of actuator dynamics on the load reduction potential of wind turbines with Distributed Controllable Trailing Edge Flaps (CRTEF)

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OUTLINE

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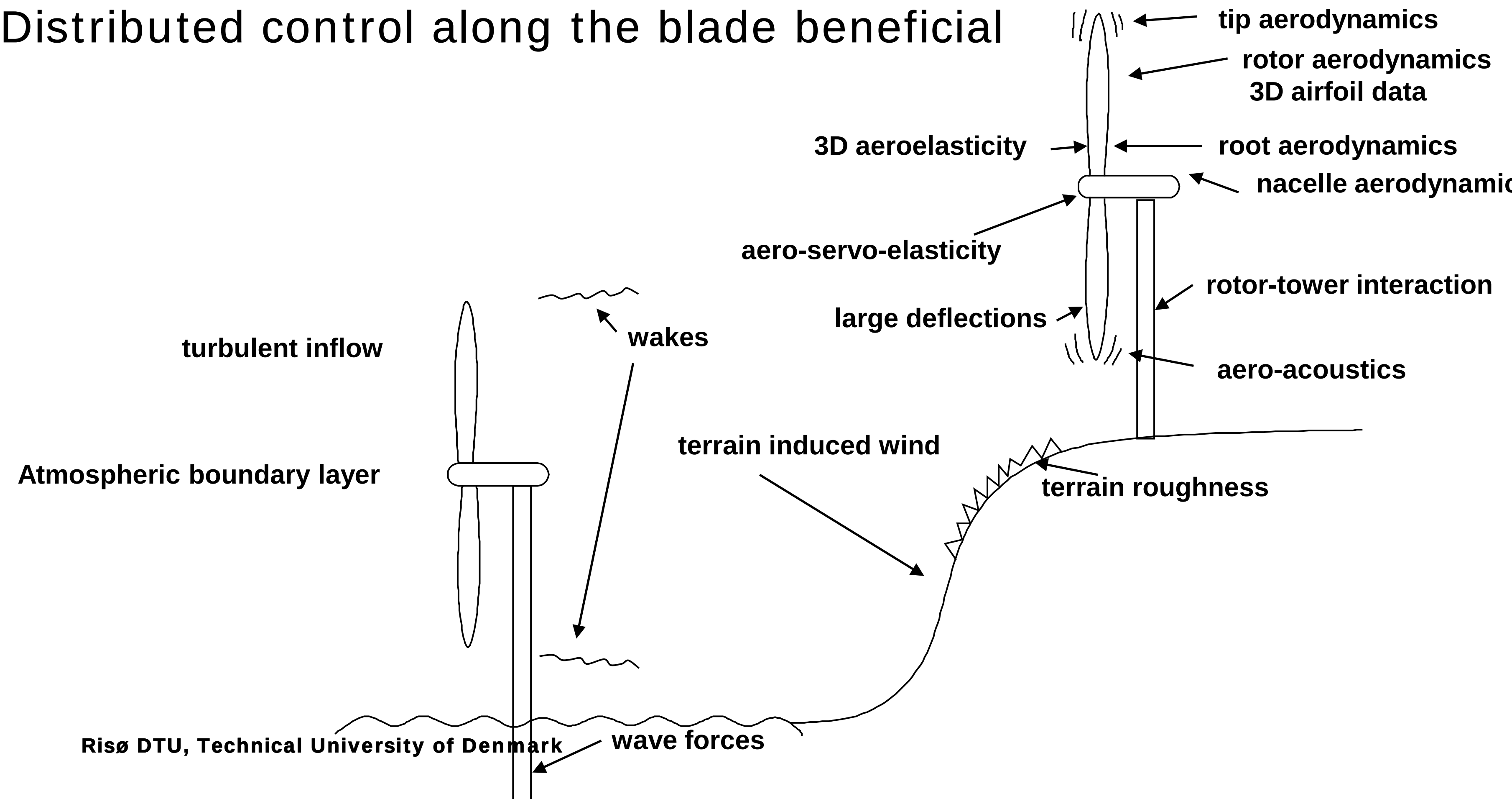
- Aeroservoelastic model
- sysID – Controller design
- Results
- Conclusions

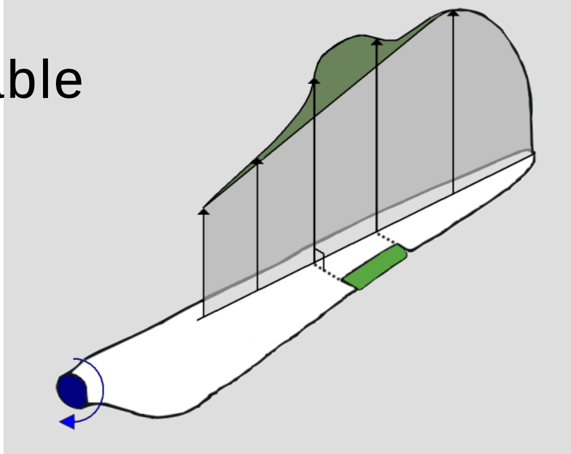
Introduction

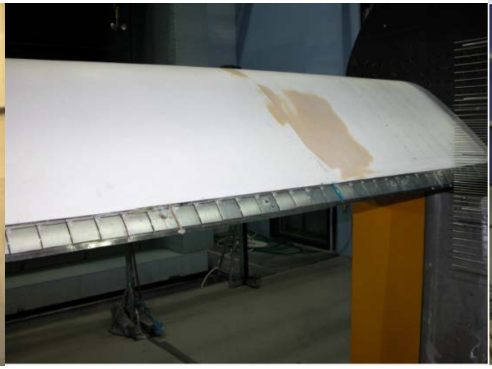
- Modern wind turbine rotors more than 120m in diameter
- Non-uniform rotor loading increase with rotor size
- Fatigue / ultimate loads as design drivers
- Fast and reliable dynamic load reduction necessary
- Distributed control along the blade beneficial

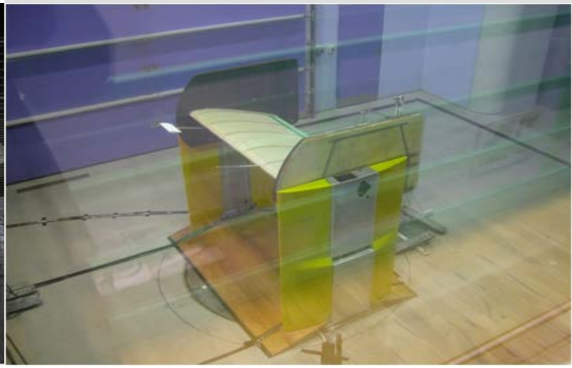


Introduction

- Actively controlled local aerodynamic surfaces can provide considerable load alleviation
- Numerical predictions with aeroservoelastic tools including active flaps models
- 2D blade section / non-rotating blade / small scale rotor wind tunnel experiments have verified concepts
- Variable geometry trailing edge concept favourable
- Actuator concepts so far invloved Piezoelectric benders,SMA deformed structure
- Reliability of actuator concepts in real scale is questionable







