Wind Turbine Flap Technology Development – from laboratory to full scale

H Aa Madsen
hama@dtu.dk

In cooperation with

DTU Wind Energy
Department of Wind Energy
Flap or morphing airfoil

Morphing trailing edge counteract disturbances from turbulent inflow

Flaps add a third control option to the traditional rotor speed and pitch control

Wind Turbine control

- Rotor speed
  - aero loading \( f_r(r) \approx (r \Omega)^2 \)

- Pitch
  - aero loading \( f_p(r) \approx k p_{ang} \)

- Flap
  - aero loading \( f_{fl}(r) \approx k_{fl} f_{ang}(r) \)
Ideally flap control can be very efficient and counteract most of the inflow disturbances.

Measure relative velocity and inflow angle (unsteady)

Normal force loading: 

\[ F_N = \frac{1}{2} \rho V_r^2 C_N(\alpha)c \]

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

where \( \overline{\alpha} \) and \( \overline{V_r} \) are exclude band filtered from 0.1 to 1Hz and \( f_c \) is the control signal.

\( K_\alpha \) and \( K_{V_r} \) are constants determined in order to maximize load reduction.

Inflow data from a five hole pitot tube.
But limitations in the real world

- bandwidth of the flap actuation
- amplitude limits
- non-optimal control inputs
- cost of the technology
- robustness
Example of a flap system used in a steady position

The negative flap deflection decreases most extreme loads and reduces blade tip deflection - SWT-4.0-130 turbine

<table>
<thead>
<tr>
<th>Extreme loads</th>
<th>Channel</th>
<th>DLC</th>
<th>Rel. diff. positive flap deflection [%]</th>
<th>DLC</th>
<th>Rel. diff. negative flap deflection [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower bottom bending fore-aft</td>
<td>DLC13_</td>
<td>4.2</td>
<td></td>
<td>DLC13_</td>
<td>-3.1</td>
</tr>
<tr>
<td>Tower bottom bending side-to-side</td>
<td>DLC62_</td>
<td>0.6</td>
<td></td>
<td>DLC62_</td>
<td>0.0</td>
</tr>
<tr>
<td>Tower top bending fore-aft</td>
<td>DLC24_</td>
<td>-2.5</td>
<td></td>
<td>DLC24_</td>
<td>-0.2</td>
</tr>
<tr>
<td>Tower top bending side-to-side</td>
<td>DLC24_</td>
<td>3.1</td>
<td></td>
<td>DLC24_</td>
<td>0.4</td>
</tr>
<tr>
<td>Shaft torsion</td>
<td>DLC13_</td>
<td>1.2</td>
<td></td>
<td>DLC13_</td>
<td>-0.5</td>
</tr>
<tr>
<td>Shaft thrust</td>
<td>DLC13_</td>
<td>3.2</td>
<td></td>
<td>DLC13_</td>
<td>-3.1</td>
</tr>
<tr>
<td>Hub Bending</td>
<td>DLC13_</td>
<td>2.4</td>
<td></td>
<td>DLC13_</td>
<td>-3.1</td>
</tr>
<tr>
<td>Blade root flap (min)</td>
<td>DLC13_</td>
<td>2.9</td>
<td></td>
<td>DLC13_</td>
<td>-2.7</td>
</tr>
<tr>
<td>Blade root flap (max)</td>
<td>DLC62_</td>
<td>-1.3</td>
<td></td>
<td>DLC62_</td>
<td>-0.1</td>
</tr>
<tr>
<td>Blade root edge (min)</td>
<td>DLC13_</td>
<td>-0.2</td>
<td></td>
<td>DLC24_</td>
<td>-1.0</td>
</tr>
<tr>
<td>Blade root edge (max)</td>
<td>DLC13_</td>
<td>-0.2</td>
<td></td>
<td>DLC13_</td>
<td>-2.0</td>
</tr>
<tr>
<td>Blade tip deflection</td>
<td>DLC13_</td>
<td>4.7</td>
<td></td>
<td>DLC13_</td>
<td>-6.1</td>
</tr>
</tbody>
</table>

Table 1: Relative load comparison between a flap with positive and negative deflection with respect to a flap with neutral deflection

Ref. Alejandro 2018
Example of a flap system used in a dynamic control

Case:
- DTU 10MW rotor stretched 5% in radius
- Increase in AEP of 3.4%
- Flap system included to reduce the increase in loads
- 30% of the blade length, starting from the tip, with 10% chordwise length, flap angles range between -15/+15 degrees.

