Adaptive Trailing Edge Flap

Recent development within smart blades

2010 Wind Turbine Blade Workshop
Albuquerque, NM

Aeroelastic Design Program
Wind Energy Division

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Risø DTU
National Laboratory for Sustainable Energy

Foreword

Project activities through 3 research projects since 2003:

10 Scientists, 5 PhD students, 6 Master student

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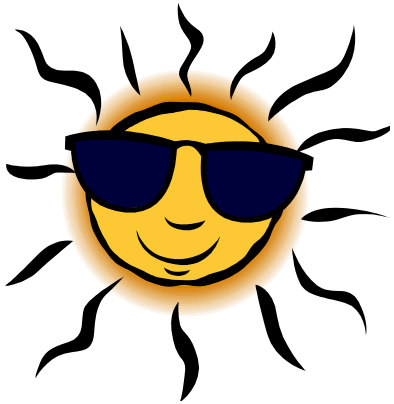
* **Advanced load alleviation for wind turbines using adaptive trailing edge flaps: Sensoring and control**
Andersen, Peter Bjørn
RISØ-PhD--61(EN)

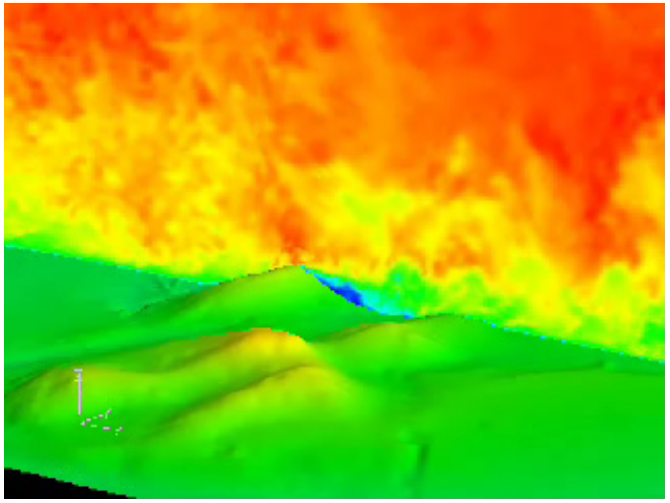


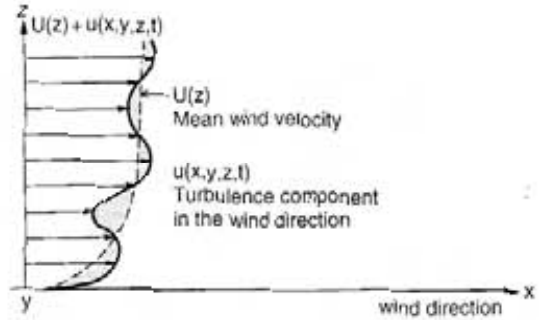
Outline

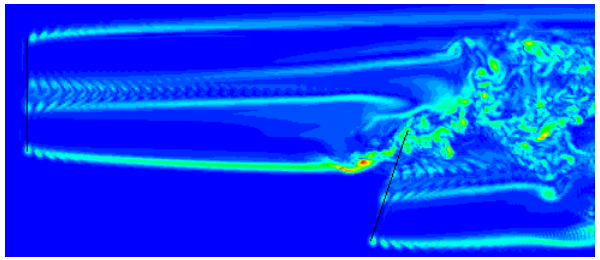
- Introduction:
  - The problem
  - A solution
- Model:
  - In HAWC2
- Validation:
  - CFD comparison
  - Wind Tunnel Tests
- Results: Simulation
  - Test case
  - Stochastic Wind Field
  - Wake Situation
- Results: Stability
- Realization:
  - Sensors
  - Actuators
- First Full scale Test (preliminary)
- Conclusion and future…

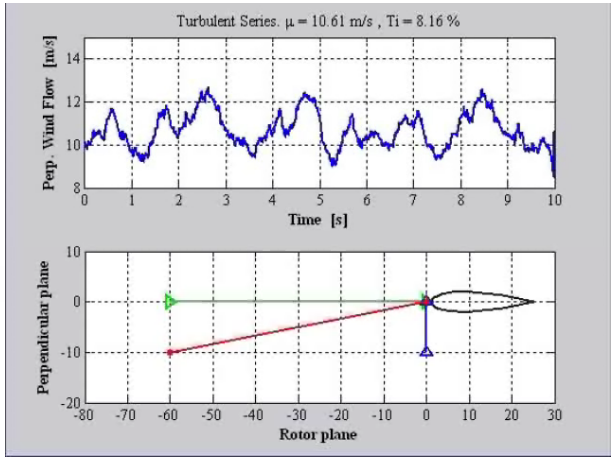
Introduction: the problem

- *What is the problem?*









- Not uniform flow (nor in time, nor in space)
- Variable forcing on elastic structure

  ➔ Dynamic loading, fatigue.

Introduction: a solution?

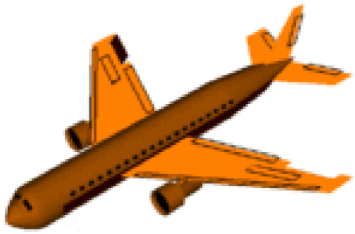
- *Is there any solution?*

- Nature: Kestrel
- Compensates for inflow fluctuations by:

  Adapting geometry of lifting surfaces

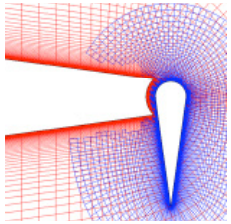
- Airplanes:
- Same solution, control on the lift by modifying geometry of wing:

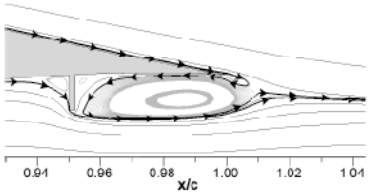
  Trailing Edge Flaps

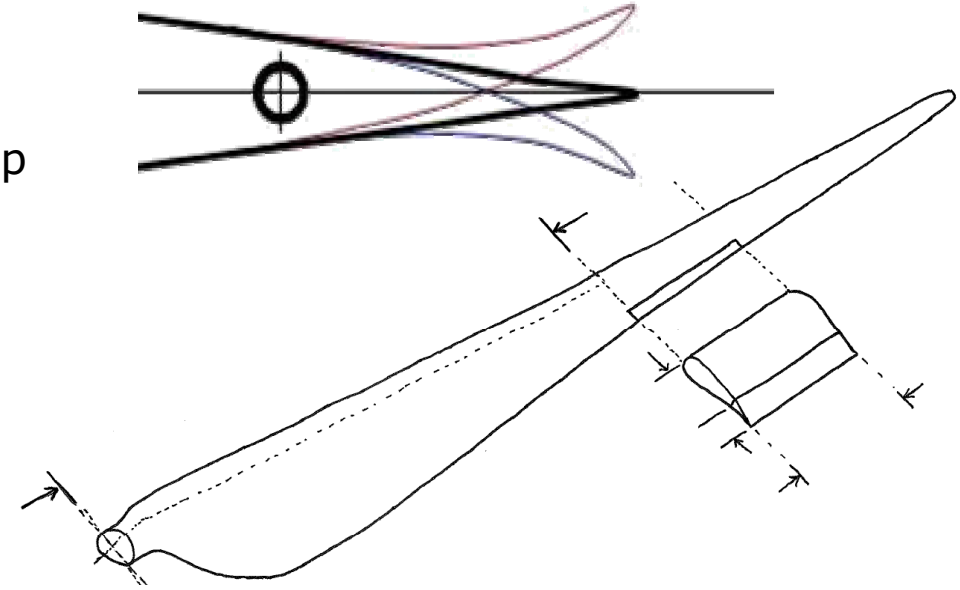


Introduction: a solution?

- *And on Wind Turbine Blades?*
- Try the same:
  Apply Adaptive Trailing Edge Flap
- [Other solutions:]
  Rigid rotating flaps, deploying tabs, etc.