The CRTEF concept

Main objective:

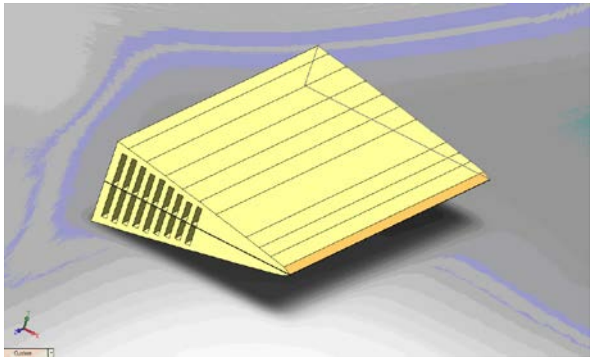
- Develop a robust, simple, trailing edge flap system for active load control purposes

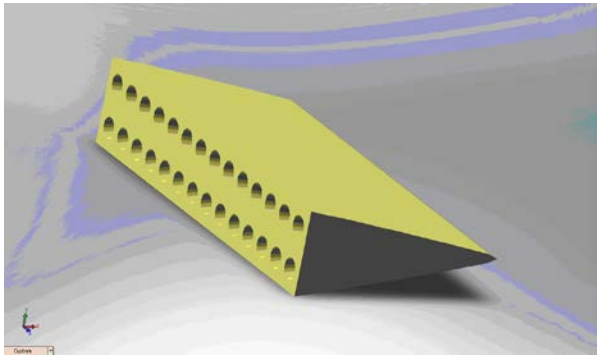
Preliminary design in GAP project:

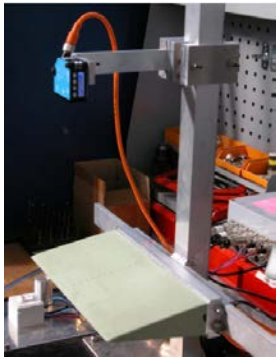
- A flap in an elastic material (e.g. rubber) with a number of reinforced voids that can be pressurized providing a deflection – Testing of first prototypes

Focus of current INDUFLAP project:

- Industrial adaptation of the flap prototypes – system optimization

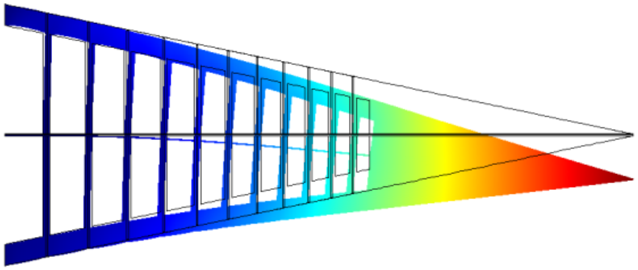


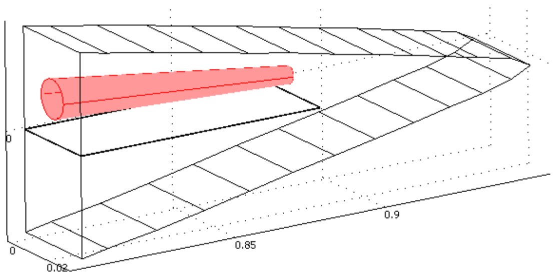


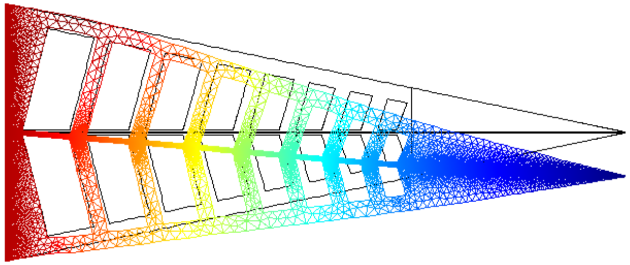


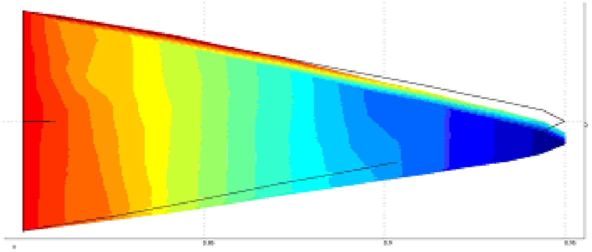
The CRTEF concept

- FE simulations
- Span-wise voids / Chord-wise voids concepts
- Various void shapes
- Internal reinforcement
- On average ±5º flap angles could be achieved with 1-2 bar differential pressure



