Technical University of Denmark

Development of the controllable rubber trailing edge flap (CRTEF) technology for MW turbines

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Development of the controllable rubber trailing edge flap (CRTEF) technology for MW turbines

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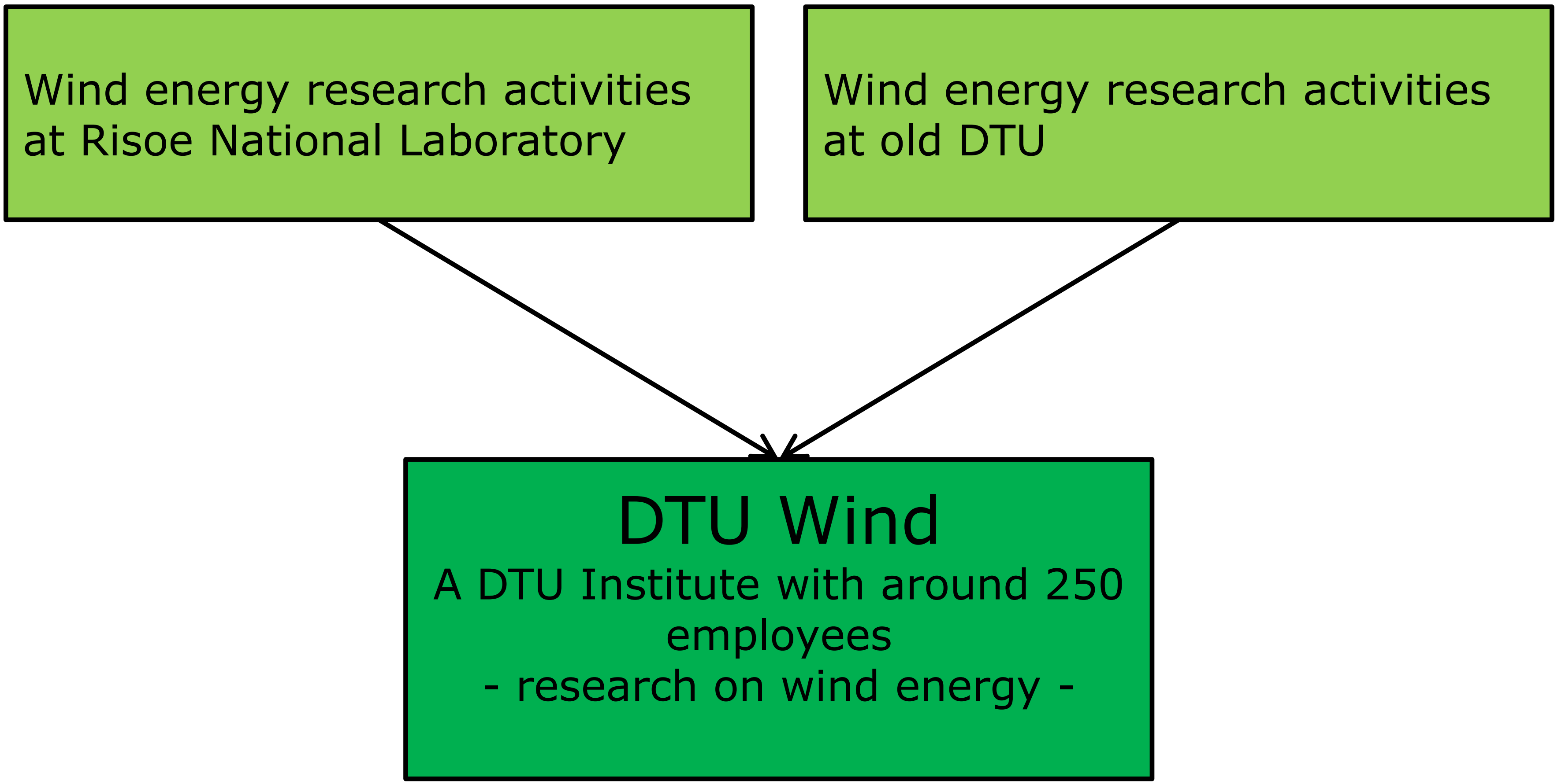
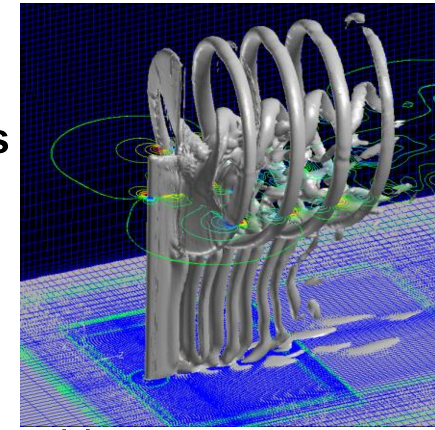
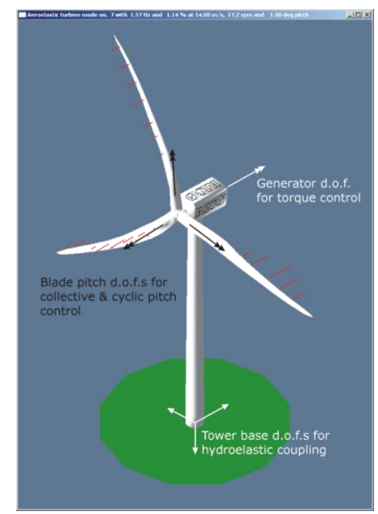
DTU Wind formed January 1st 2012



Aeroelastic Design Group at DTU Wind



- **EllipSys2D**
  - 2D CFD code used mainly for computation on **2D airfoil sections**
- **EllipSys3D**
  - 3D CFD code used for **rotor computations** and flow over terrain
- **Hawc2**
  - Aeroelastic multibody code for aeroelastic time simulation of wind turbines
- **HAWCStab2**
  - code for computation of aeroelastic stability
- **HAWTopt**
  - tool for design and **optimization of rotors**
- **AirfoilOpt**
  - tool for design and **optimization of airfoils**



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Advances in Wind Turbine Rotor Blades,
13-15 February, 2012 Swissôtel Bremen

OUTLINE

- Background
- Potential load reductions by flap control
- Development of the CRTEF technology
- Challenges in the implementation of the flap system on MW turbines
- Outlook

Background

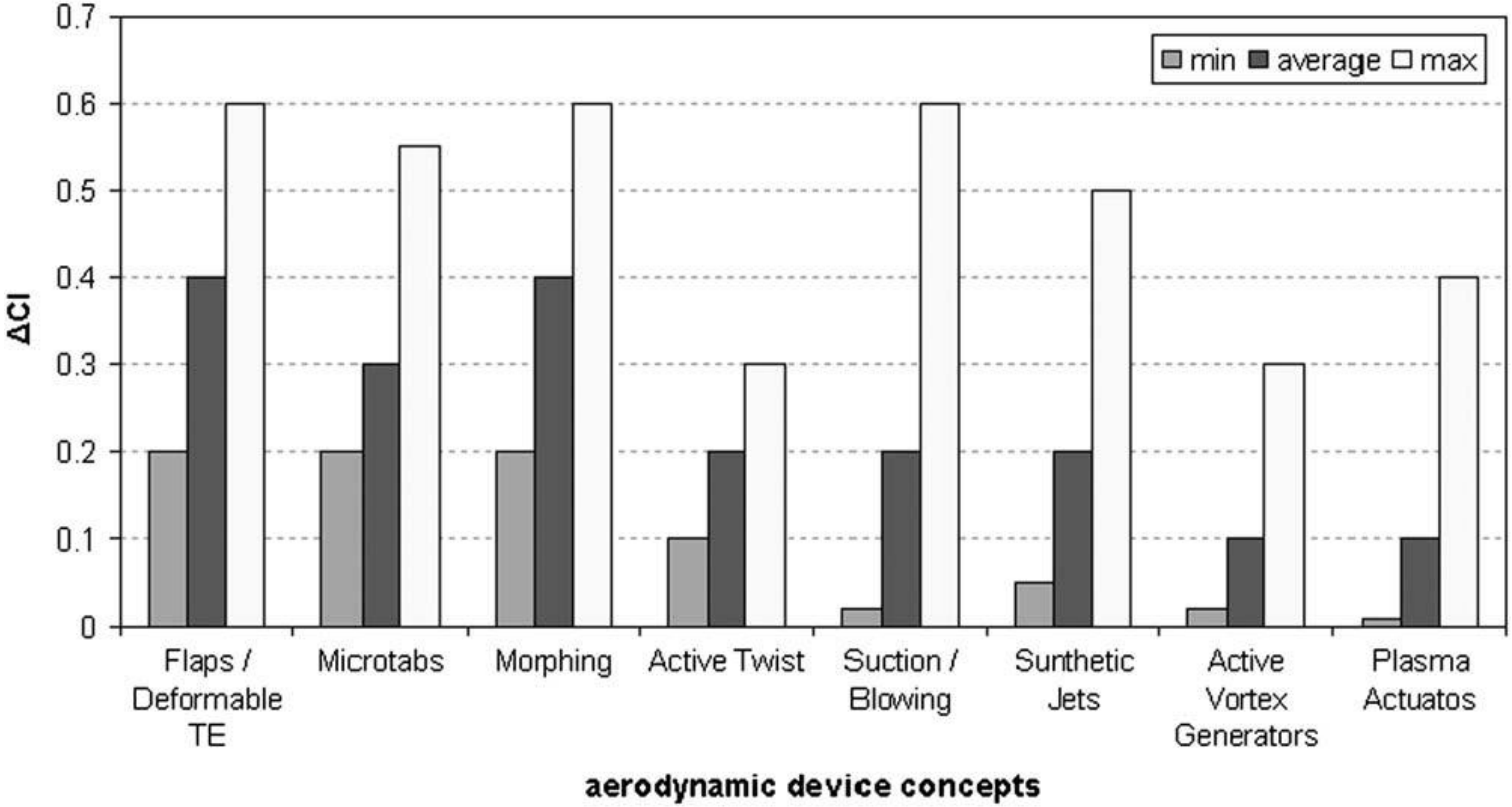
- non-uniform rotor loading from turbulence increases with size of rotor
- a distributed control along the blade has advantages for load alleviation and for stability control
- numerical studies (e.g. Buhl 2005 and Andersen 2009) show considerable load reduction potentials using flap control

Buhl T, Gaunaa M, Bak C. Potential load reduction using airfoils with variable trailing edge geometry. Journal of Solar Energy Engineering 2005; 127: 503–516.