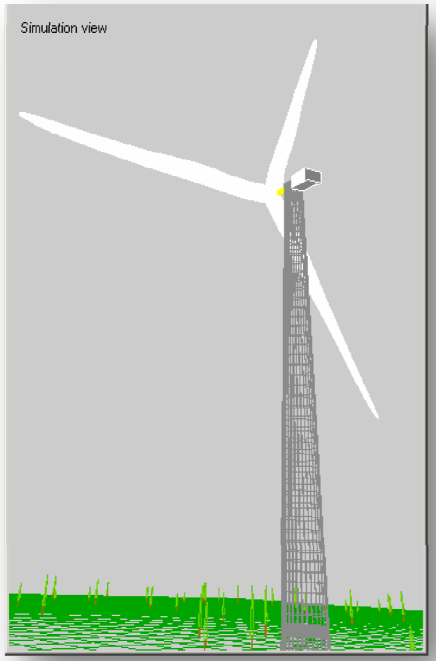


- Same 'kestrel principle':
  - Adapt geometry to compensate fluctuations
  - Control of the loads: local along blade span, faster than pitching

"Adapt to Avoid Fatigue"

How to model it?

- Wind Turbine Model involves 3+1 parts:
  - Aerodynamic
  - Structural
  - Control
  - +1: wind conditions.



- Different approaches available for a smart rotor
- Different degrees of complexity and accuracy

  (CFD, panel methods, vortex lines, FEM,multi-body… etc etc.)

…model in HAWC2:

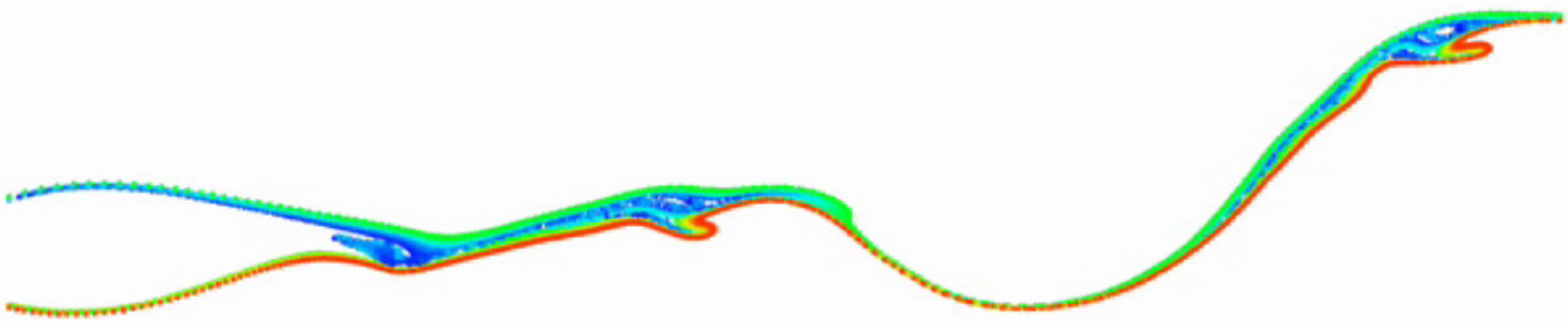
- Enough complex…
  to simulates effect (and benefits?) of ATEF on WT loading
- Enough simple…
  to implement in time marching code

- Aerodynamics in HAWC2:
  - BL type of model, extend for flap
  - Induced velocity: BEM, or Near+Far Wake

Validation: does all this make sense?

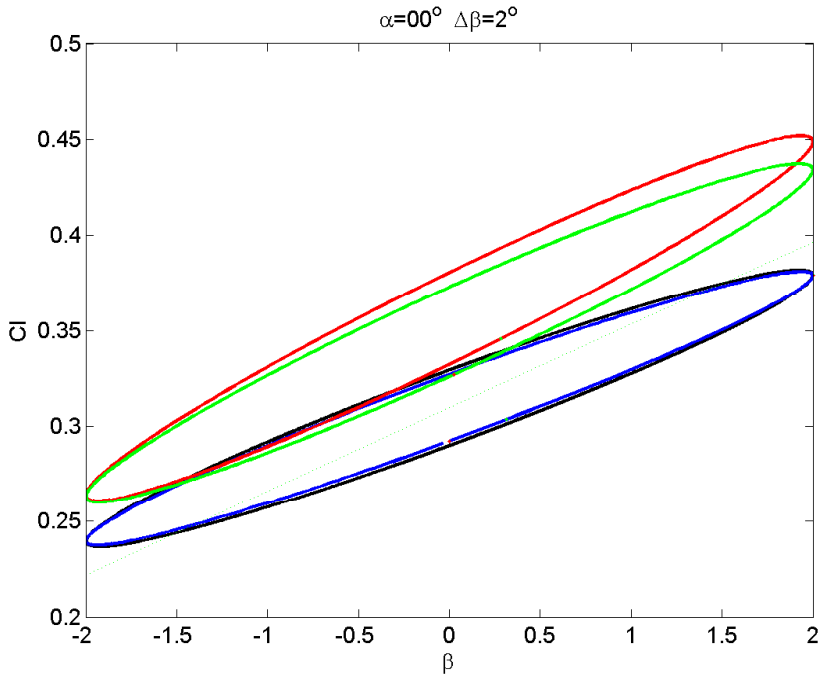
- Validation with…
  - 2D CFD
  - Wind Tunnel Test

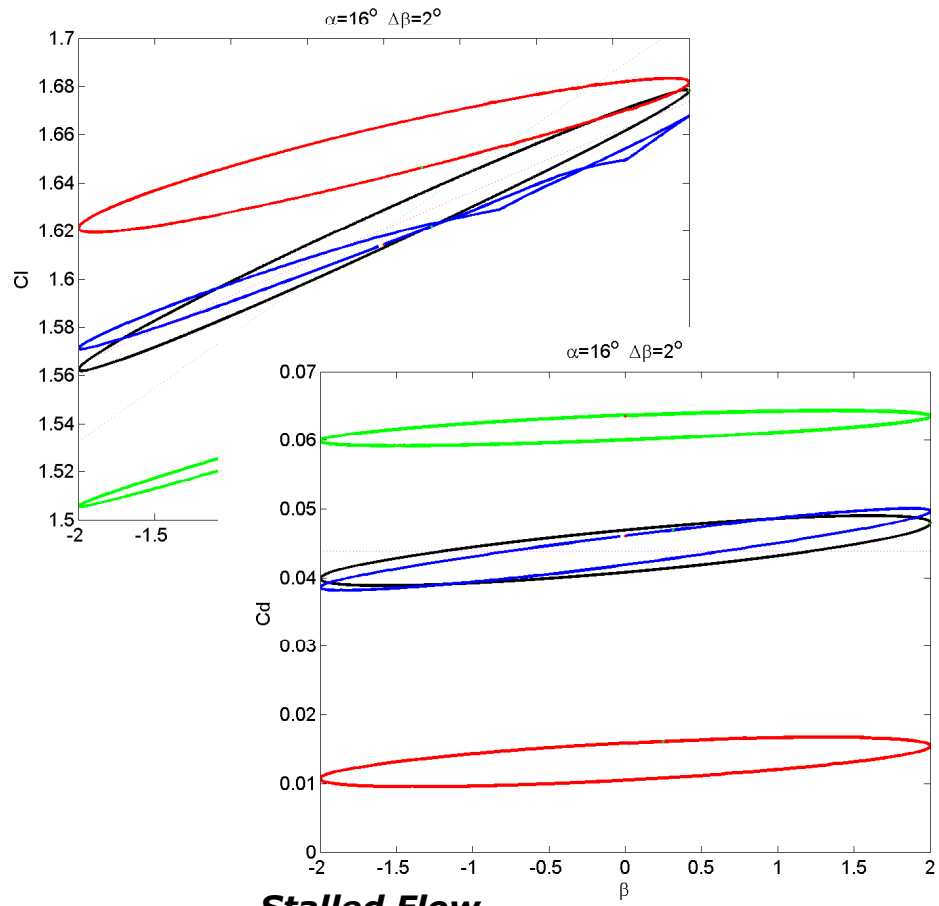
- Validation of…
  - Aerodynamic model (2D)
  - Proof Of Concept