Ref. Barlas 2016
The flap technology
Use flap technology from aircraft?

Too complex

Fig. 3B

Fig. 3C
Strong requirements from the wind turbine industry to the technology

- robust and reliable (25 years lifetime)
- no metal parts
- no electronics
- no mechanical parts
- scalable to large blade sizes (+100m)

piezo electric actuators in wind tunnel exp. 2007
Basic flap design that full-fills these requirements

- a flap in an elastic material
- pneumatically activated
- two main concepts

separate hose
add/on flap

internal voids
full morphing TE
The development stages

- CAD version
- FEM simulations
- Design iterations – FSI based optimization
- Lab model – simplified manufacturing
- Lab testing – performance - fatigue
- Wind tunnel tests (typical leading to new design iteration)
- Lightning testing
- Final prototype manufacturing – co-extrusion
- Testing functionality and performance on an outdoor rotating test rig in atmospheric flow
- Full scale testing
FEM – FSI optimization

• Design variables: voids position/size
• Response: Cl, Cd, safety factor
• Optimization with Multi-Objective Genetic Algorithm (max(Cl), min(Cd), SF≥1.5)

<table>
<thead>
<tr>
<th></th>
<th>DX [mm]</th>
<th>DW [mm]</th>
<th>DH [mm]</th>
<th>delta [deg]</th>
<th>SF [-]</th>
<th>δCl [-]</th>
<th>δ(Cl/Cd) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM</td>
<td>7</td>
<td>3</td>
<td>9</td>
<td>7.9</td>
<td>2.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FSI</td>
<td>6.94</td>
<td>2.72</td>
<td>8.98</td>
<td>6.9</td>
<td>3.1</td>
<td>0.22</td>
<td>-12%</td>
</tr>
</tbody>
</table>
Lab models – simplified testing
Wind tunnel tests – CFD computations

Sandia Blade Workshop 2018
Helge Aagaard Madsen DTU, Denmark
Final prototype manufacturing - co-extrusion

- Allows designs with optimal combination of soft and stiff material
- Solve gluing problems with Santoprene as the surface can be covered with a layer suited for gluing
One flap system tested for lightning damage

The Santoprene flap material showed a higher withstand voltage in tracking tests than GFRP
Sketch of the rotating test rig

- Intended to close the gap between wind tunnel and full scale testing

Test rig based on a 100 kW turbine. Rotation of a 10m long boom with an airfoil section of 2x1m

Pressure measurements

Test rig based on a 100 kW turbine. Rotation of a 10m long boom with an airfoil section of 2x1m
Blade section for rotating test rig

2x1 m blade section + end caps

Blade section mounted on the 10m long boom in the workshop - instrumentation

Pressure taps in chordwise and spanwise direction
Flap testing on the rotating rig
Example of measured flap performance on the rotating rig

Flap design from the Innwind.EU project

<table>
<thead>
<tr>
<th>Case</th>
<th>$+\Delta C_L$</th>
<th>$-\Delta C_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD</td>
<td>+0.21</td>
<td>-0.25</td>
</tr>
<tr>
<td>Wind tunnel</td>
<td>+0.18</td>
<td>-0.24</td>
</tr>
<tr>
<td>Rotating rig</td>
<td>+0.18</td>
<td>-0.20</td>
</tr>
</tbody>
</table>

Poul La Cour wind tunnel - DTU (!)
Full-scale tests

• Testing on a multi-MW turbine in Denmark since Dec 2017
• Test and validation under real weather conditions
• Testing planned until end of 2018
• For further information: http://www.induflap.dk/
Conclusions

- A complete development line for flap technology from prototype to full scale has been developed in cooperation with two industrial partners.

- A considerable amount of testing in wind tunnels and on a rotating rig has been conducted.

- Full scale testing of first prototypes initiated and will contribute with new important information about a possible commercialization of the technology.
Thank you for your attention