Andersen, P.B., Henriksen, L., Gaunaa, M., Bak, C., Buhl, T. ”Deformable trailing edge fl aps for modern megawatt wind turbine controllers using strain gauge sensors”. WIND ENERGY Wind Energ. (2009) Published online. DOI: 10.1002/we.371

Background

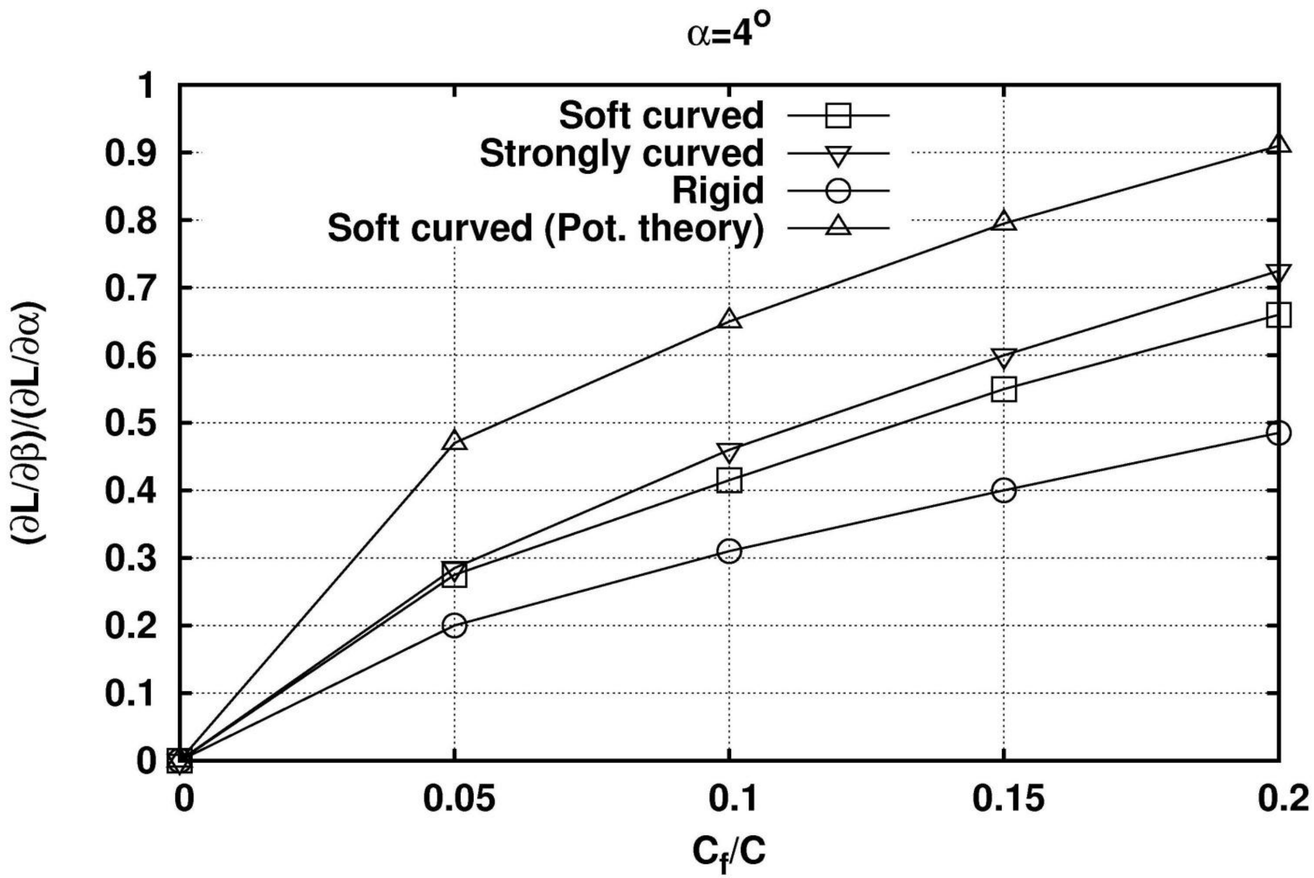
Flaps are among the best devices for changing lift



From Barlas, T.K., vanKuik, G.A.M., 2010, —Review of state of the art in smart rotor control research for wind turbines‖, Progress in Aerospace Sciences, vol. 46, pp. 1–27

Background

Deflecting a flap of 10-15% of blade chord 2 deg., the same change in lift as pitching the whole blade 1 deg. can be achieved



Troldborg, N., 2005, ―Computational study of the RisøB1-18 airfoil with a hinged flap providing variable trailing edge geometry‖, Wind Engineering, vol. 29, pp. 89–113.

Potential load reductions by flap control

What has been achieved in the past ? - numbers from a recent PhD study ?

Chapter	turbulent mean wind speed	controller type	one flap 10% of blade	flaps in total 30% of blade	flaps in total 60% of blade
3.4	7m/s	Type C	18%	42%	47%
3.4	7m/s (6)	Type C	-	36%	-
3.2	10m/s	Type A	25%	37%	-
3.3	10m/s	Type B	30%	40%	-
3.4	11m/s	Type C	31%	41%	43%
3.5(7)	11m/s D2.4	Type DMW	-	28%	38%
3.5	11m/s D6	Type DMW	-	29%	49%
3.5	11m/s D10	Type DMW	-	34%	70%
3.5	11m/s D6(8)	Type DMW	-	30%	52%
3.4	18m/s	Type C	23%	34%	42%

Andersen, P.B. “ADVANCED LOAD ALLEVIATION FOR WIND TURBINES USING ADAPTIVE TRAILING EDGE FLAPS: SENSORING AND CONTROL”. PhD thesis report, Risø DTU, February 2010

What has been achieved in the past ?
- numbers from a review paper

Table III. Comparison of results from aeroservoelastic investigations with active flaps on the Upwind 5MW RWT.

article	c_f [%]	dr_f/r [%]	δ [$\pm^\circ$]	T.I. [%]	shear exp. [-]	V_{av} [m/s]	reduction in std of RBM [%]	reduction in DEL [%]	controller
Riziotis et al. 2008	10	15-47	6	-	0.2	8, 12, 16	30-35 (range)	-	PID
Andersen et al. 2008	10	63	8	14-18	0.14	7, 11, 18	-	36.2-47.9	HPF+inflow
Lackner et al. 2009	10	20	10	NTM, ETM	0.2	8, 12, 16, 20	-	5.6-24.6	PID
Barlas et al. 2009	10	20	10	NTM	0.2	8, 11.4, 16	5.7-22.4	-	PID
Andersen et al. 2009	10	15-30	8	-	11.4	-	-	25-37	HPF
Resor et al. 2010	10	24	10	6	0.2	15	26-30.9	27-31.3	PD, HPF+notch
Wilson et al. 2010	10	24	10	6	0.2	15	13.3	15.5	LQR
Berg et al. 2010	10	25	10	6	0.2	15	8.7-18.1	10.9-17	PD, LQR
this article	10	18	8	6, NTM	0.2	7, 11.4, 15	10.9-30.7	10.9-27.3	MPC+inflow

Barlas, Thanasis; Van Der Veen, Gijs; van Kuik, Gijs; Model Predictive Control for wind turbines with distributed active flaps: Incorporating inflow signals and actuator constraints. Article first published online: 17 NOV 2011 DOI: 10.1002/we.503

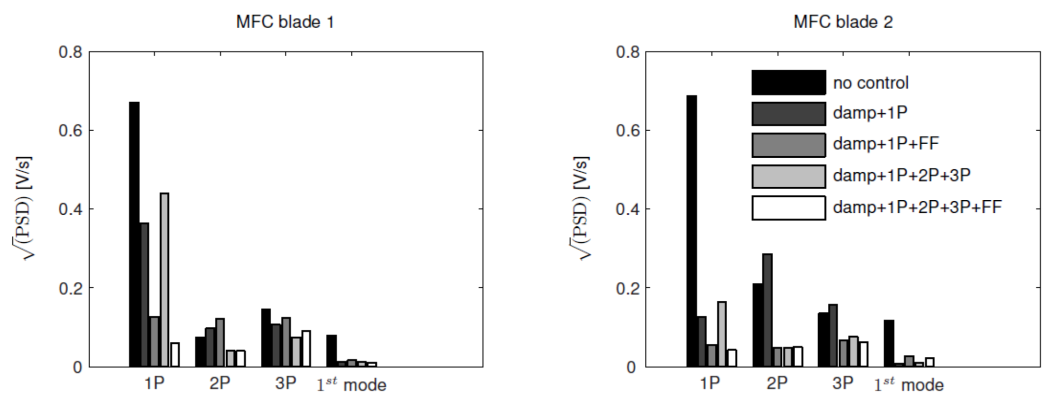
What has been achieved in the past ?
- rotor measurements in wind tunnel

OJF rotor tests TUDelft

PZT flaps and sensors

Advanced MIMO optimal controls + feed forward

FeedBack (FB)				FeedForward (FF)	Performance			
damping	1P	2P	3P		MFC blade 1	MFC blade 2	[%]	[%]
-	-	-	-	-	0.151	0.207	-	-
✓	✓	-	-	-	0.047	0.044	69	79
✓	✓	✓	✓	-	0.058	0.029	62	86
-	-	-	-	✓	0.085	0.134	43	35
✓	✓	-	-	✓	0.025	0.020	83	90
✓	✓	✓	✓	✓	0.018	0.024	88	88



Up to 90% load reduction

´´Two-Degree-of-Freedom Active Vibration Control of a Prototyped "Smart" Rotor´´
Jan-Willem vanWingerden, Anton Hulskamp, Thanasis Barlas, Ivo Houtzager, Harald Bersee, Gijs van Kuik, and Michel Verhaegen
IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY 2010

What has been achieved in the past ? - V27 full scale test at Risoe

Electric motor flaps, strain gauges, Pitot tubes

Model Predictive control

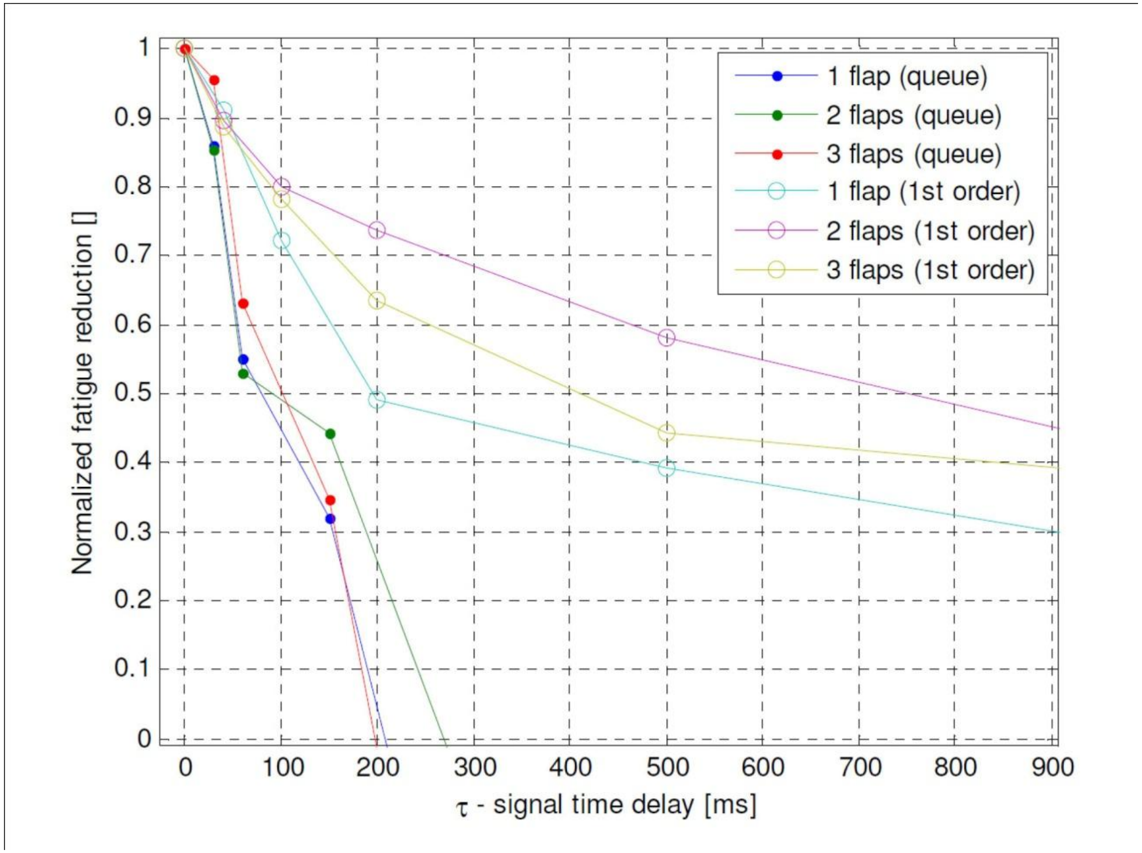
Up to 13% load reduction (limited actuator performance)

´´Full-scale test of Trailing Edge Flaps on a Vestas V27 wind turbine. Active load reduction and system identification´´
Damien Castaignet, Thanasis Barlas, Thomas Buhl, Niels K. Poulsen, Jens Jakob Wedel- Heinen, Niels A. Olesen, Christian Bak and Taeseong Kim.
Wind Energy 2012 (to appear)

What are the main parameters that constrains the load reduction potentials ?