Validation: CFD, aerodynamics

- Validation of 2D aerodynamic model





Attached Flow

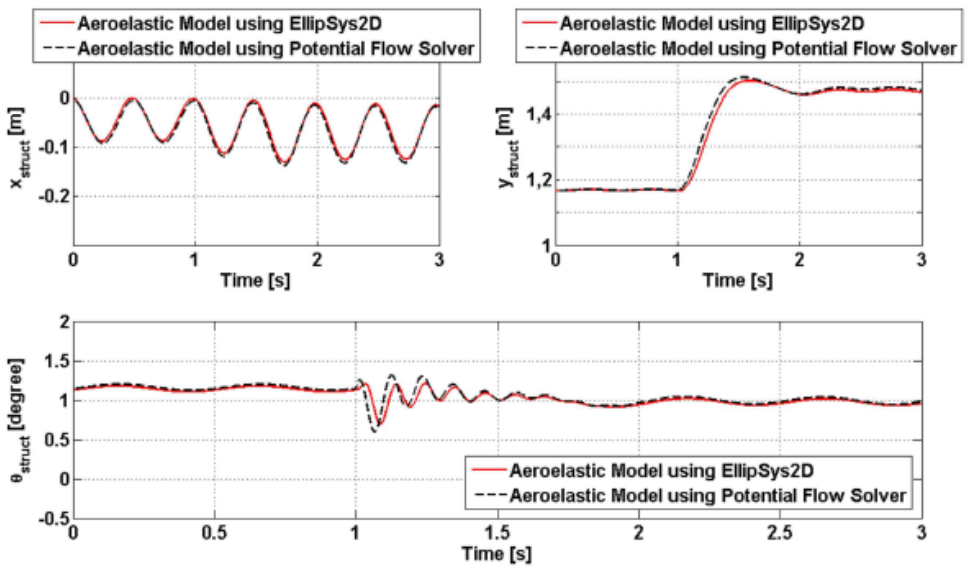
aoa=0° , k=0.1
Black: EllipSys2d
Blue: DynStall
Red: PotTheory, Green: Foil1W
Similar agreement in Cd and Cm

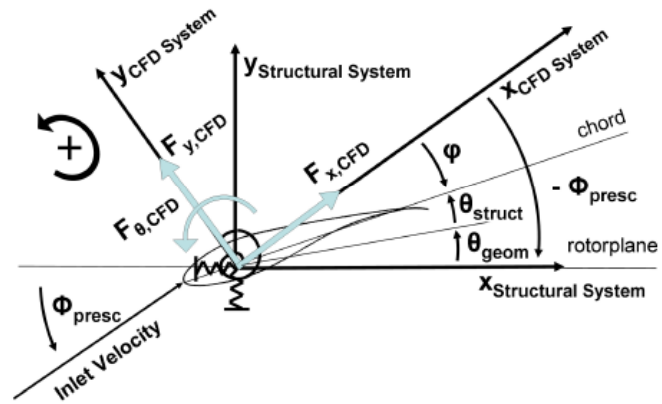
Stalled Flow

aoa=16° , k=0.1
Captures the dynamic, less good agreement due to problems in deriving input from steady curve data (better on Cd)

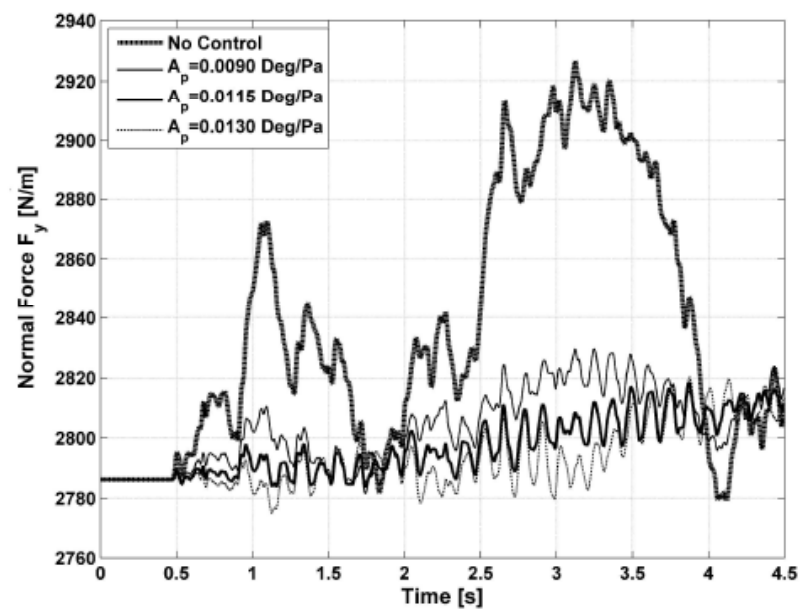
CFD: proof of concept

- 2D CFD coupled with servoelastic model:





- Good agreement of response from 2 models
- Flap control allows for reduction in fluctuations of normal force



Validation: Wind Tunnel

- *Dec 2005:*

Prescribed motion.