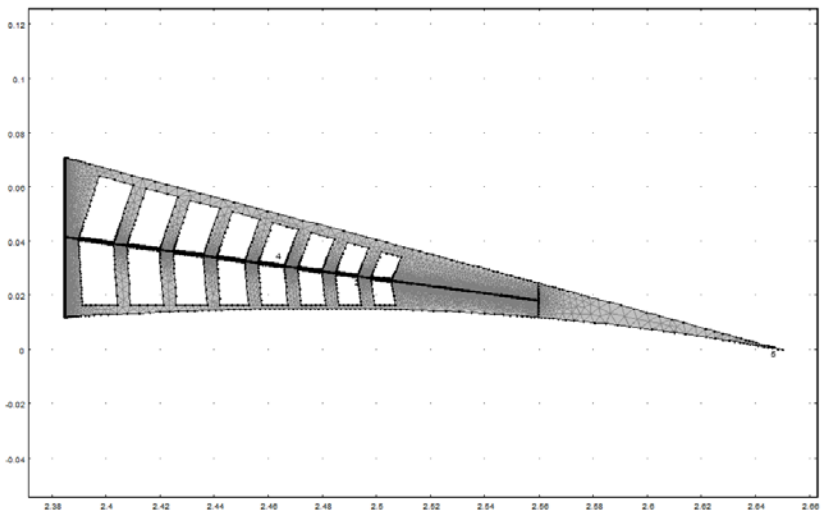


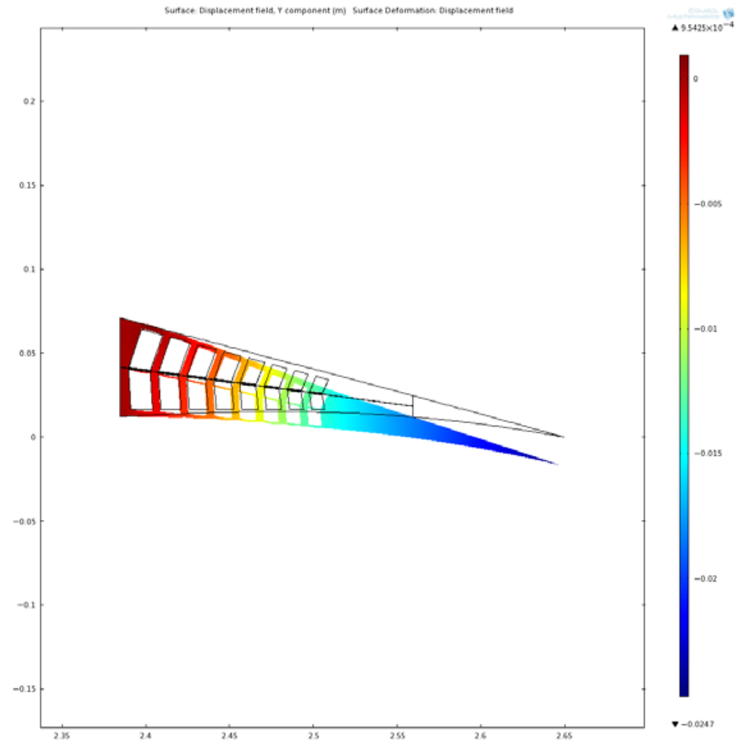




The CRTEF concept

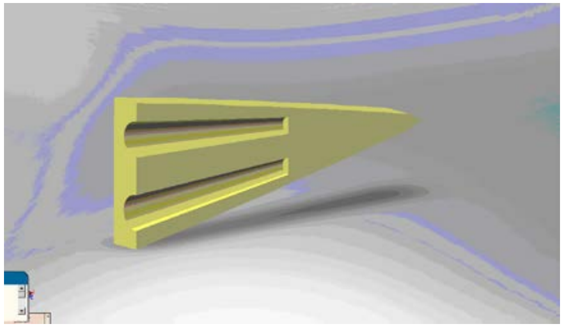
- FE optimization
- Maximize trailing edge deflection
- Minimize local surface deformation
- Minimize deflection under aerodynamic loads
- Vary size of voids, reinforcement layer, stiff trailing edge
- ±5° flap angles with stiffer design

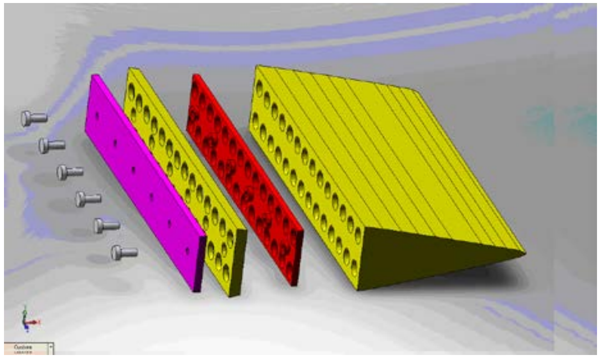


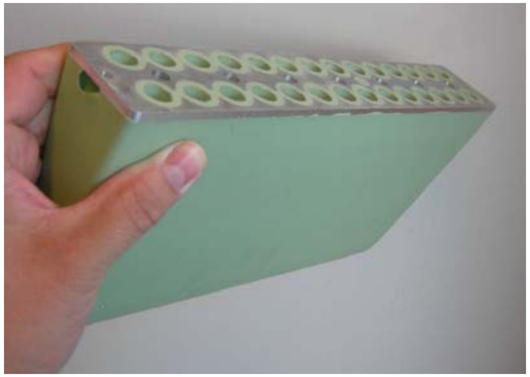


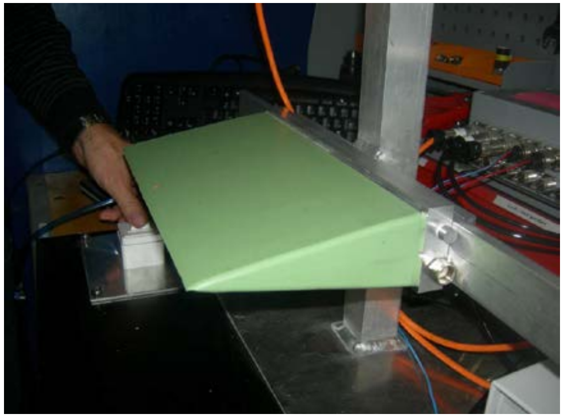
The CRTEF concept

- CRTEF prototypes with chord-wise voids
- ~5° flap deflection at P=8bar
- Silicon rubber with reinforced cylindrical voids