- sensor input
- actuation time constants
- limits on size of flaps
- limits on actuation amplitude

Influence of flap actuation time constants



Andersen, P.B. "ADVANCED LOAD ALLEVIATION FOR WIND TURBINES USING ADAPTIVE TRAILING EDGE FLAPS: SENSORING AND CONTROL". PhD thesis report, Risø DTU, February 2010

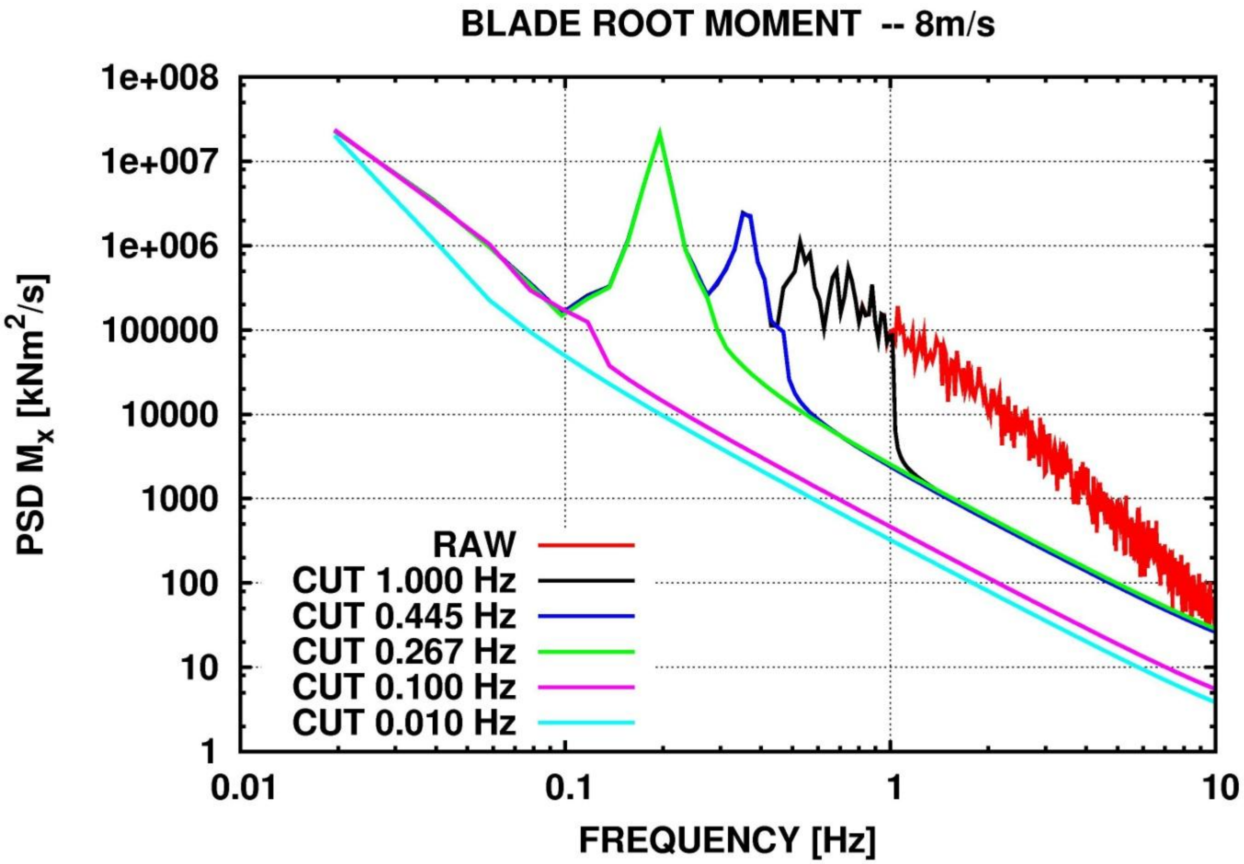
Case from an investigation on load reduction potential being conducted at the moment

Aeroelastic simulations on the 5MW reference wind turbine

- constant rpm
- 8m/s turbulent inflow
- both a flexible and stiff structural model simulated

The ideal load reduction potential

The flapwise moment low pass filtered at different cut off frequencies



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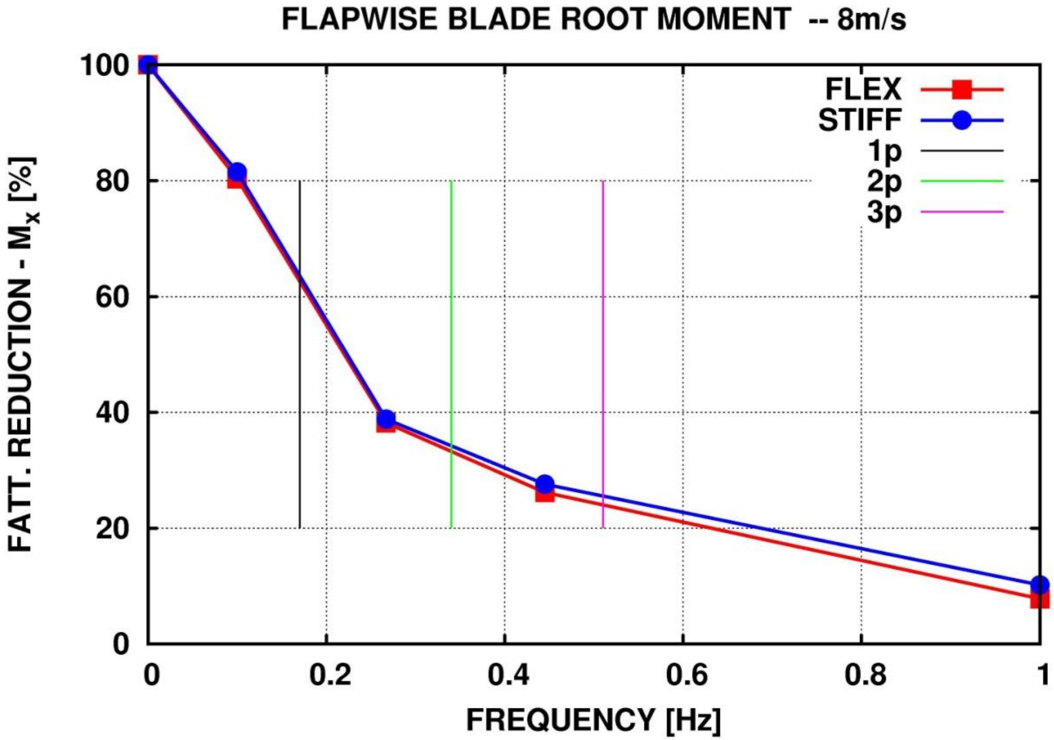
The ideal load reduction potential

- The flapwise moment low pass filtered at different cut off frequencies.
- Then rainflow counting on the processed signals



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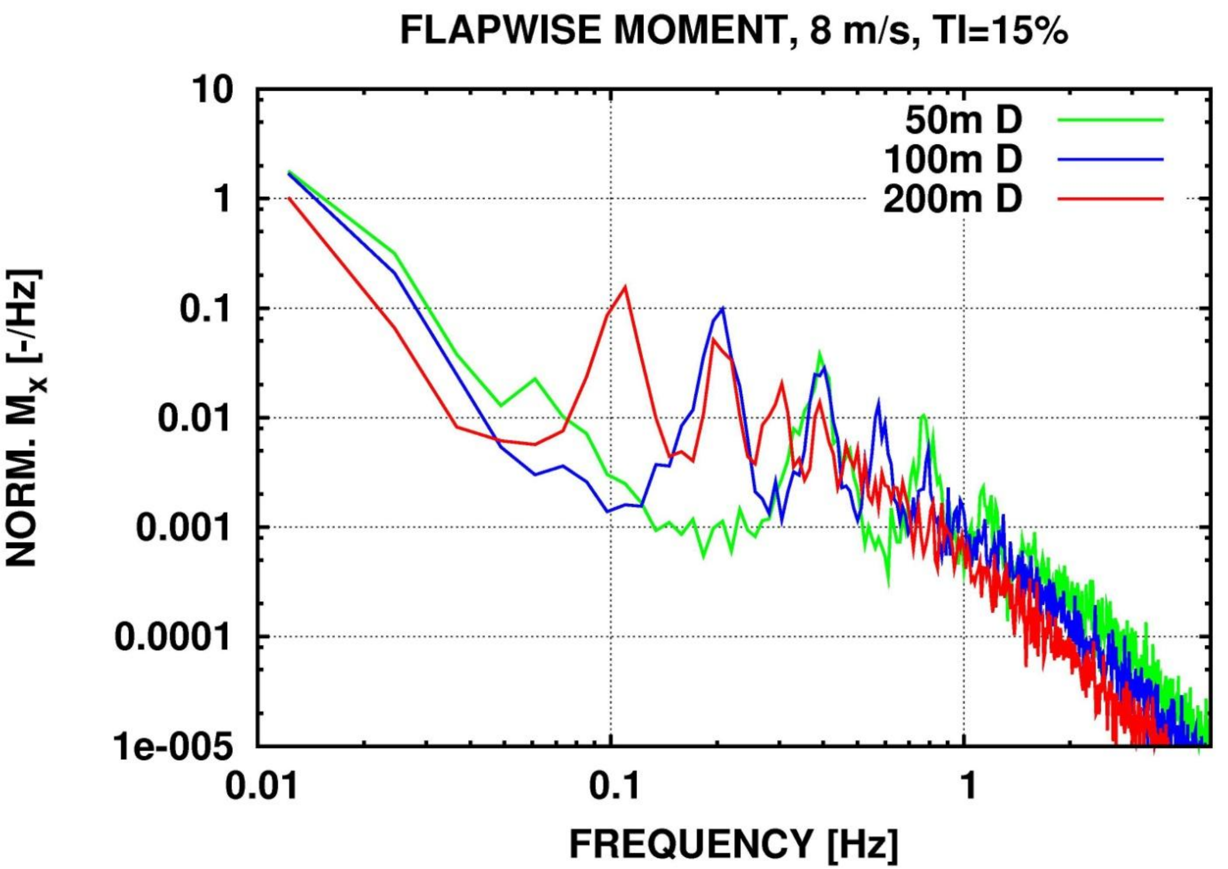
Influence of turbine size on spectra of flapwise bending moments