Piezo Actuator

- *Jun 2009:*

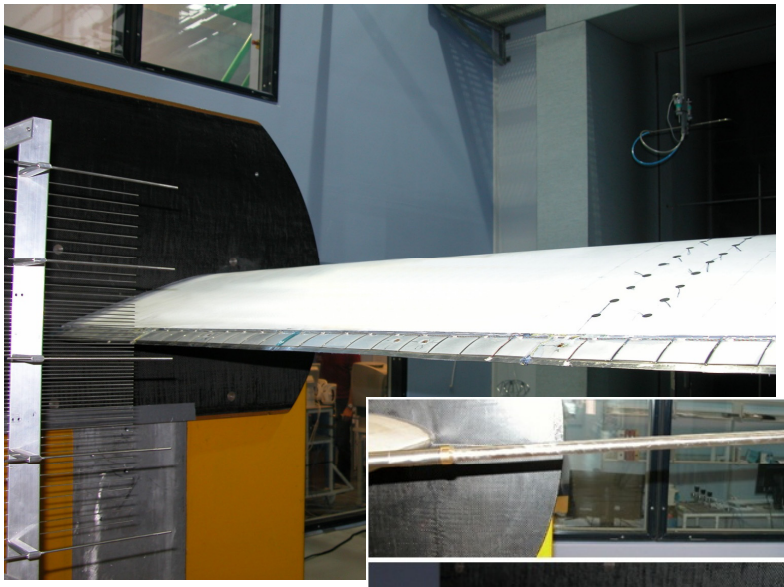
Closed loop, feedback control

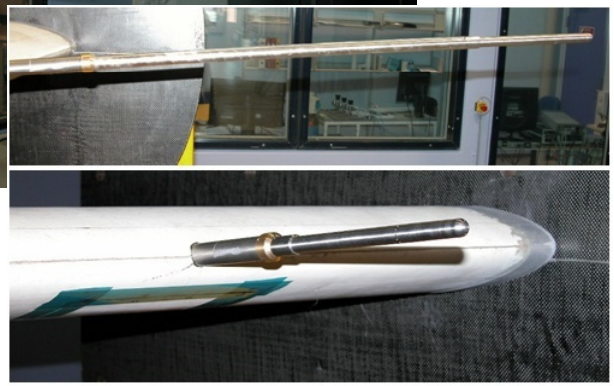
Piezo, Pitot, Dp

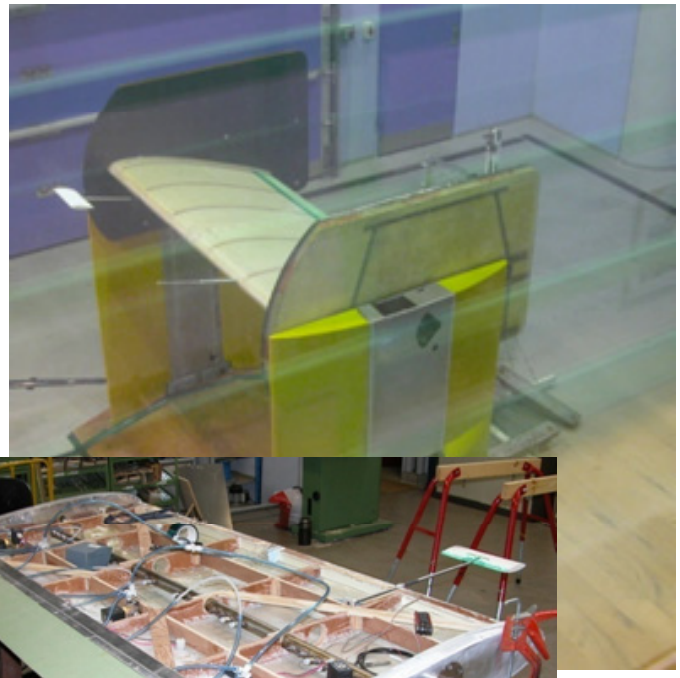
- *Dec 2009:*

Prescribed motion

Rubber TE actuator



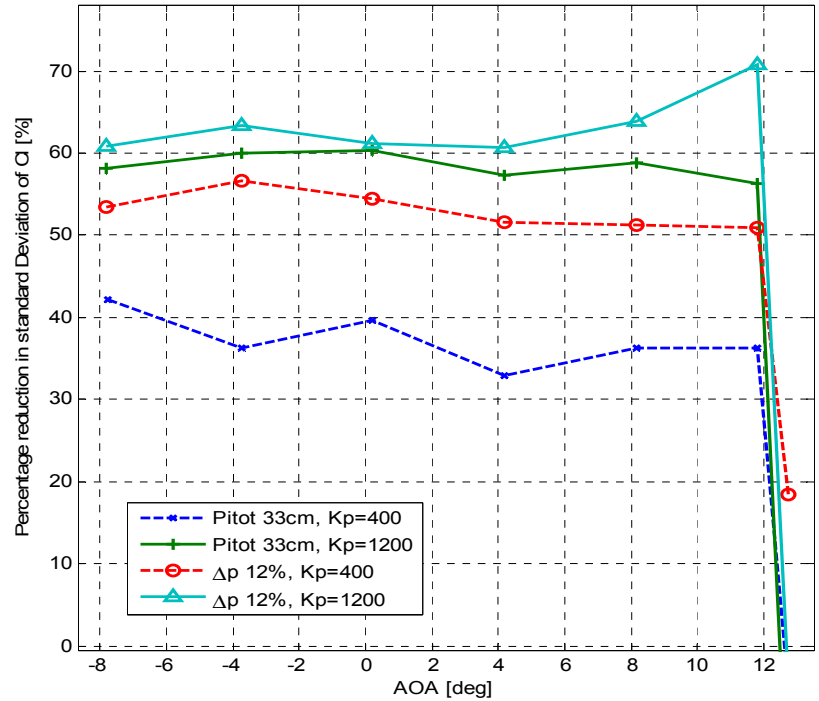


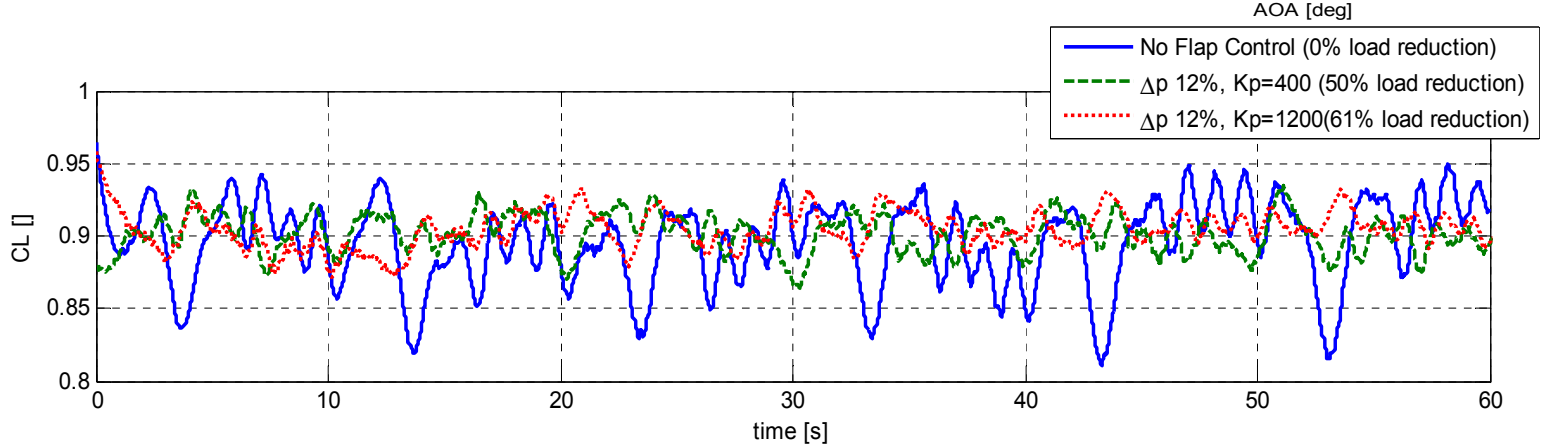


Validation: Wind Tunnel

- Open Loop:
  - Flap can compensate for oscillations in lift force
  - Piezo and Rubber actuators tested
- Closed Loop:
  - Flap control can reduce fluctuation in the lift force
  - Reduction up to 60 % reported

➔ Concept proved





Results: does it do something?

- Simulations on 5 MW NREL reference turbine.
  - Flap sections of 6.3 m (10%)
  - 1, 2, or 3 flap sections
- Wind Conditions:
  - Stochastic Wind: Mann box, according to IEC 61400-1
  - Wake situation: DWM model
- Flap Control, based on:
  - Elastic sensors (SG)
  - Inflow sensors (Pitot)
  - Combination + traditional