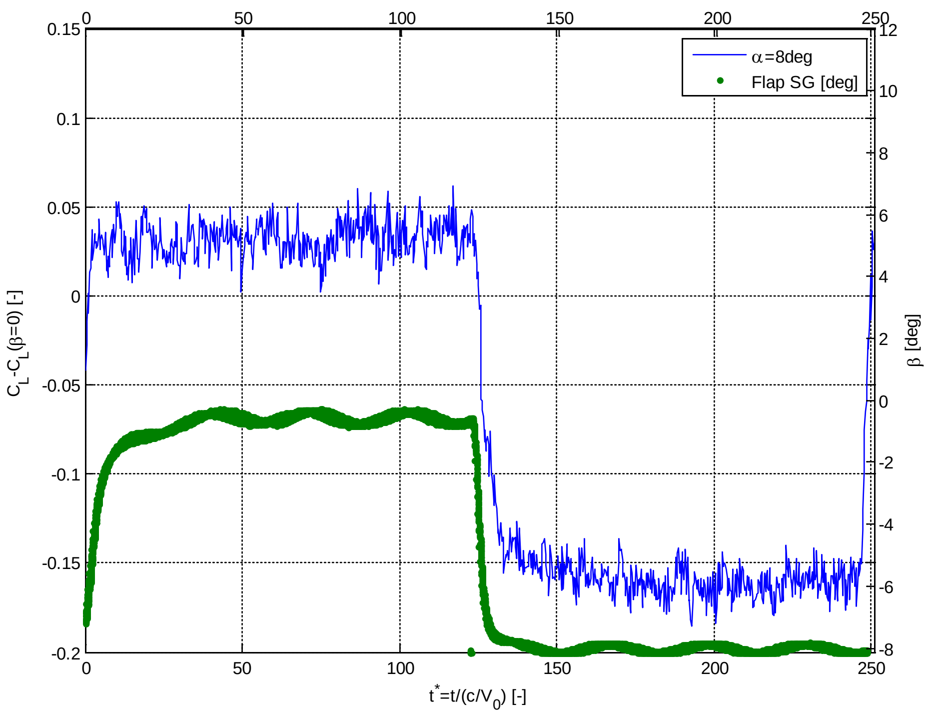


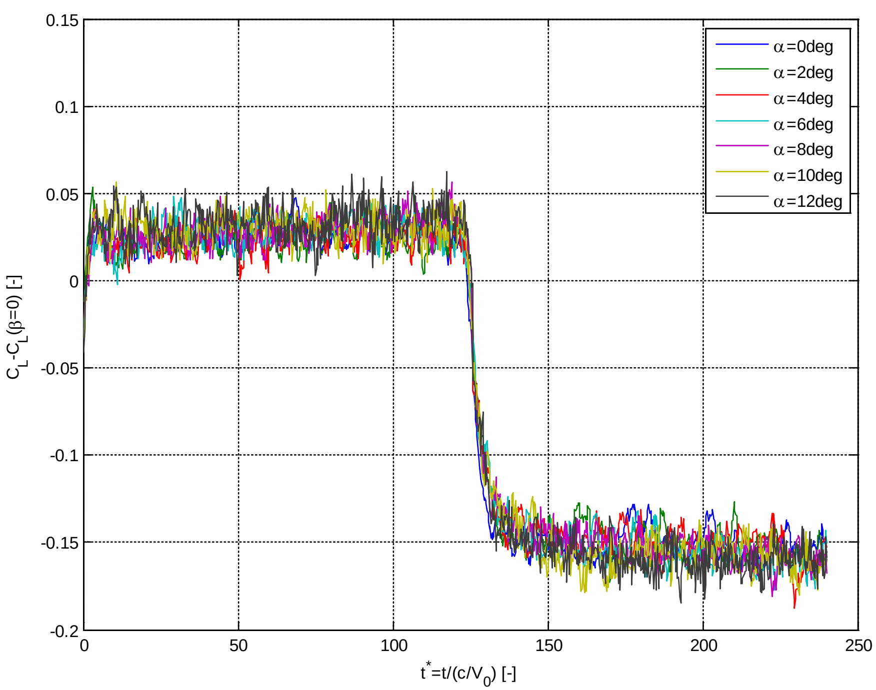
The CRTEF concept

- 1.9m span, 1m chord NACA0015 airfoil section
- Tested at Velux wind tunnel
- $Re=1.2x10^6$ and $2.43x10^6$

The CRTEF concept

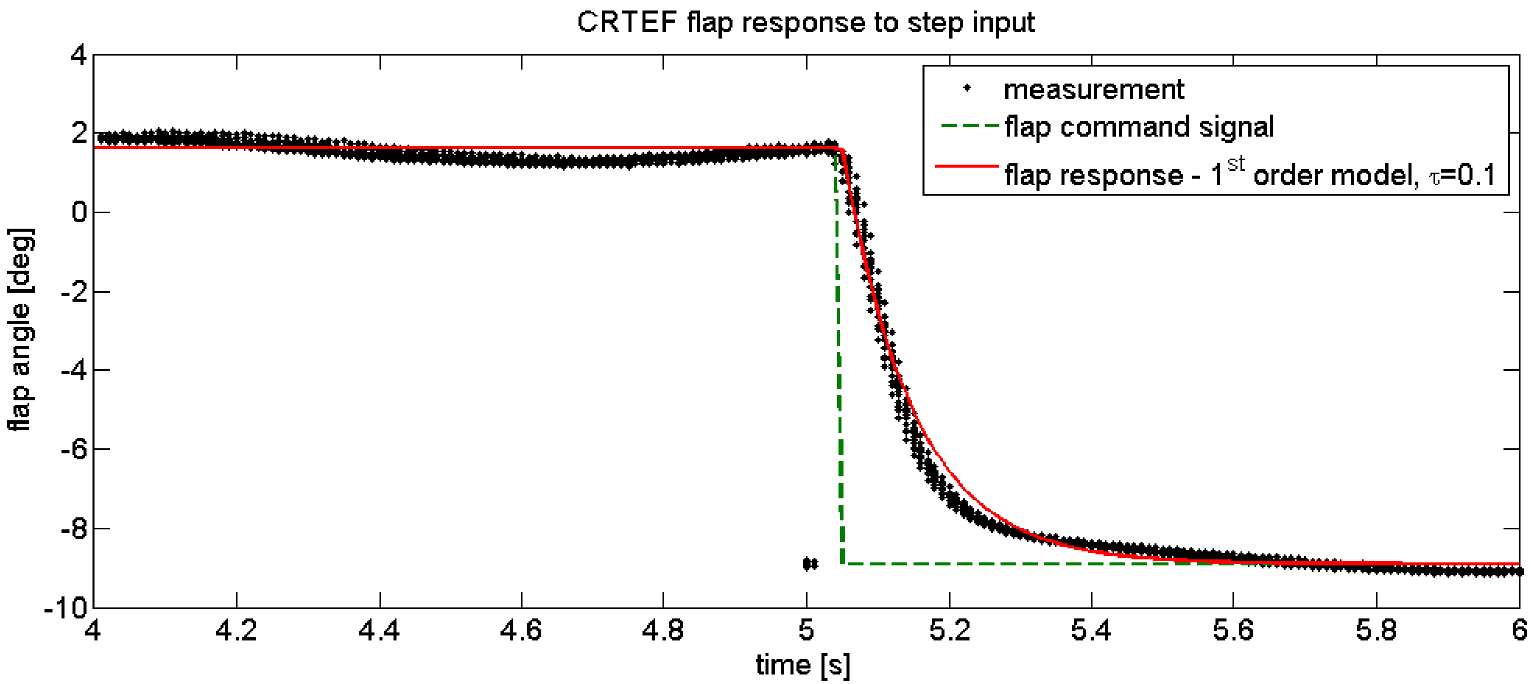
- ➢Actuator transient response
- ➢Unsteady aerodynamics
- ➢Negligible influence of aerodynamic loads on actuator
- ➢ΔC_l around 0.2 achieved





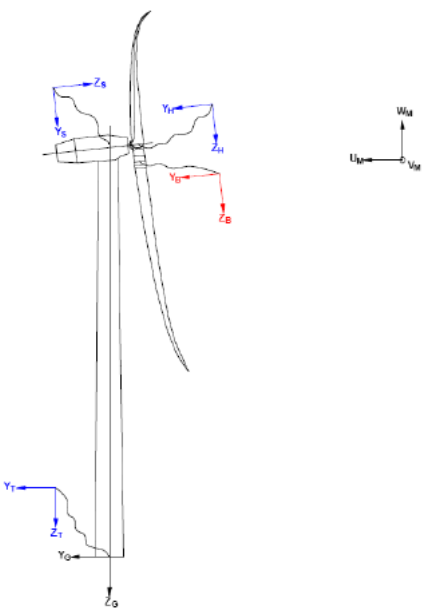
The CRTEF concept

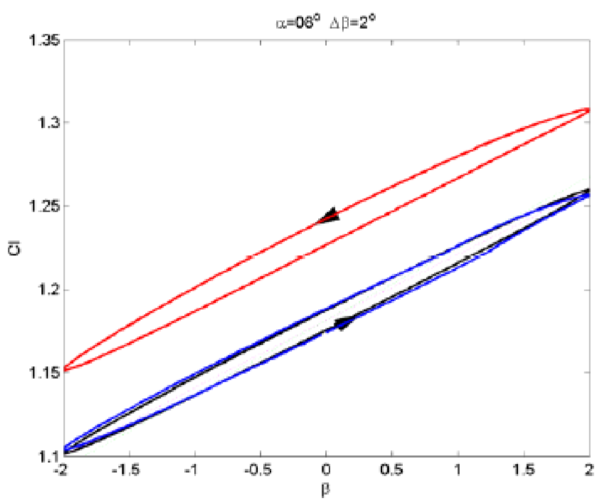
- Actuator dynamics
- A time constant of 0.1s measured
- Good approximation with first order system $$G(s) = \frac{1}{1 + s\tau}$$