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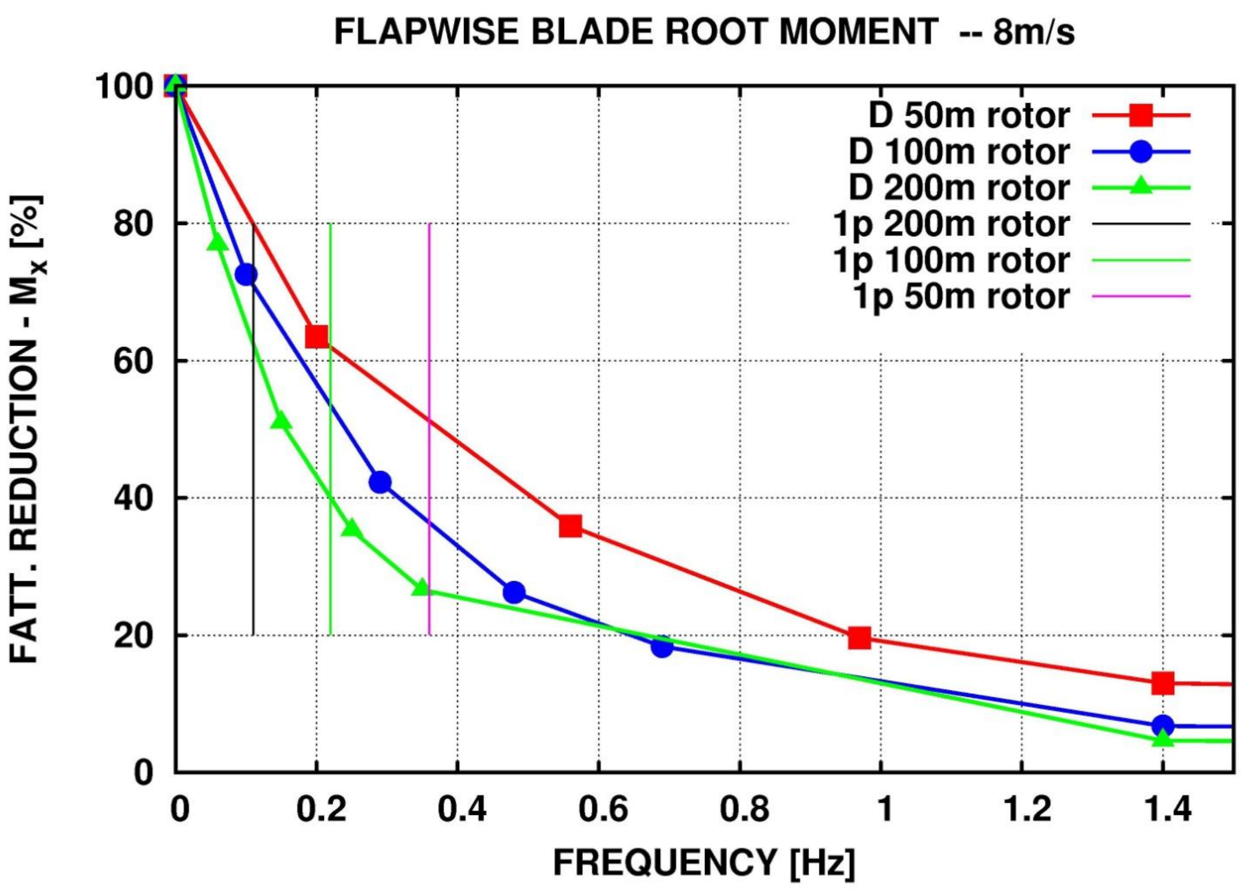
Influence of turbine size on load reduction potential



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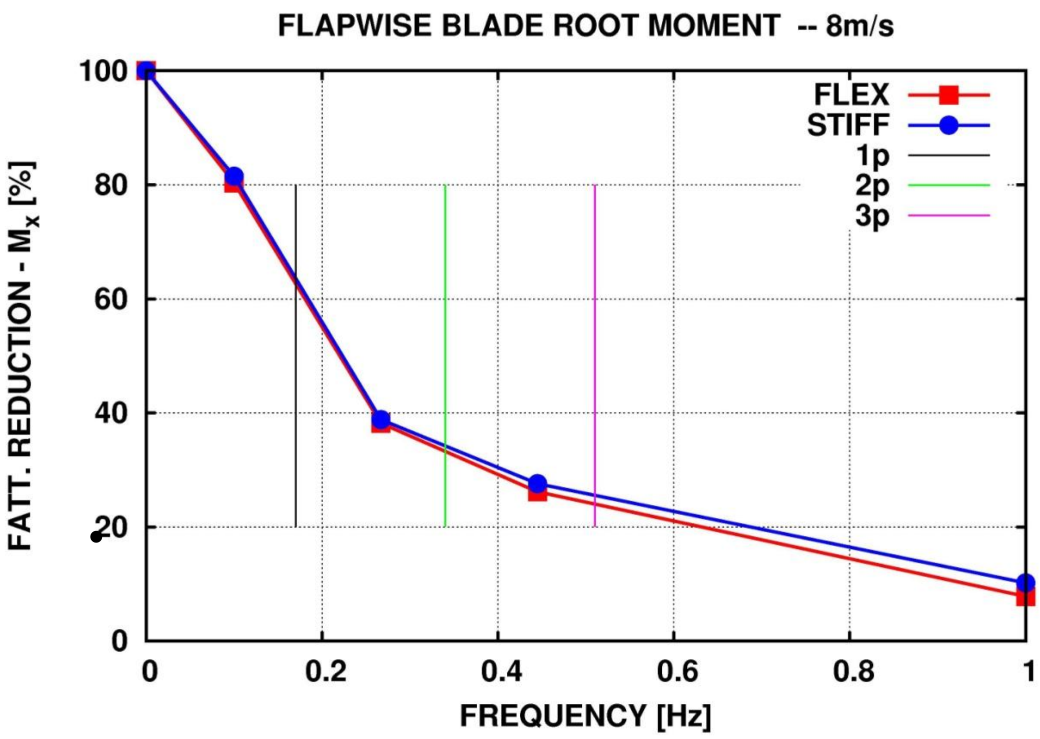
Load reduction potential – what can be achieved ?

- can we achieve something like this with flap control if we had the ideal control signal ?
- what would it require of the flap characteristics, e.g. by trying to alleviate the dynamic loads between 0.1 and 1Hz



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Ideal control input

Ideal control signal based on inflow. We look at one radial position.

Control

Inflow angle α and relative velocity V_r is measured (available) at radius 50 m.

$\overline{\alpha}$ and $\overline{V_r}$ are exclude band filtered from 0.1 to 1 Hz

$$f_c = K_\alpha \left(\alpha - \overline{\alpha}\right) + \left(\frac{V_r^2 - \overline{V_r^2}}{V_r^4}\right) K_{V_r}$$

Where f_c is the control to the flap and the constants used were:

$K_\alpha = 0.000165$ and $K_{V_r} = -4.4$

Load reduction of normal force at radius 50 m

Derivation of controlled force at radius 50m:

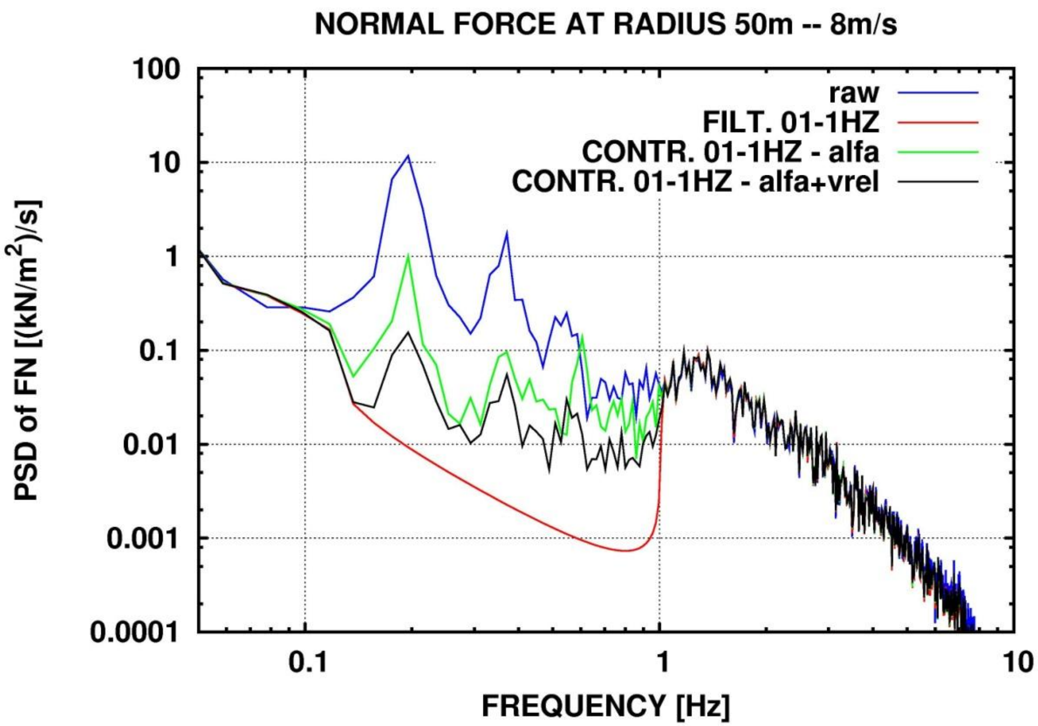
F_N is the raw normal force and F_{Nc} is the controlled force.