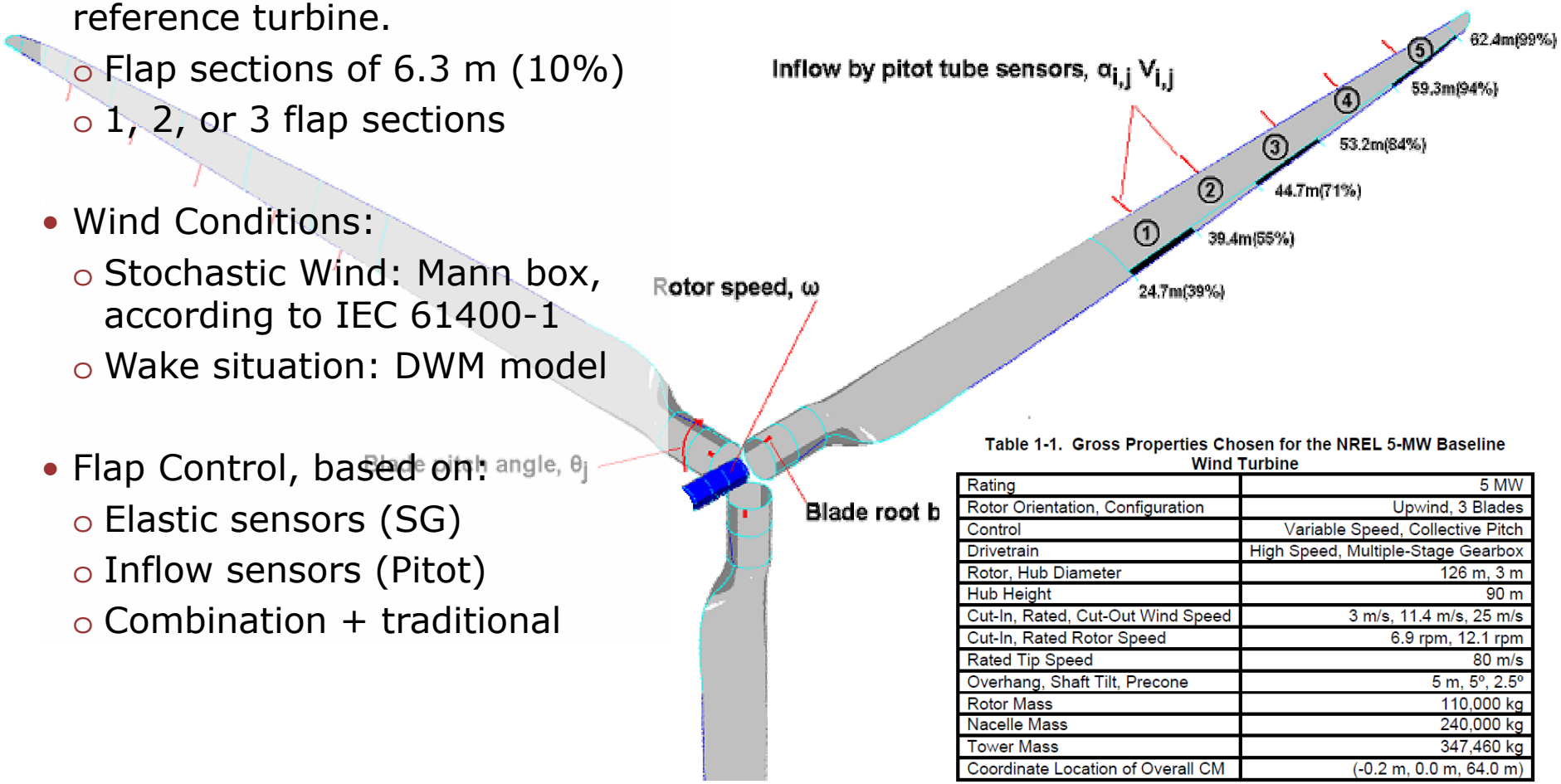
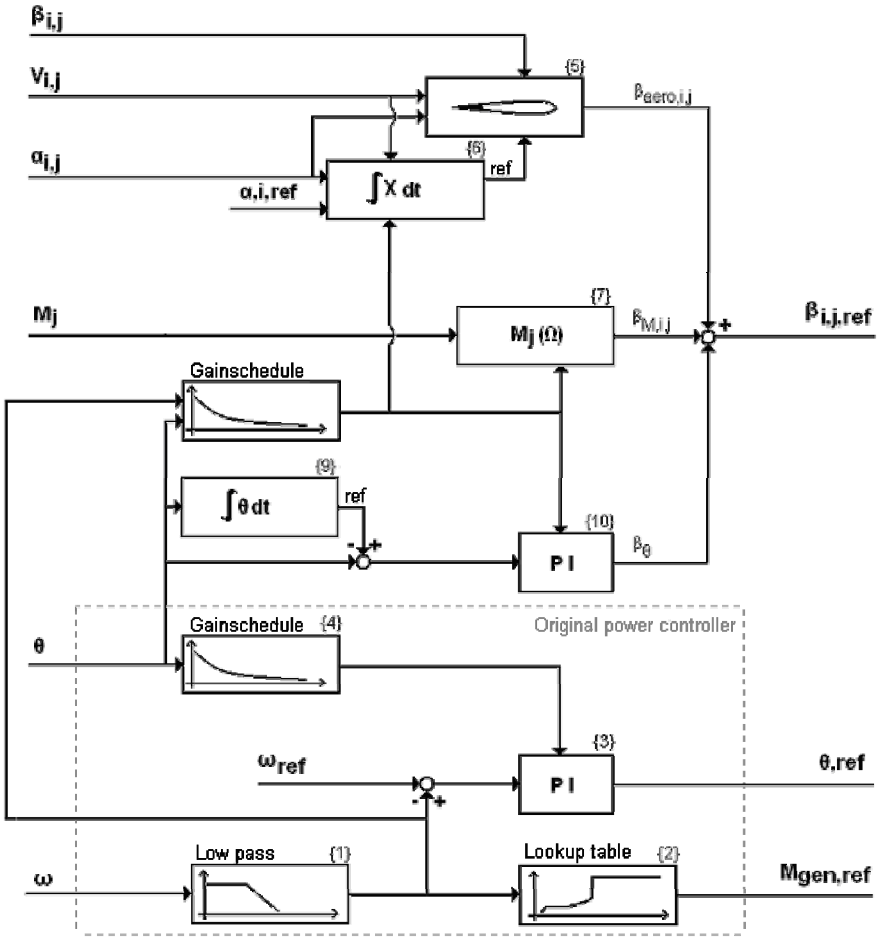


Table 1-1. Gross Properties Chosen for the NREL 5-MW Baseline Wind Turbine

Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5º, 2.5º
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of Overall CM	(-0.2 m, 0.0 m, 64.0 m)

Control Model

- Traditional control of a PRVS turbine, combined to TE flaps control:

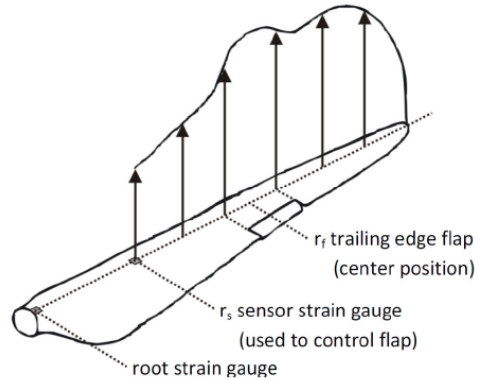


- Blade Pitch, generator torque:
  - Power control
  - Inflow slow variations
- Flap Control:
  - Compensate for faster variations in the inflow

Flap Control:

- Simple PI controllers
- Based on input from:
  - 'Structure' sensors (strain gauges along blade)
  - 'Inflow' sensors (Pitot tube)

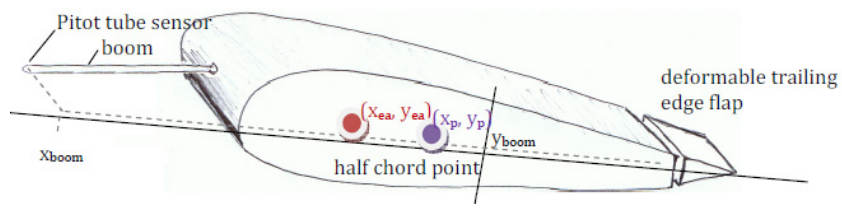
Results: Stochastic Wind



- Control based on structure deformation sensor:

	One flap,6m	Two flaps per blade,12m		Three flaps per blade,19m		
	#1	#1	#2	#1	#2	#3
Mean flap pos r_f [m]	45	34	45	30	45	54
Sensor pos r_s [m]	28	20	28	20	28	36
K_P [deg·KNm^{-1}] / τ [s]	0.044/ 0.05	0.071/ 0.32	0.032/ 0.04	0.060/ 0.35	0.034/ 0.10	0.025/ 0.03
Standard deviation flap deflaction [deg]	4.9	4.2	3.8	3.7	3.4	2.1
Fatigue reduction	25%	34%		37%		

- Control based on in flow sensor:

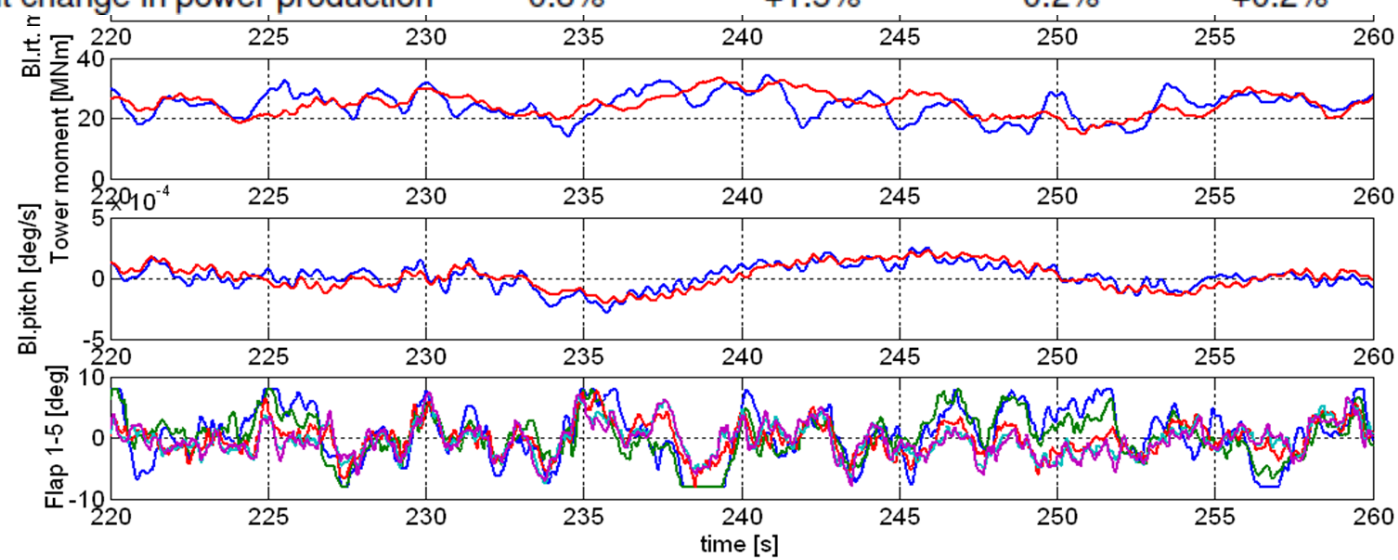


	One flap, 6m	Two flaps per blade, 12m		Three flaps per blade, 19m		
	#1	#1	#2	#1	#2	#3
Pitot tube, flap [m]	44	34	46	30	43	54
K_P [deg·KNm^{-1}] / τ [s]	-6.5/ 0.075	-7.0/ 0.125	-5.0/ 0.075	-7.5/0.125	-4.5/0.075	-2.0/0.050
Fatigue reduction	30%	37%		40%		

Results: Stochastic Wind

- Combination of control sensors:

Reduction in	<7m/s> K_α =0 (Figure 6)	<7m/s> K_α =1 (Figure 6)	<11m/s> (Figure 8)	<18m/s> (Figure 9)
Max blade1, flapwise root moment	10%	6%	15%	24%
Max tower, flowwise root moment	8%	3%	7%	15%
Blade1, flapwise fatigue load reduction	38%	36%	46%	48%
Tower, flowwise fatigue load reduction	33%	30%	20%	33%
Pitch rate, standard deviation	n/a	n/a	10%	18%
Mean power prod. (–loss) without flaps	1375KW	1375KW	4694KW	5291KW
Mean power prod. (–loss) with flaps	1364KW	1395KW	4682KW	5300KW
Percent change in power production	-0.8%	+1.5%	-0.2%	+0.2%



Results: Wake

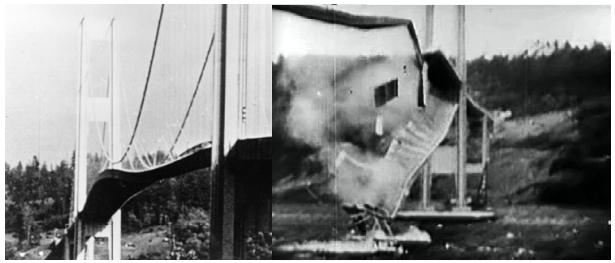
- Single Flap Section (6.3 m), Dynamic Wake Meander model:

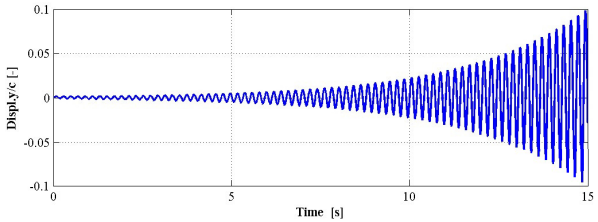
sensor [unit]	material param.	power control only	flap control A	flap control B	flap control C
Blade flapwise root moment [kNm]	10	5974 (0.0%)	2433 (59.3%)	2595 (56.6%)	2278 (61.9%)
Yaw moment [kNm]	4	4968 (0.0%)	2027 (59.2%)	2164 (56.4%)	1732 (65.1%)
Tower flowwise root mom. [kNm]	4	11980 (0.0%)	4745 (60.4%)	5813 (51.5%)	4892 (59.2%)
Mean electrical power [kW]	-	4832 (0.0%)	4789 (-0.9%)	4746 (-1.8%)	4734 (-2.0%)

Results: Stability

Aim:

- Aeroelastic instabilities: Flutter and Divergence
  - No problem on actual WT (2x)
  - What if ATEF modifies stability limits?
- Develop a tool to determine stability limits of a section equipped with ATEF control.

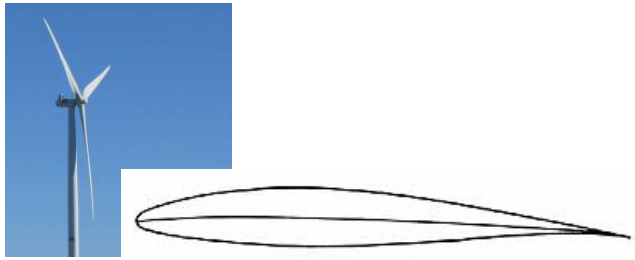


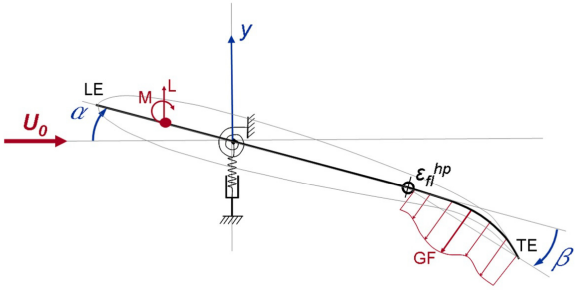


Method:

- Simplified Model:

  2D section, attached flow (potential model), simple controller
- Eigenvalues analysis:
  - Set of Diff.Eq. linearized, matrix formulation
  - Generalized Eigenvalue problem
  - Eigenvalues describe frequency and damping of the system modes





