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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Wind energy research activities at Risoe National Laboratory

Wind energy research activities at old DTU

DTU Wind
A DTU Institute with around 250 employees
- research on wind energy -
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
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

Andersen, P.B., Henriksen, L., Gaunaa, M., Bak, C., Buhl, T. ”Deformable trailing edge flaps 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


"Development of the CRTEF technology for MW turbines". Advances in Wind Turbine Rotor Blades, 13-15 February, 2012 Swissôtel Bremen
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.


"Development of the CRTEF technology for MW turbines". Advances in Wind Turbine Rotor Blades, 13-15 February, 2012 Swissôtel Bremen
Potential load reductions by flap control
What has been achieved in the past?
- numbers from a recent PhD study?

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

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

"Development of the CRTEF technology for MW turbines". Advances in Wind Turbine Rotor Blades, 13-15 February, 2012 Swissôtel Bremen
What has been achieved in the past? - numbers from a review paper

<table>
<thead>
<tr>
<th>article</th>
<th>$c_f$ [%]</th>
<th>$d r_f / r$ [%]</th>
<th>$\delta$ [±°]</th>
<th>T.I. [%]</th>
<th>shear exp. [-]</th>
<th>$V_{\alpha o}$ [%]</th>
<th>reduction in std of RBM [%]</th>
<th>reduction in DEL [%]</th>
<th>controller</th>
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</thead>
<tbody>
<tr>
<td>Riziotis et al. 2008</td>
<td>10</td>
<td>15-47</td>
<td>6</td>
<td>-</td>
<td>0.2</td>
<td>8, 12, 16</td>
<td>30-35 (range)</td>
<td>-</td>
<td>PID</td>
</tr>
<tr>
<td>Andersen et al. 2008</td>
<td>10</td>
<td>63</td>
<td>8</td>
<td>14-18</td>
<td>0.14</td>
<td>7, 11, 18</td>
<td>-</td>
<td>36.2-47.9</td>
<td>HPF+inflow</td>
</tr>
<tr>
<td>Lackner et al. 2009</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>NTM, ETM</td>
<td>0.2</td>
<td>8, 12, 16, 20</td>
<td>-</td>
<td>5.6-24.6</td>
<td>PID</td>
</tr>
<tr>
<td>Barlas et al. 2009</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>NTM</td>
<td>0.2</td>
<td>8, 11.4, 16</td>
<td>5.7-22.4</td>
<td>-</td>
<td>PID</td>
</tr>
<tr>
<td>Andersen et al. 2009</td>
<td>10</td>
<td>15-30</td>
<td>8</td>
<td>-</td>
<td>11.4</td>
<td>-</td>
<td>-</td>
<td>25-37</td>
<td>HPF</td>
</tr>
<tr>
<td>Resor et al. 2010</td>
<td>10</td>
<td>24</td>
<td>10</td>
<td>6</td>
<td>0.2</td>
<td>15</td>
<td>26-30.9</td>
<td>27-31.3</td>
<td>PD, HPF+notch</td>
</tr>
<tr>
<td>Wilson et al. 2010</td>
<td>10</td>
<td>24</td>
<td>10</td>
<td>6</td>
<td>0.2</td>
<td>15</td>
<td>13.3</td>
<td>15.5</td>
<td>LQR</td>
</tr>
<tr>
<td>Berg et al. 2010</td>
<td>10</td>
<td>25</td>
<td>10</td>
<td>6</td>
<td>0.2</td>
<td>15</td>
<td>8.7-18.1</td>
<td>10.9-17</td>
<td>PD, LQR</td>
</tr>
<tr>
<td>this article</td>
<td>10</td>
<td>18</td>
<td>8</td>
<td>6, NTM</td>
<td>0.2</td>
<td>7, 11.4, 15</td>
<td>10.9-30.7</td>
<td>10.9-27.3</td>
<td>MPC+inflow</td>
</tr>
</tbody>
</table>

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

"Development of the CRTEF technology for MW turbines". Advances in Wind Turbine Rotor Blades, 13-15 February, 2012 Swissôtel Bremen
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

Up to 90% load reduction

"Two-Degree-of-Freedom Active Vibration Control of a Prototyped "Smart" Rotor"
Jan-Willem van Wingerden, 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”
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
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 1 Hz

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Ideal control input

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

Control

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

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

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

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:

\[ F_{Nc} = F_N - f_c V_R^2 \]

Ideal fatt. reduction: 42%

Control – alfa: 35%

Control – alfa+vrel: 40%
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%
Flap amplitude limits the load reduction potential

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Development of the CRTEF technology
Background for the CRTEF development

Promising 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)


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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 autumn 2008 promising 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
Wind tunnel experiment Dec. 2009

airfoil section + flap during instrumentation

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

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Wind tunnel experiment  Dec. 2009

two different inflow sensors
Lift changes integrated from pressure measurements

![Graph showing lift changes over time with pressure measurements and flap settings.]
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

Prototype CRTEF tested in laboratory

Project

End of project

Prototype ready for test on MW turbine

**Participants:**

- DTU Elektro
- DTU AED
- DTU Fiberlab

**Industrial partners:**

- Rehau A/S
- HYDRA tech A/S (AVN Energy A/S)
- 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

"Development of the CRTEF technology for MW turbines". Advances in Wind Turbine Rotor Blades, 13-15 February, 2012 Swissôtel Bremen
Example of COMSOL simulation on a new prototype with chordwise voids
Studies of implementation and integration of flaps in blades

"Development of the CRTEF technology for MW turbines".
Advances in Wind Turbine Rotor Blades,
13-15 February, 2012 Swissôtel Bremen
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

Pressure measurements

Pitch actuator

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The rotating outdoor test rig based on a 100kW turbine platform
# PhD project on lightning

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

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

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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!