$$F_{Nc} = F_N - f_c V_R^2$$

Ideal fatt. reduction: 42%

Control – alfa: 35%

Control – alfa+vrel: 40%



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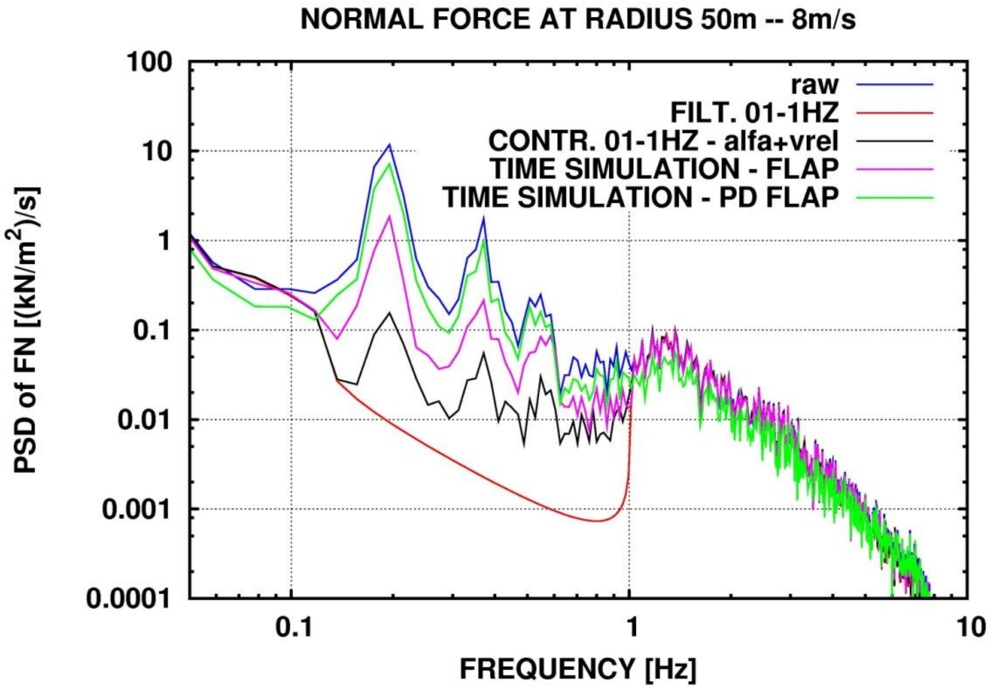
Load reduction of normal force at radius 50 m with flap

Derivation of controlled force at radius 50m:

F_N is the raw normal force and F_{Nc} is the controlled force.

$$F_{Nc} = F_N - f_c V_R^2$$

Ideal fatt. reduction:	42%
Control – alfa:	35%
Control – alfa+vrel:	40%
Time simulation flap:	33%
Time simulation PD flap:	20%



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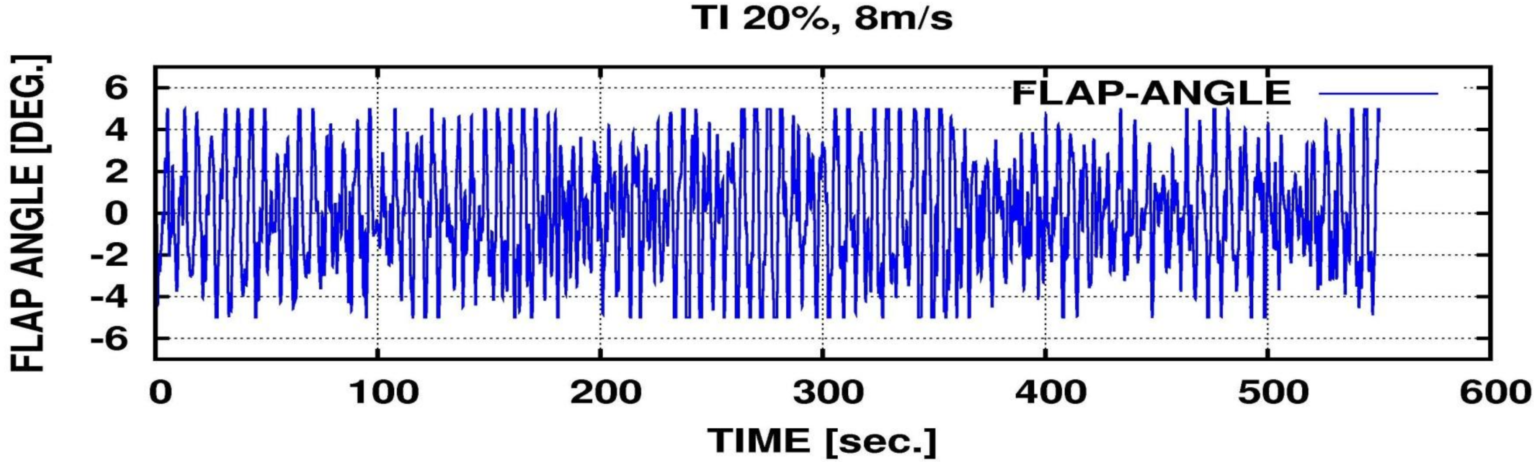
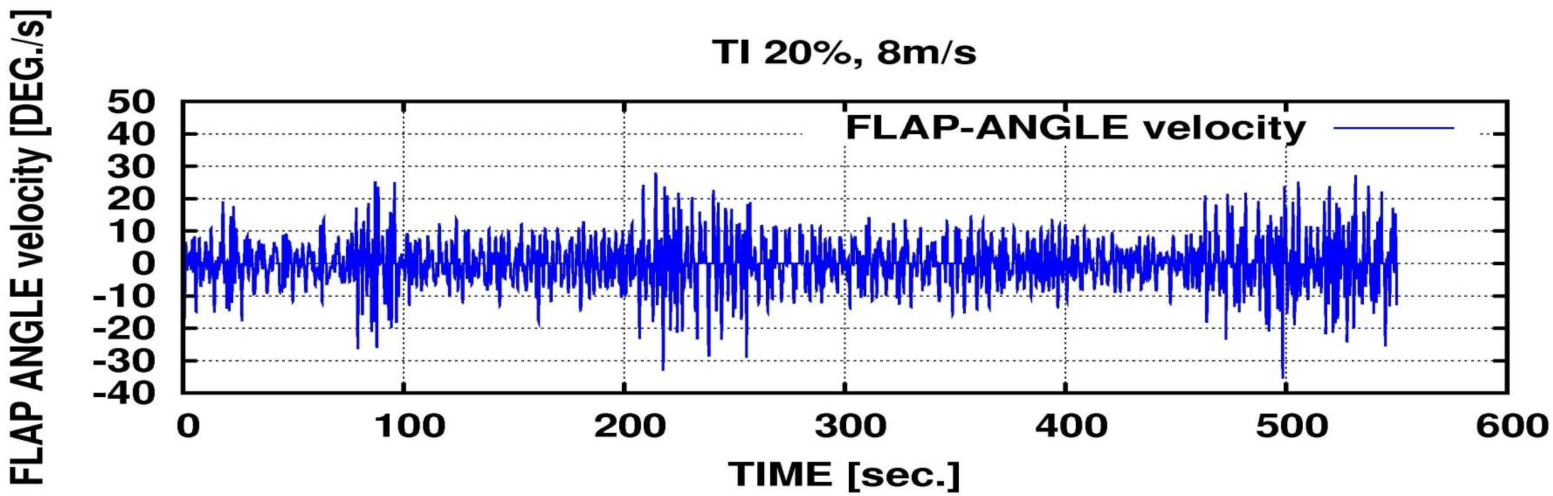
Flap amplitude limits the load reduction potential





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Development of the CRTEF technology

Background for the CRTEF devlopment

Promissing load reduction potentials from numerical simulations but what flap technology can be used ?

- piezo electric flaps (Bak et al. 2007)
- deployable tabs (van Dam et al. 2007)

Bak C, Gaunaa M, Andersen PB, Buhl T, Hansen P, Clemmensen K, Møller R. Wind tunnel test on wind turbine airfoil with adaptive trailing edge geometry. [Technical Papers] Presented at the 42 AIAA Aerospace Sciences Meeting and Exhibit 45 AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 2007; 1–16.

van Dam CP, Chow R, Zayas JR, Berg DA. Computational investigations of small deploying tabs and flaps for aerodynamic load control. Journal of Physics 2007; 5. 2nd EWEA, EAWE The Science of Making Torque from Wind Conference, Lyngby, 2007; 1–10.

The CRTEF development

Development work started in 2006

Main objective: Develop a robust, simple controllable trailing edge flap

The CRTEF design:

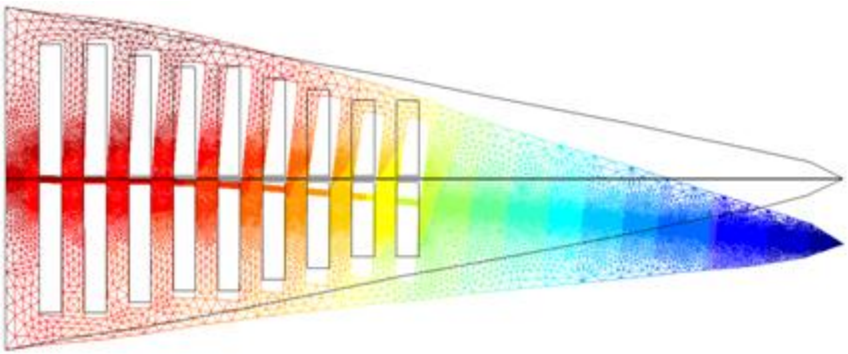
A flap in an elastic material as e.g. rubber with a number of reinforced voids that can be pressurized giving a deflection of the flap.

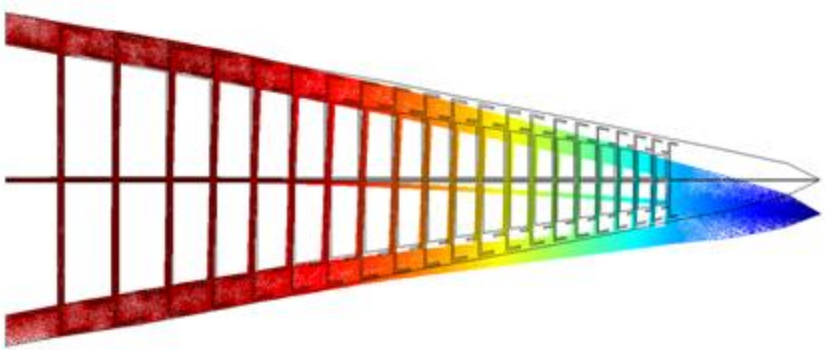
Some milestones in the CRTEF development

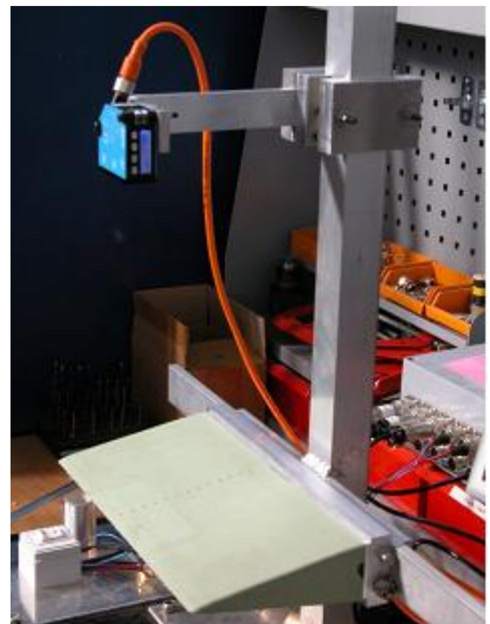
- in 2007 a 1m long prototype rubber trailing edge flap was tested – problems with its robustness
- in autumm 2008 promissing results with a 30 cm prototype with chordwise voids
- December 2009 wind tunnel testing of 2m long flap section
- In March 2011 the 3 year project INDUFLAP with participation of industrial partners was initiated