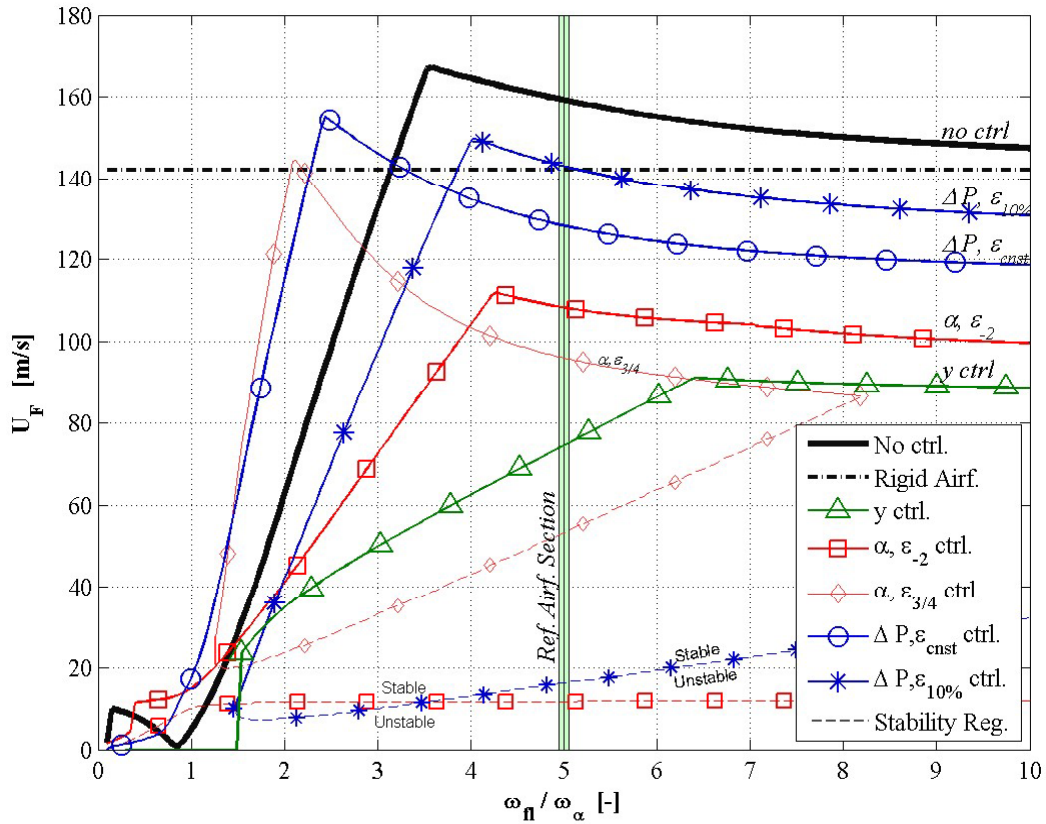
Results: Stability

FLAP AFFECTS STABILITY LIMITS

- Limits lowered by control.
- Not trivial dependence on:
  - Structural proprieties
  - Control algorithm and gain
  - Measurement point
  - Time lag

➢ Good News: High limit for not controlled flap (light, stiff)

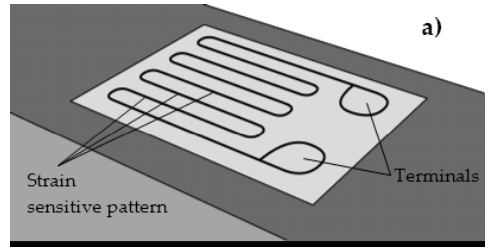
Control stop does not jeopardize stability

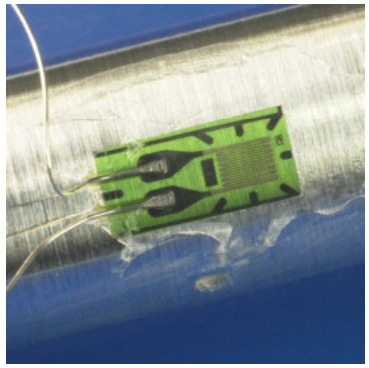


How to make it for real?

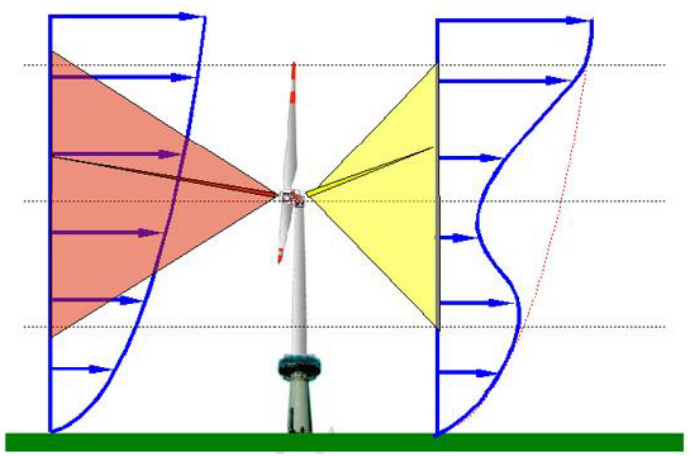
Input Sensors:

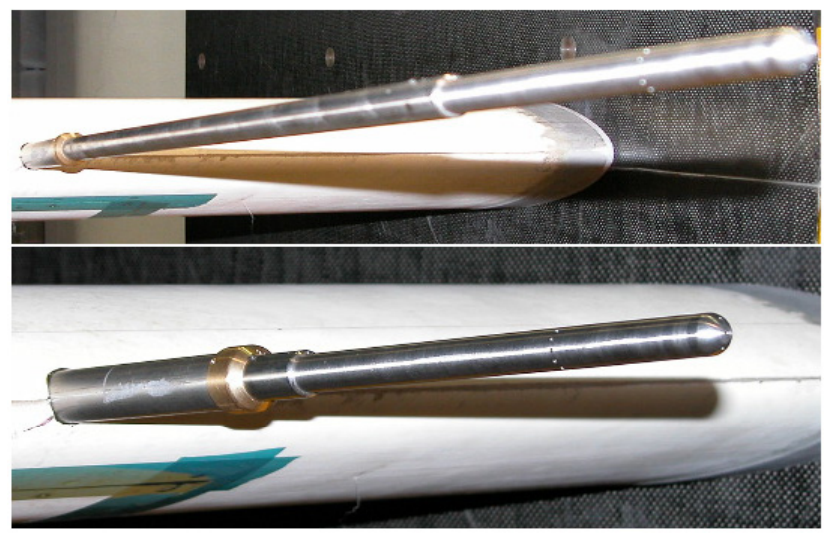
- Structural deformation:
  - Strain gauges along the blade





- Inflow sensor:
  - 5-hole Pitot's tube
  - Pressure difference
  - [Maybe one day…]

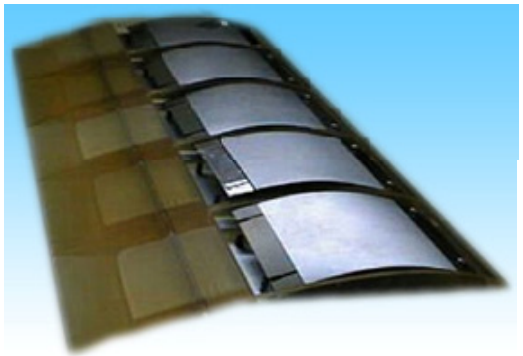


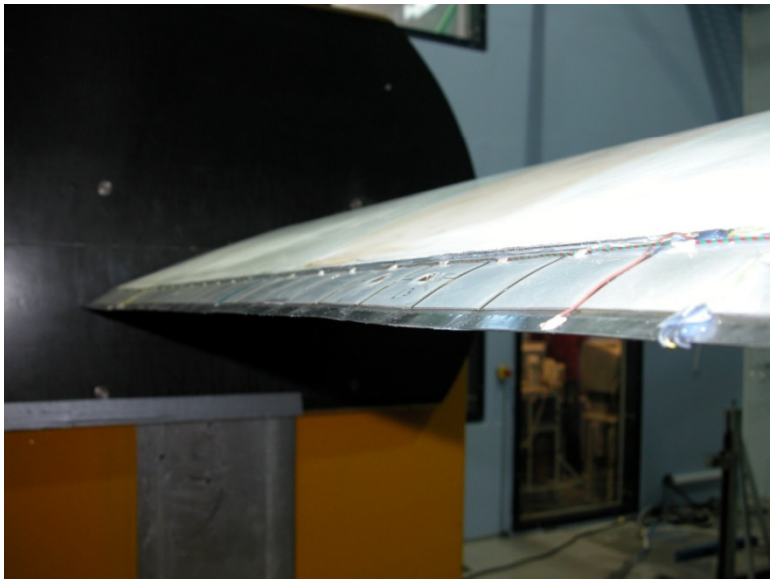


How to make it for real?