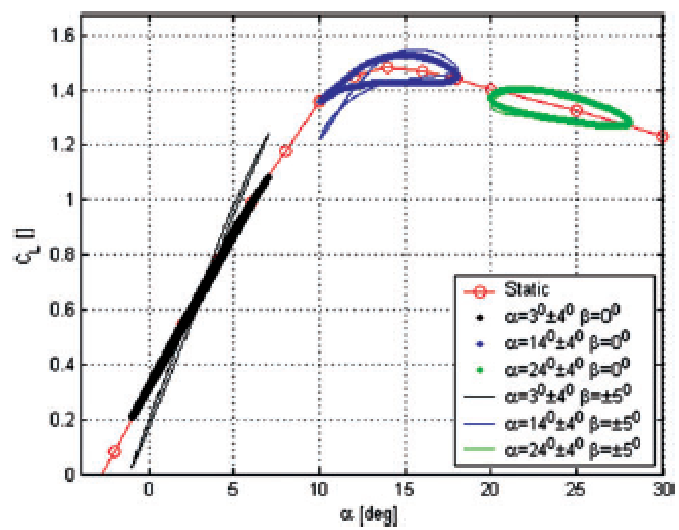


Aerosservoelastic model

- Multi-body BEM based aeroelastic code HAWC2
- Gaunaa-Andersen dynamic stall model for variable geometry airfoils
- NREL 5MW RWT model
- Normal power regulation with generator torque and collective pitch

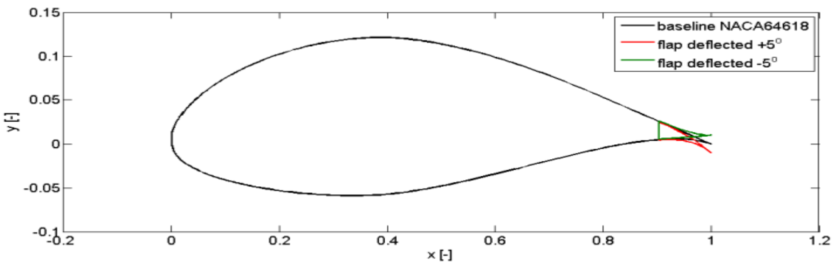


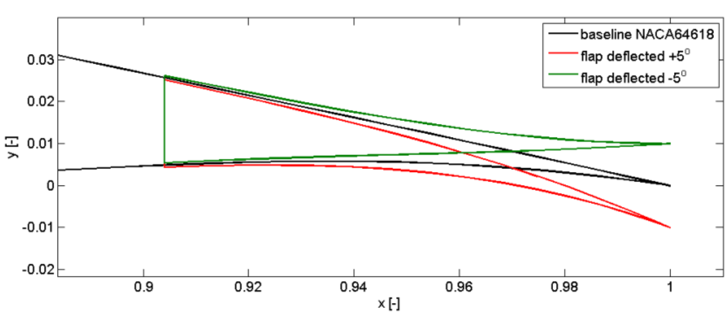


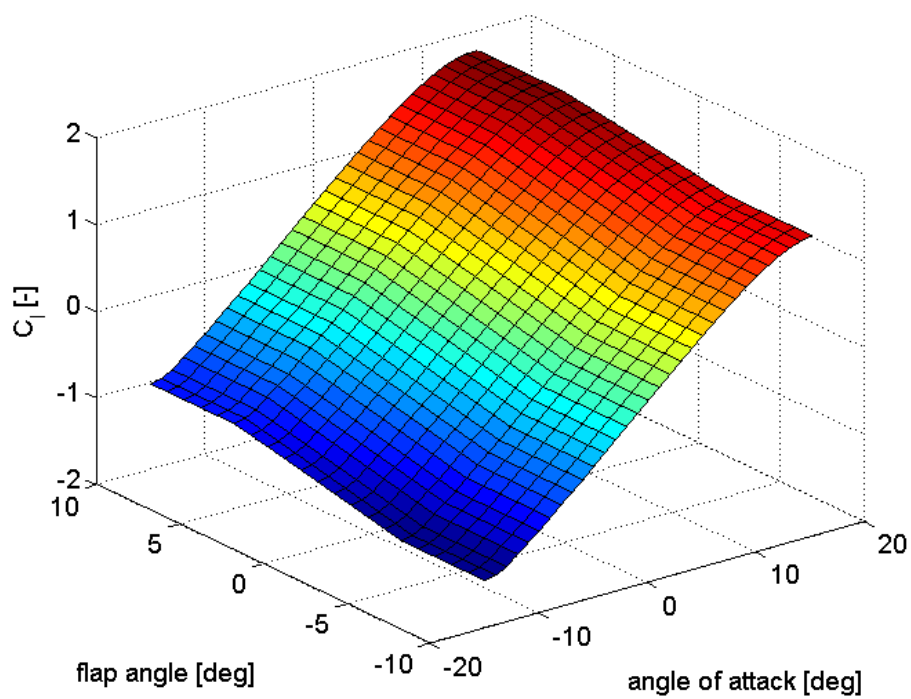


Aerosevoelastic model

- Exact CRTEF deflection shape
- Steady aerodynamic data for CRTEF on NACA64618 calculated with 2D CFD (Ellipsys)
- $\pm 5^{o}$ CRTEF operating angle range ($\Delta C_l \approx 0.2$)
- Indicial response parameters for NACA64618 from CFD