The CRTEF development
- early work

Comsol 2D analyses







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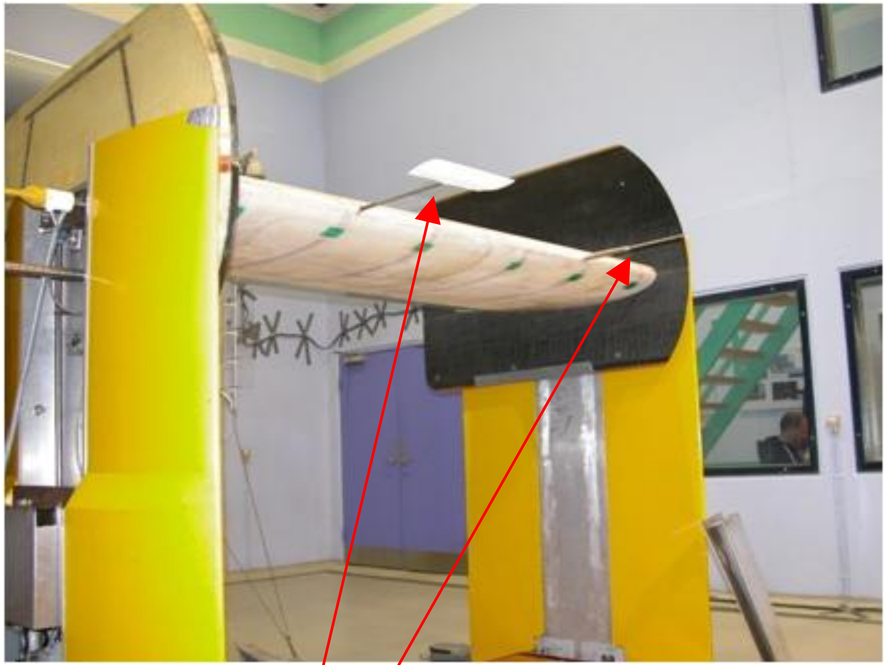
Wind tunnel experiment Dec. 2009

airfoil section + flap during instrumentation

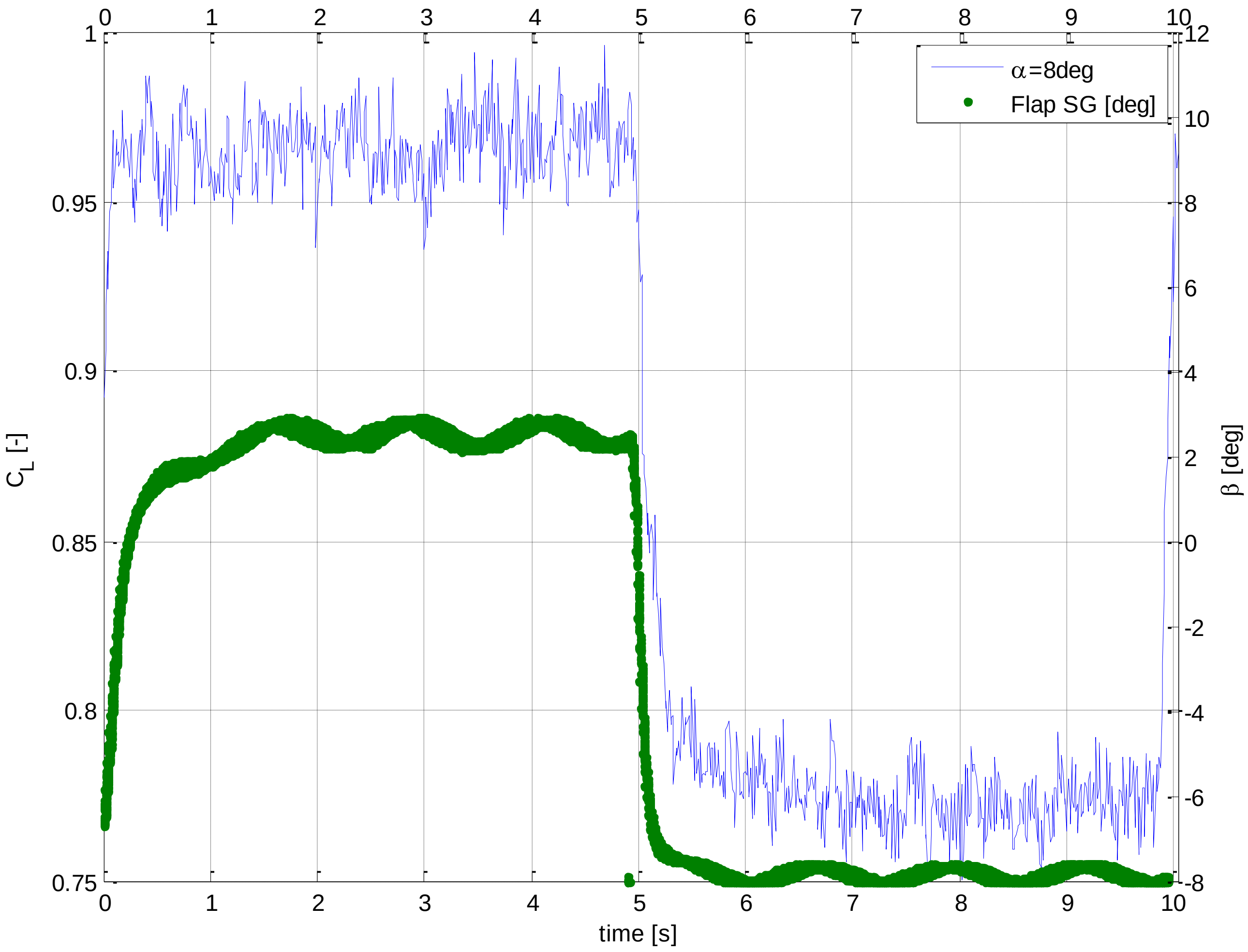
the 2m airfoil section with the flap in the VELUX wind tunnel, December 2009

Wind tunnel experiment Dec. 2009



two different inflow sensors

Lift changes integrated from pressure measurements



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New project on the CRTEF development

The 3 year project **Industrial adaptation of a prototype flap system for wind turbines –INDUFLAP was** initiated in March 2011

Start of project	Project	End of project
Prototype CRTEF tested in laboratory	→	Prototype ready for test on MW turbine

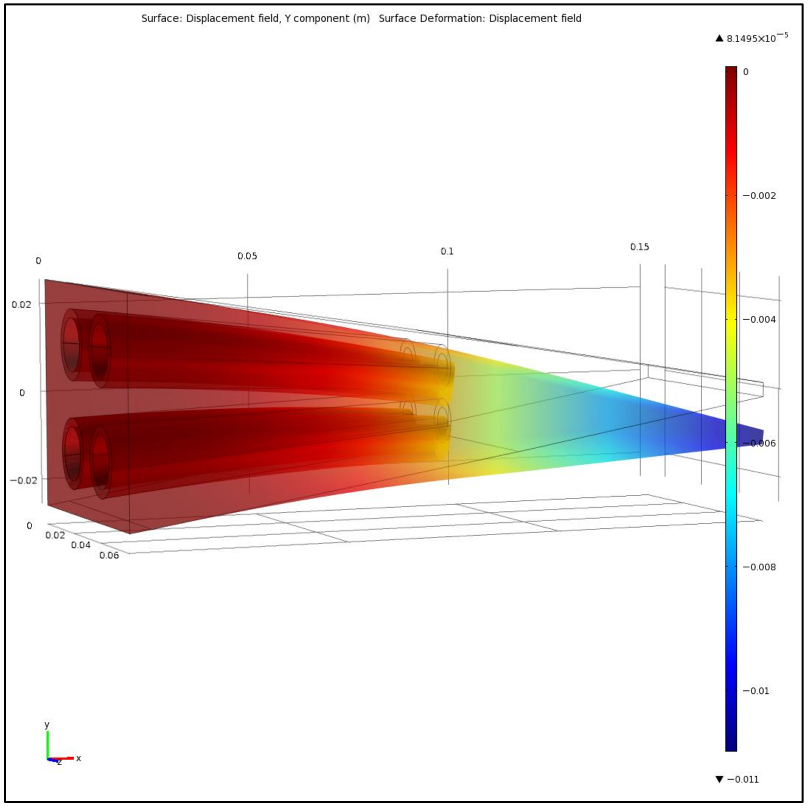
Participants:	**Industrial partners**
DTU Elektro	Rehau A/S
DTU AED	HYDRA tech A/S (AVN Energy A/S)
DTU Fiberlab	Dansk Gummi Industri A/S

Project activities/investigations

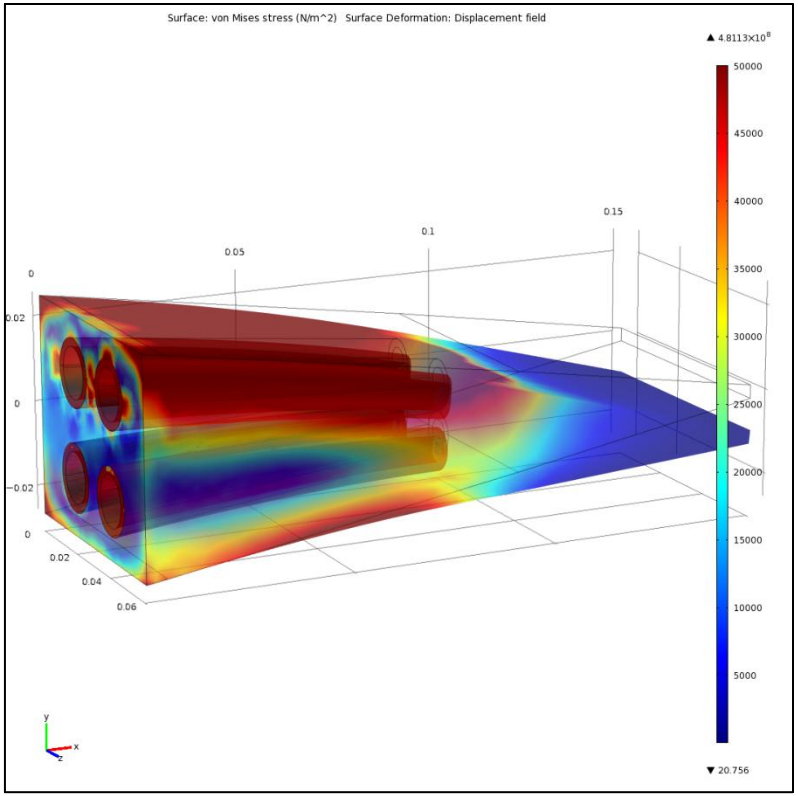
- new designs (void arrangement, reinforcement, manufacturing process)
- new materials
- performance (deflection, time constants)
- robustness, fatigue, lightning
- manufacturing of 30 cm and 2 m prototypes
- integration of flap system in blade
- pneumatic supply
- control system for flap and integration with pitch
- testing of 2 m sections outdoor in rotating rig
- preliminary sketch of system for MW turbine blade

