On the potential load reduction on wind turbines by flap control using measurements of local inflow to the blades

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ON THE POTENTIAL LOAD REDUCTION ON WIND TURBINES BY FLAP CONTROL USING MEASUREMENTS OF LOCAL INFLOW TO THE BLADES

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Outline

- Background/motivation
- Approach used in the study
- Results
- Summary
Potential load reductions by flap control?
Why using trailing edge flaps?

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.


Presentation at XXIII ICTAM
19-24 August 2012, Beijing, China
What has been achieved in the past?

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

<table>
<thead>
<tr>
<th>article</th>
<th>( c_f ) [%]</th>
<th>( \Delta r_f / r ) [%]</th>
<th>( \delta ) [(\pm^\circ)]</th>
<th>T.I. [%]</th>
<th>shear exp. [-]</th>
<th>( V_{\alpha} ) [%]</th>
<th>reduction in std of RBM [%]</th>
<th>reduction in DEL [%]</th>
<th>controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riziots 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>
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<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>
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<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
What are the main parameters that constrain the load reduction potentials?

- controller
- sensor input
- actuation time constants
- limits on size of flaps
- limits on actuation amplitude
- limits on flap angle velocity
Approach

We assume:

- ideal controller
- ideal flow sensor input

What load alleviation can then be achieved?

Influence of:

- flap amplitude
- flap angle velocity
- flow sensor separation
- actuation time constants
An investigation on maximum load reduction potential using inflow sensor

Aeroelastic simulations on the 5MW reference wind turbine

- constant rpm
- 8m/s turbulent inflow
- both a flexible and stiff structural model simulated
The maximum load reduction potential

The flapwise moment low pass filtered at different cut off frequencies

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The maximum 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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Load reduction potential – what can be achieved?

- the maximum load alleviation potential is found by numerical filtering
- can we achieve something like this with flap control if we have the ideal control signals?
- what would it require of the flap characteristics, e.g. by trying to alleviate the dynamic loads between 0.1 and 1Hz

The maximum load reductions for 0.1-1Hz are:

- m=3  63%
- m=10  48%
Ideal control signals – inflow data in the form of **inflow angle** and **relative velocity**

Inflow data from a five hole pitot tube

Inflow data from a small sensor airfoil

Wind tunnel test of flaps and inflow sensors
Control by inflow signals – aero normal force loading at one radial position considered

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

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

where \( \bar{\alpha} \) and \( \bar{V}_r \) 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.

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Control by inflow signals – aero force loading at one radial position considered

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

where \( F_{Nc} \) is the controlled normal force

Flap control: \( f_c \) Flap aerodynamics + flap actuator dynamics \( F_{Nc} \)

The flap control is numerically simulated by the aeroelastic code HAWC2 where the flap aerodynamics and flap actuator dynamics are modelled.
Load reduction of normal force at radius 50 m – 10% TI

Ideal control – fatigue reductions

\[ m=3 \]

Maximum: 50.8%
Alfa control: 43.1%
  percentage of max.: 84.9%
Alfa+vrel control: 49.0%
  percentage of max.: 96.5%

\[ m=12 \]

Maximum: 42.7%
Alfa control: 39.1%
  percentage of max.: 91.7%
Alfa+vrel control: 41.5%
  percentage of max.: 97.4%
Load reduction of normal force at radius 50 m – 10% TI

Flap control – fatigue reductions

m=3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>50.8%</td>
</tr>
<tr>
<td>Flap – alfa</td>
<td>41.2%</td>
</tr>
<tr>
<td>percentage of max.</td>
<td>81.2%</td>
</tr>
<tr>
<td>Flap – alfa-vrel</td>
<td>44.9%</td>
</tr>
<tr>
<td>percentage of max.</td>
<td>92.3%</td>
</tr>
</tbody>
</table>

m=12

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>42.7%</td>
</tr>
<tr>
<td>Flap – alfa</td>
<td>37.9%</td>
</tr>
<tr>
<td>percentage of max.</td>
<td>88.9%</td>
</tr>
<tr>
<td>Flap – alfa-vrel</td>
<td>41.5%</td>
</tr>
<tr>
<td>percentage of max.</td>
<td>97.4%</td>
</tr>
</tbody>
</table>
Load reduction of normal force at radius 50 m – 10% TI

Raw normal force

Flap controlled normal force

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Flap amplitude saturates considerably at TI=20%
Load reduction of normal force at radius 50 m – influence of turbulence

Flap angle constrained to: +/- 5 deg.
Influence of frequency band on flap actuation speed – ti=10%

Band 0.1-1.0 Hz

Std. dev. = 3.52 deg/s

Fatt red. = 42.9%

Band 0.1-2.0 Hz

Std. dev. = 6.93 deg/s

Fatt red. = 57.9%
Influence of separation of flow sensor position from flap position
FN at radius 50 m controlled from an inflow sensor at different inboard separation distances
FN at radius 50 m controlled from an inflow sensor at different inboard separation distances

Bandwidth on inflow signal should be adjusted to avoid non-correlated control signals for increasing distance to flow sensor.
Influence of actuator time constant
Influence of actuator time constant

![Diagram showing the influence of flap actuator time constant on relative fatigue load alleviation for different rotor diameters and bandwidths.](Image)

- **126m Diameter rotor**
- **80m Diameter rotor**

**Figure Legend:**
- **RELATIVE FATIGUE LOAD ALLEVIAION m=10 [-]**
- **TIME CONSTANT [s]**
- **BW 0.1-0.32Hz**
- **BW 0.1-0.36Hz**
- **BW 0.1-0.61Hz**
- **BW 0.1-0.60Hz**
- **BW 0.1-0.90Hz**
- **BW 0.1-1.20Hz**
Preliminary analysis of measurements on an 80m diameter rotor
Example of 2MW rotor with inflow sensors

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

Aero normal forces measured at four radial positions by pressure holes

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

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NM80 turbine – measured inflow at $R=30m$

alpha

relative velocity

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19-24 August 2012, Beijing, China
NM80 turbine – control of FN at R=30m from inflow measurement

Fatt. Red. 35.6%
NM80 turbine – control of FN at R=30m from inflow measurement

NM80, FN AT RADIUS 30m, Sept. 1st, 10:00

Fatt. Red. 35.6%
Conclusions (1of2) on use of inflow data for load alleviation control

- for the optimal positioned inflow sensor more than 90% of the absolute achievable load reduction can be obtained by a flap

- information on the relative velocity variations contributes with about 10% to the load reduction

- flap aerodynamics (aerodynamic response delay) reduce only minorly the ideal load reduction potential
Conclusions (2 of 2) on use of inflow data for load alleviation control

- one inflow sensor could be used for a 5-10m long flap, bandwidth 0.1-1Hz

- for bigger separation distance the control signal bandwidth should be reduced

- rotor size has considerable influence on reduction of load alleviation due to flap actuator time constant
Thank you for your attention!