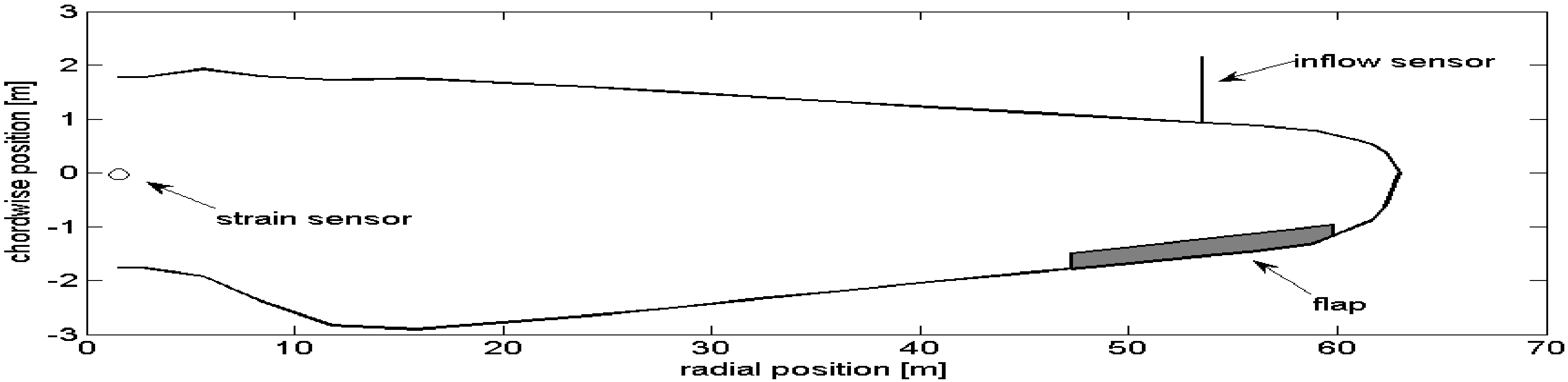






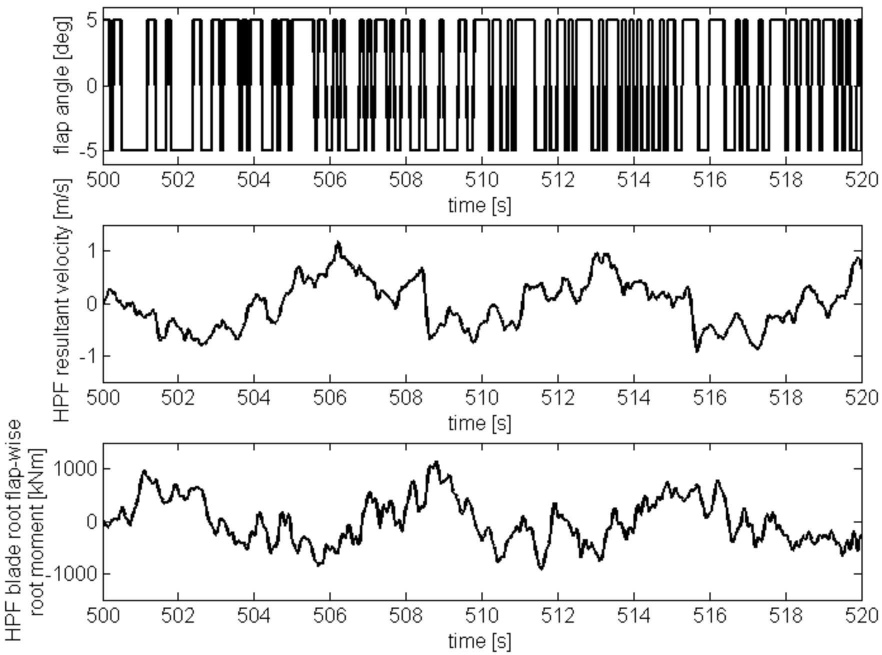
SysID – Controller design

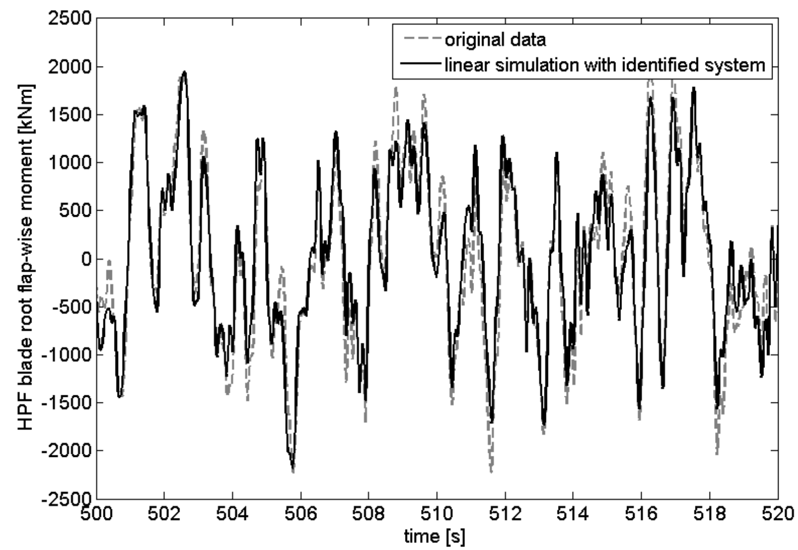
- One flap per blade
- Root strain sensor – Mid-flap location inflow sensor
- 10%c flap on NACA64618



SysID – Controller design

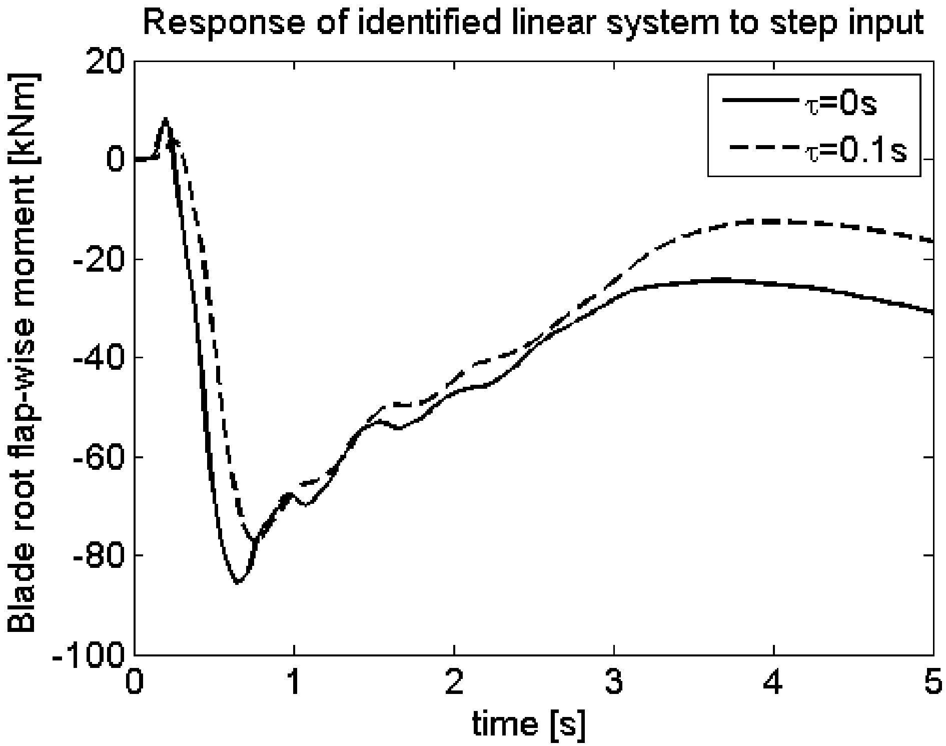
- One flap per blade
- Root strain sensor – Mid-flap location inflow sensor
- System identification with flap GBN signal
- PBSID subspace sysID algorithm (TUDelft)
- Linear model verification