Example of COMSOL simulation on a new prototype with chordwise voids

Contour plot of deflection



Contour plot of stress



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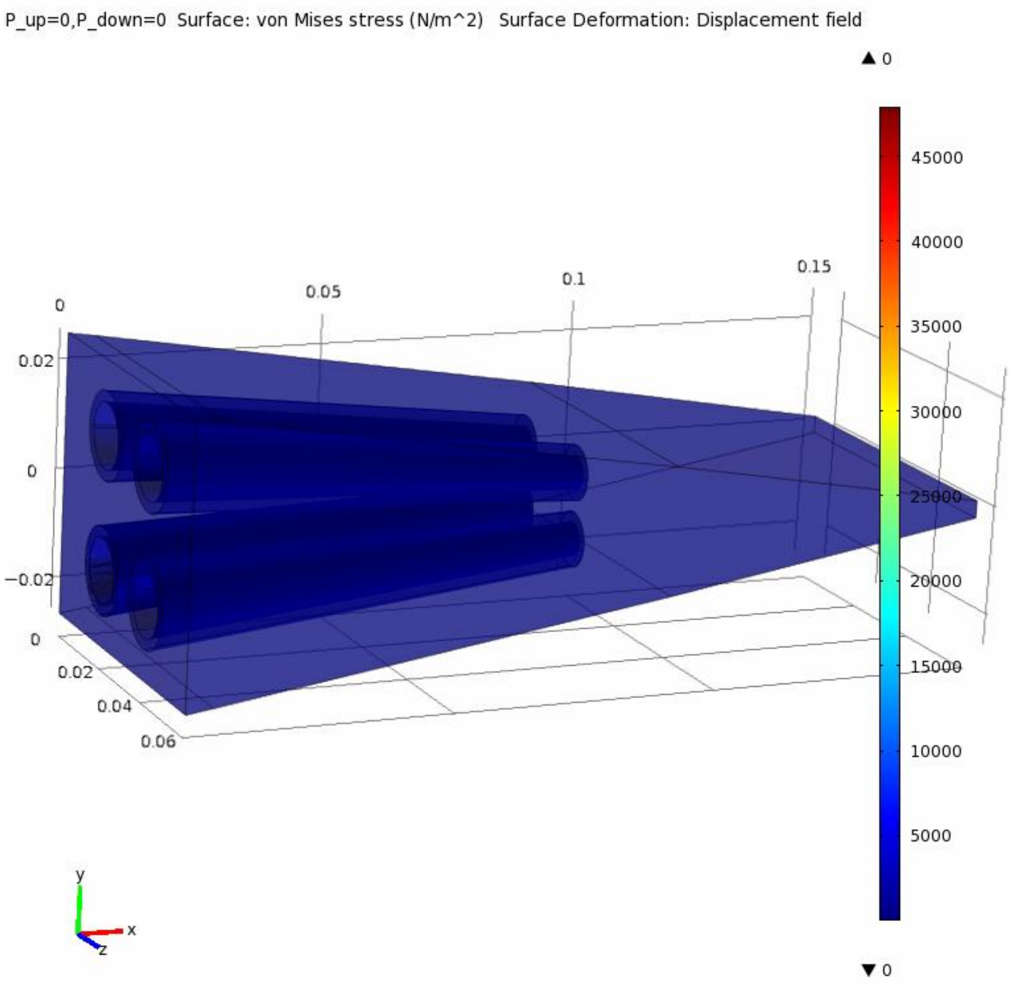
Example of COMSOL simulation on a new prototype with chordwise voids



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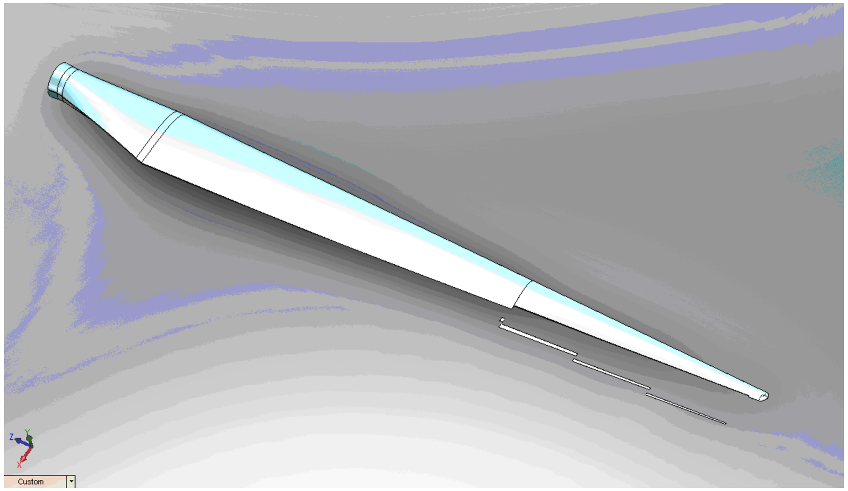
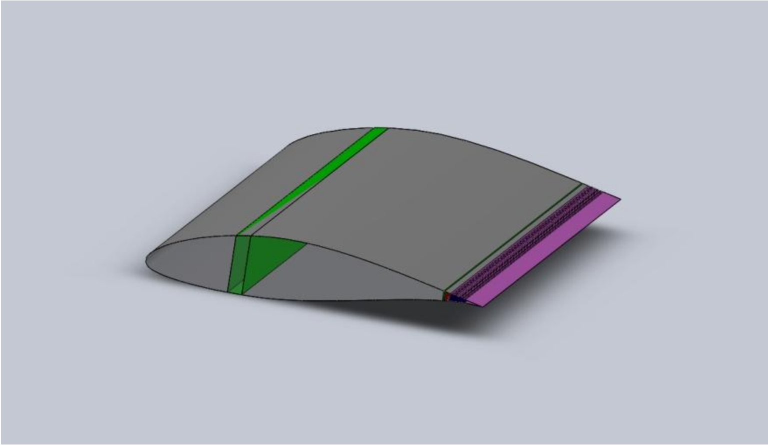
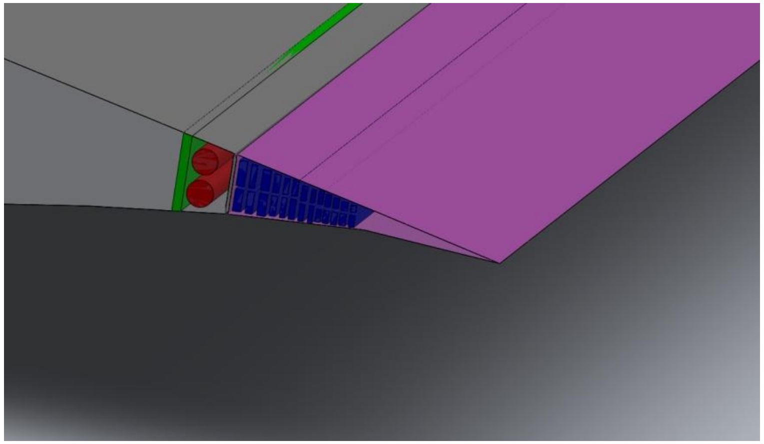
Studies of implementation and integration of flaps in blades







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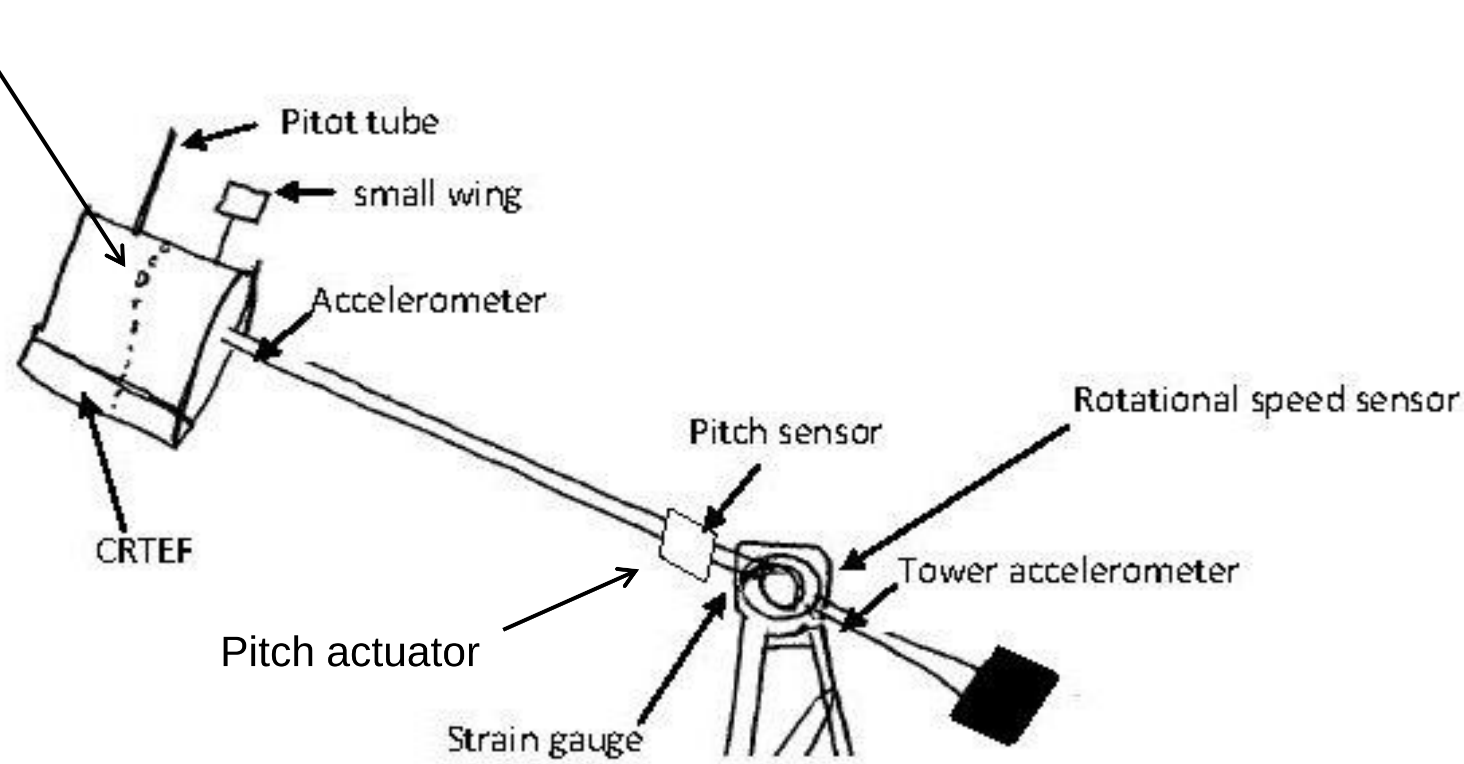
Flaps to be tested on a rotating outdoor test rig

Test rig based on a 100 kW turbine
- rotation of a 10m long flexible arm with an airfoil section of about 2x1m



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The rotating outdoor test rig based on a 100kW turbine platform