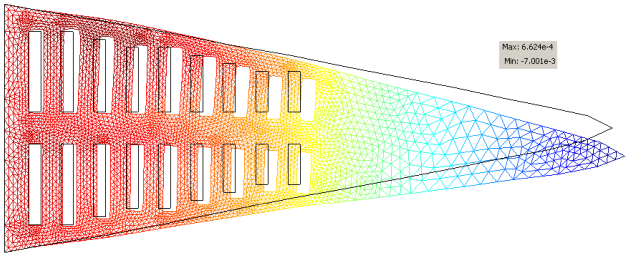
Flap Actuators:

- Piezoelectric plates
  - Continuous deformation shape
  - Fast, stiff, light, etc.
  - But… out of lab? Fragile…



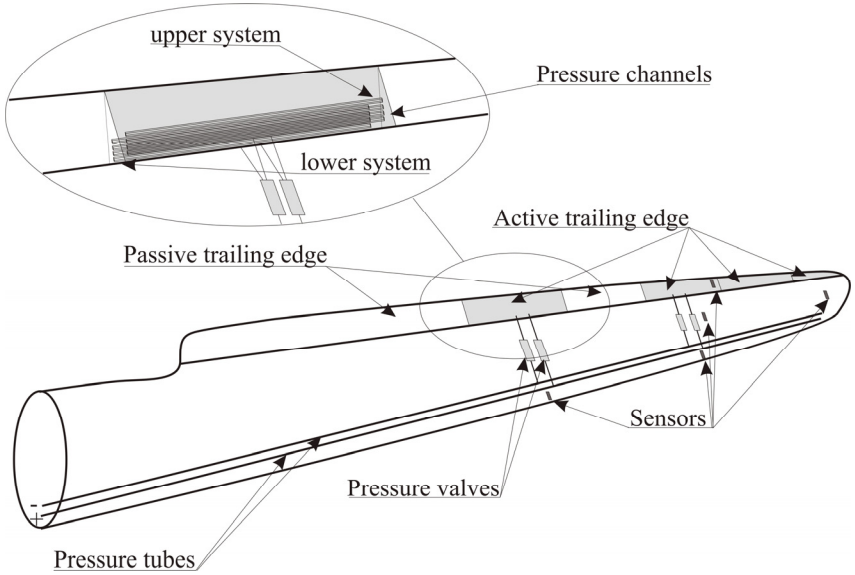


How to make it for real?



Flap Actuators:

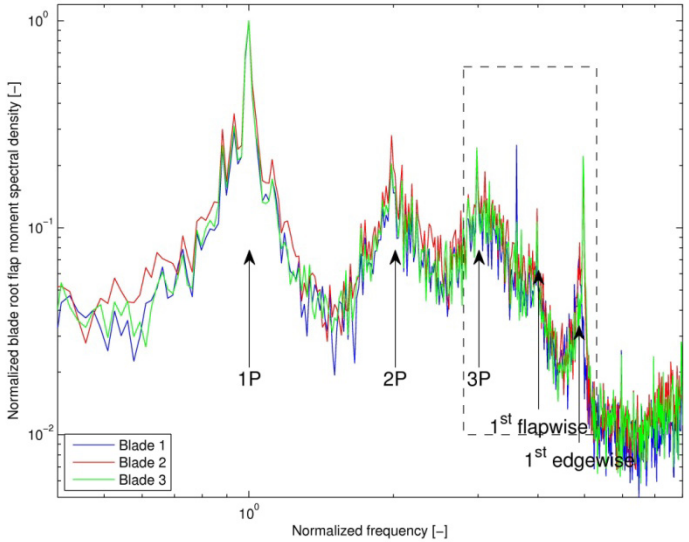
- Rubber Trailing Edge Flap
  - Cont. deformation shape
  - Compressed air through chambers
  - Currently under test…

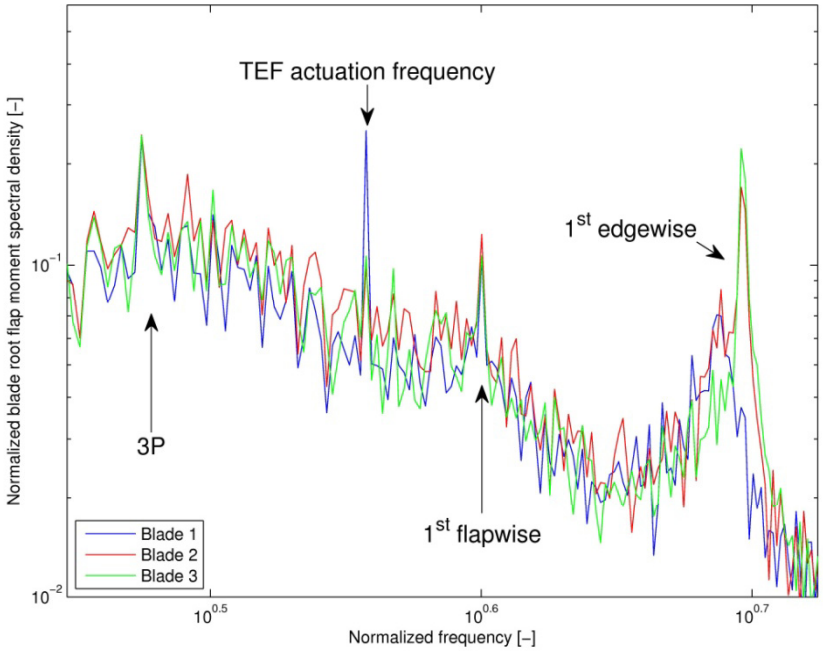


First full scale test (preview)

- …still a lot to do…
- First full scale test campaign:
  - Vestas-V27 (225 kW, 27 m diam.)
  - February 2010 (outside…Denmark…)
- Prescribed flap motion: limited flap deflection, but positive results!
  - Clear effect on Blade Root Moment
  - Measured spectra close to simulated

[*D. Castaignet et al.*; Results from the first full scale wind turbine equipped with trailing edge flaps
28th AIAA Applied Aerodynamics Conference]





Future…

To-do list…

- Full Scale Test:
  - Keep on trying…
  - Different combination of sensors/actuators, controllers, …
- Design investigations:
  - Validate full 3D model vs. CFD
  - More advanced control strategies (MPC, MIMO, Syst.Id., …)
  - New concepts for sensors/actuators (reliability)
  - …

To conclude…

- Simulations have shown very promising results:
  - Fatigue reduction around 45 % for blade root
  - Up to 60 % in a wake situation
- To-do list still long…

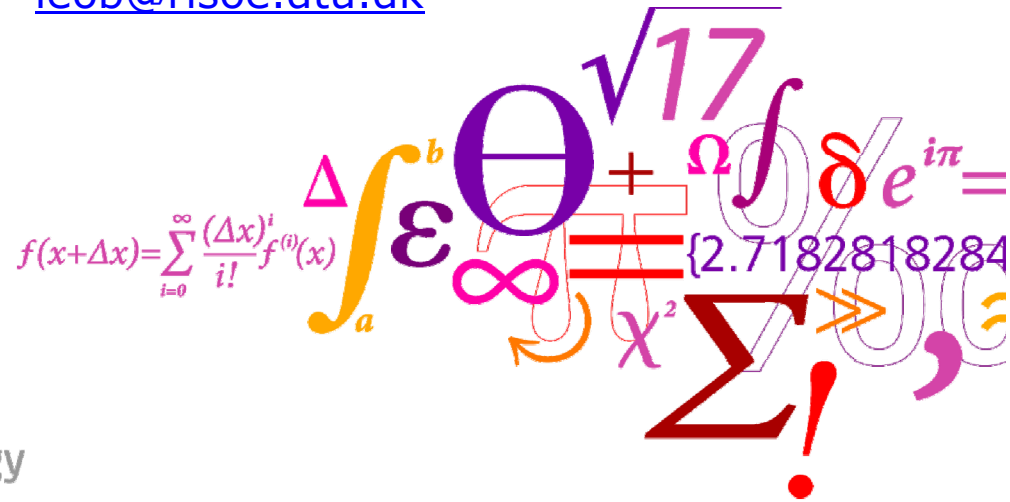
Thank you! Questions, comments…

Adaptive Trailing Edge Flap

Recent development within smart blades

Aeroelastic Design Program
Wind Energy Division

Leonardo Bergami
leob@risoe.dtu.dk



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