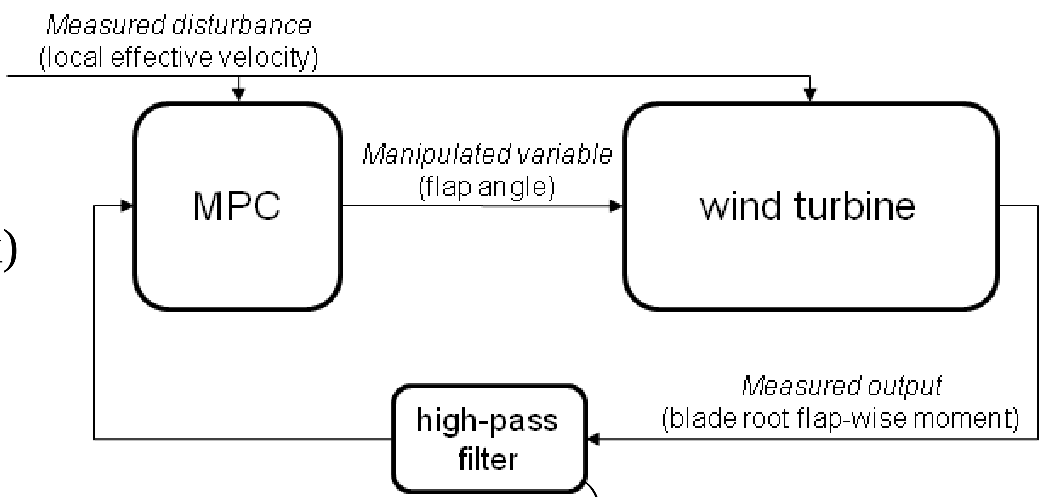
SysID – Controller design

- sysID also with inclusion of flap actuator dynamics
- Actuator lag appears in linear system dynamics



SysID – Controller design

- Model predictive control
- 1 output, 1 input, 1 measured disturbance
- Tuned controller parameters based on typical system output
- Higher prediction horizon gives optimal controller for the case of the linear model with actuator dynamics



$$x(k+1) = Ax(k) + B_u u(k) \, B_v v(k) + B_d d(k)$$

$$y(k) = Cx(k) + D_u u(k) + D_d d(k)$$

$$J(k) = \sum_{i=1}^{P} \left(\left(\left(\hat{y}(k+i) - r(k+i) \right) w_y \right)^2 + \left(u(k+i) w_u \right)^2 + \left(\Delta u(k+i) w_{\Delta u} \right)^2 \right)$$

$$u_{min} \le u(k+i) \le u_{max} \qquad \Delta u_{min} \le \Delta u(k+i) \le \Delta u_{max}$$

Results

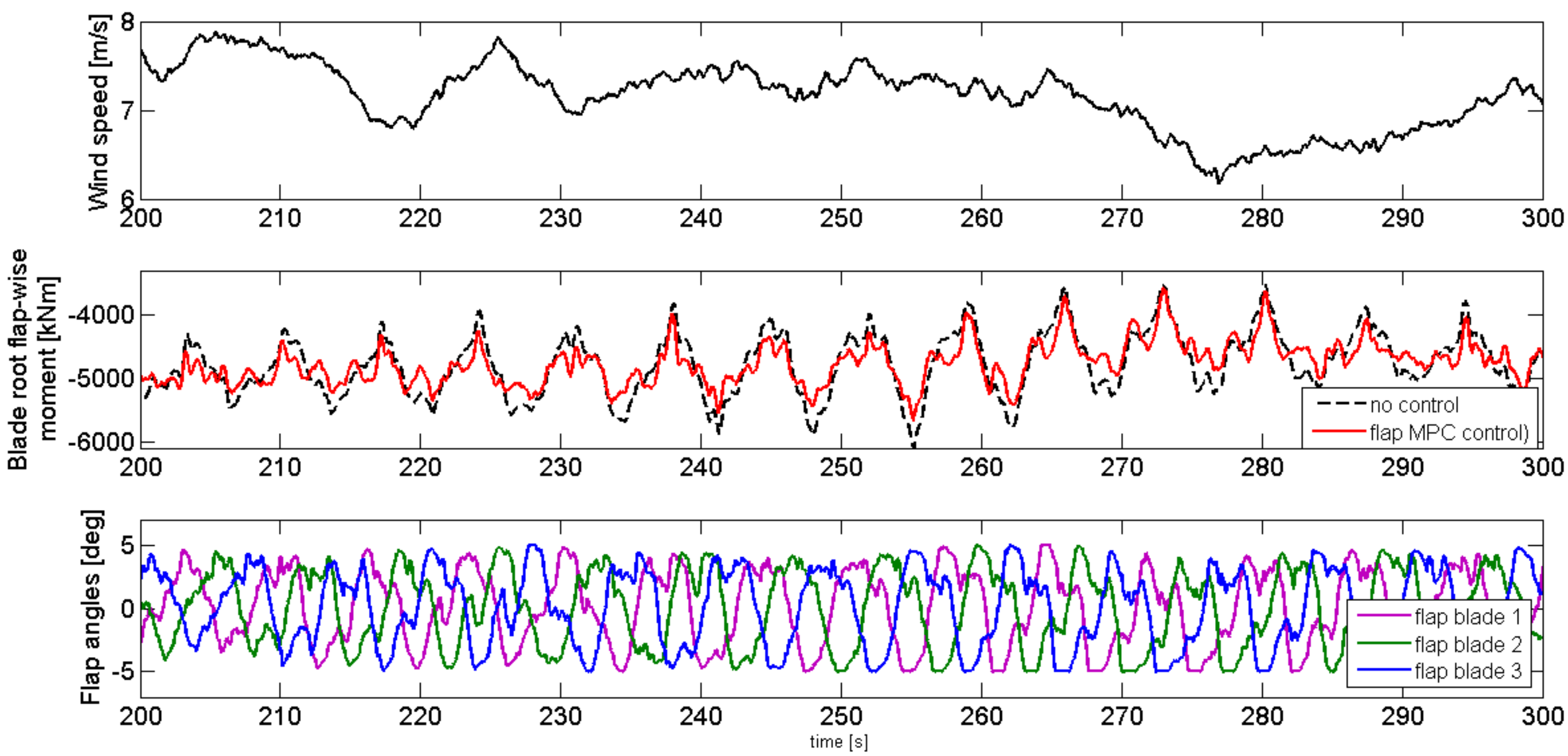
- Normal power production cases with turbulence
- Above and below rated power operating point (7m/s, 15m/s)
- Variation of actuator time constant
- Variation of controller design

case	CRTEF actuator τ in linear model with which MPC is designed [s]	***CRTEF actuator*** **τ in HAWC2 where MPC is evaluated [s]**
1	0	0
2	0	0.1
3	0	0.5
4	0	1
5	0.1	0.1
6	0.1	0.5
7	0.1	1

Results

- Considerable dynamic load reduction, seen in std of blade root flap-wise moment signal
- Strong 1P load component
- 24.6% reduction in std of blade root flap-wise moment signal