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PhD project on lightning

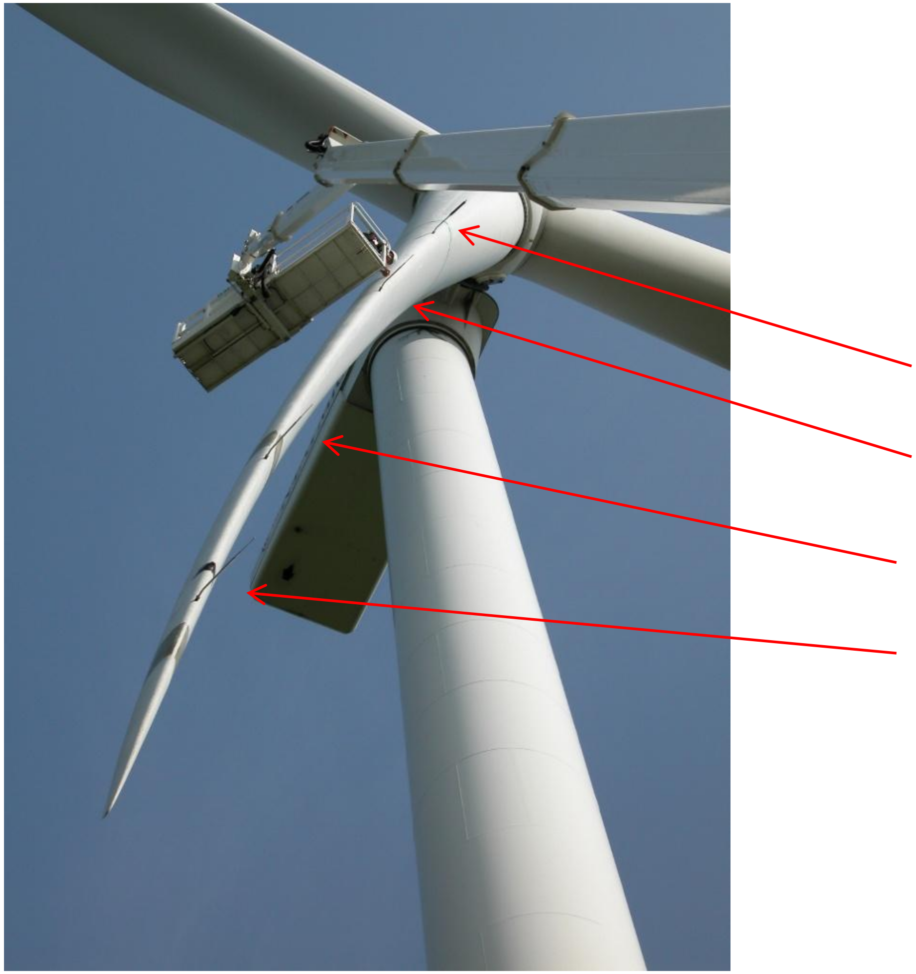
INPUT	OUTPUT
Materials and geometry: - Rubber flap - Flap-blade attachment system - Pressure system	- Test results of rubber material when exposed to lightning direct and indirect effects - Simulation model of the flap correlated with tests results
Manufacturing process	Validated solution for lightning Protection system
INDUFLAP Schedule	PhD project Schedule

Challenges in the implementation of the flap system on MW

Challenges in the implementation of the flap system on a MW turbine

- control sensors
- robustness
- fatigue
- risk of lightning
- ..

Example of 2MW rotor with inflow sensors

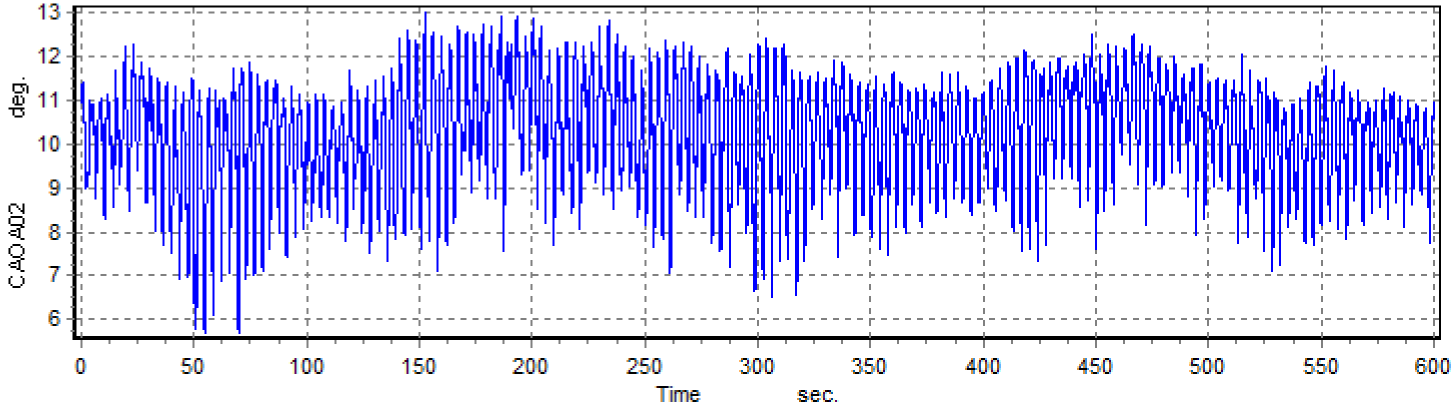


Four 5 hole pitot tubes installed on a NM80 turbine with an 80m rotor

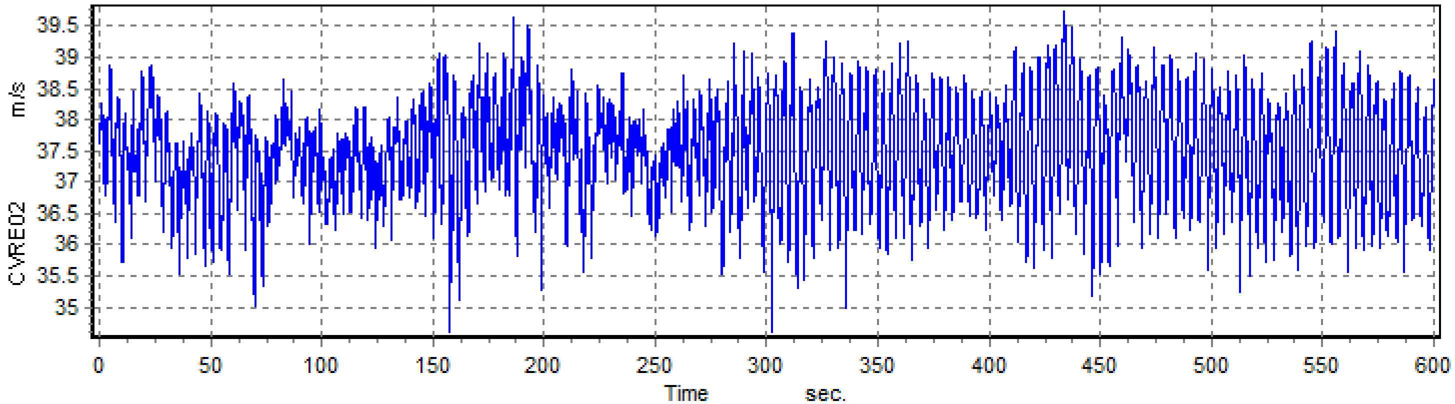
Experiment carried out within the DAN-AERO project from 2007-2010: LM, Vestas, Siemens, DONG Energy and Risø DTU

Example of measured inflow

Inflow angle

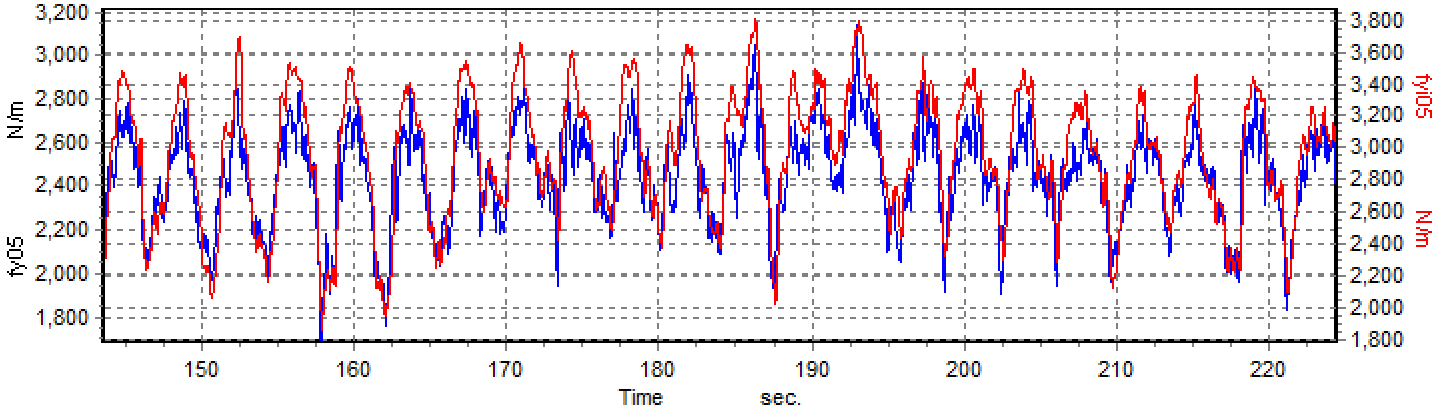


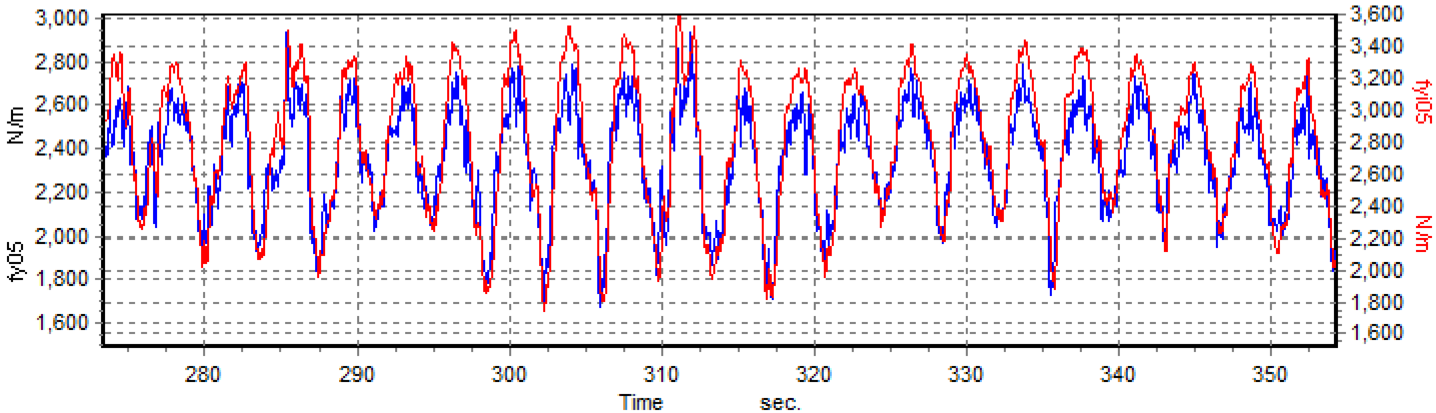
Relative velocity



Derived aerodynamic loading from measured inflow

Blue curve is normal force at radius 20m integrated from pressure taps and red curve is loading derived from inflow measurements





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Outlook

- The new INDUFLAP project with three industrial partners will show if the CRTEF technology can be ported from laboratory to industrial applications
- Rotating tests of 2m flap sections will start in mid 2012 to measure aerodynamic response from surface pressure measurements and to test sensors and control systems
- If the development work continues as expected a CRTEF prototype system will be ready for testing on a MW turbine at the end of the project (end of 2013)

Thank you for your attention!