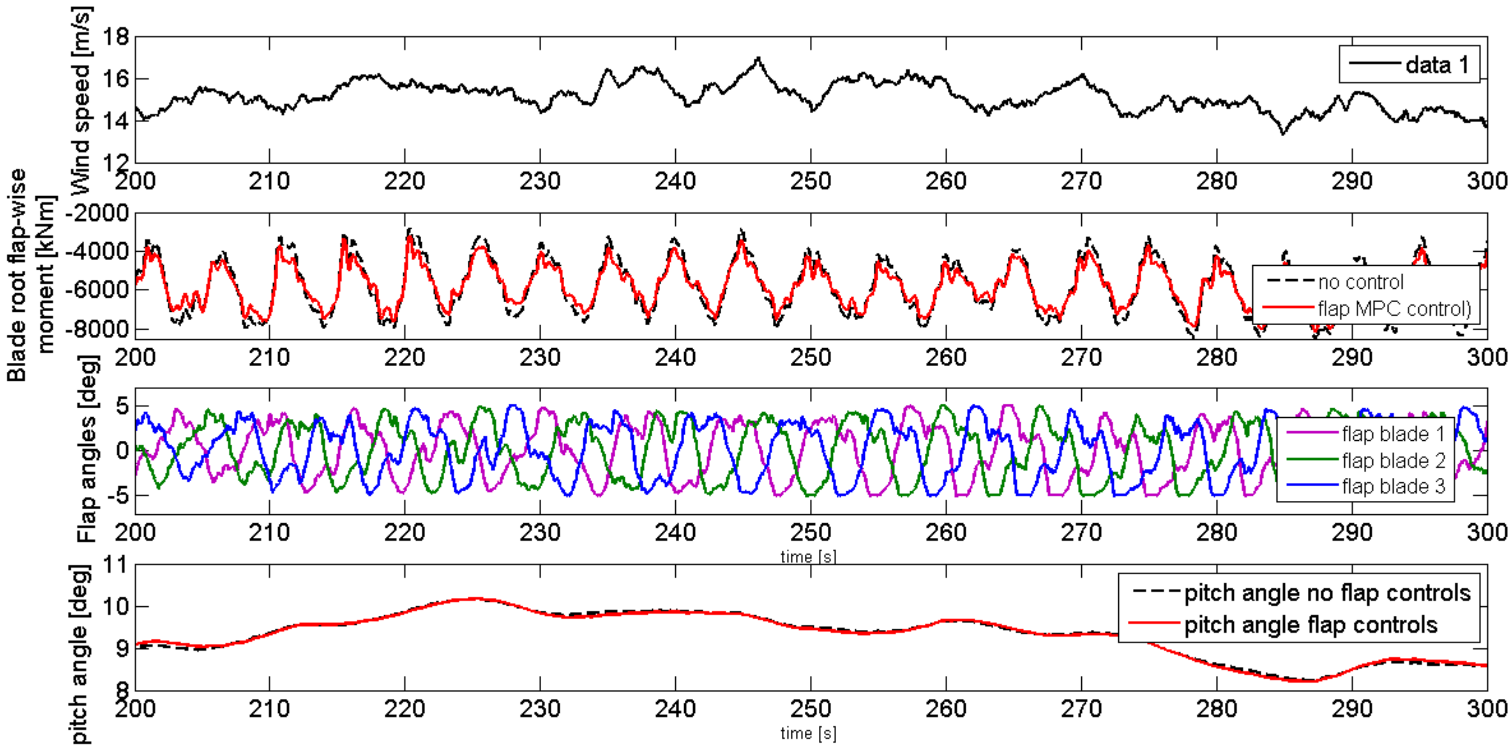
7 m/s



Results

- 20.1% reduction in std of blade root flap-wise moment signal
- Slight benefit also in reducing pitch angle std

15 m/s

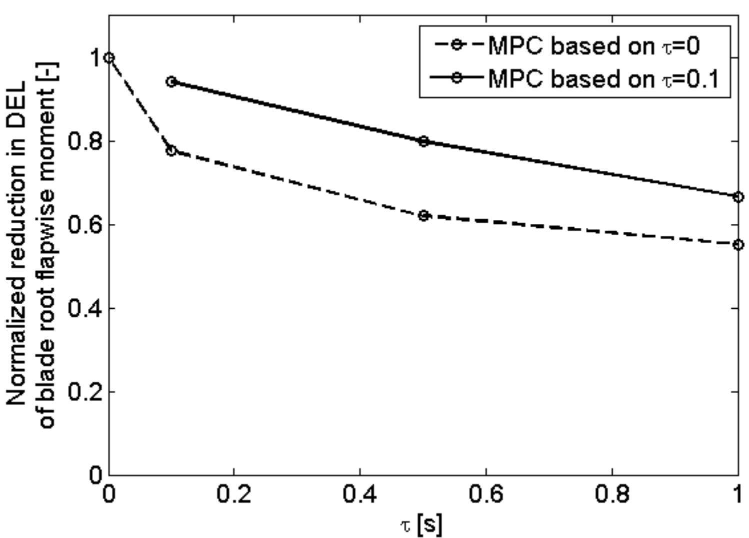


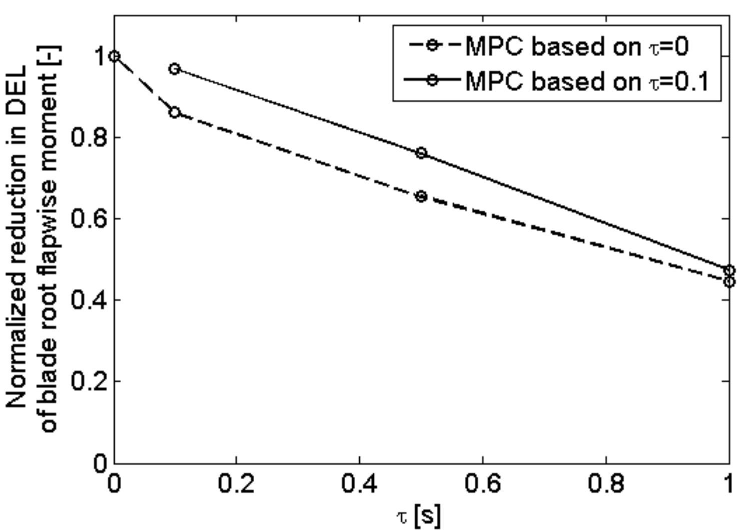
Results

- Load reduction on Damage Equivalent Load
- Load reduction potential decrease with increased actuator lag
- Design based on linear model with actuator dynamics performs up to 20% better

case	% reduction in SD of blade root flap-wise moment		**% reduction in DEL of blade root flap-wise moment**	
	7 m/s	15 m/s	7 m/s	15 m/s
1	24.60	23.86	20.13	16.99
2	22.09	22.85	15.64	14.61
3	20.66	17.61	12.48	11.12
4	15.91	10.74	11.12	7.57
5	23.60	23.27	18.97	16.44
6	22.69	17.99	16.08	12.92
7	17.56	11.33	13.41	8.04

7 m/s





15 m/s

Conclusions

Summary:

- The CRTEF concept can achieve considerable load alleviation
- Actuator dynamics have strong influence on the achieved load reduction potential
- Controller designed taking into account actuator dynamics shows improved performance

Continuation:

- Optimization of CRTEF structural design
- Integration in blade design
- Pneumatic system design
- Connection with power regulation controls
- Rotating rig tests scheduled for 2012