Wind Turbines: Innovative Concepts

Henriksen, Lars Christian

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Wind Turbines: Innovative Concepts

Lars Christian Henriksen, DTU Wind Energy

Wind Energy Theme Day for Industry: Control

Outline

• Model-based control
  – Basics: State estimation, LQ/MPC control
  – Control Design Model
    • Example: Dynamic Inflow
• Trailing edge flaps
  – The concept
  – Combining trailing edge flaps and IPC
• LiDAR enhanced control
  – Load alleviation
  – Power optimization
• Passive vs. active control
  – Bend-twist couplings
• Floating wind turbines
  – Using an Extended Kalman Filter for state estimation
Model-based Control
Model-based Control

Control Methods applied on Wind Turbines

• Classic Control Methods
  – PI Control
  – Interconnected PI Controllers and Bandpass Filters
  – ...

• Modern Control Methods
  – Linear Quadratic Control (LQ)
  – Linear Parameter Varying Control (LPV)
  – Robust Control ($H_2, H_\infty$)
  – Model Predictive Control (MPC)
  – Misc. Nonlinear Control Methods
  – ...

• Individual Pitch
  – Coleman/Multi-blade Coordinate Transformation
  – Decoupling of control loops
  – ...

• Trailing edge flaps
  – Decoupling of control loops
  – ...

• LiDAR
  – Feed forward of measure wind
  – ...

Hi 13, Herning 2013, September 4th
Model-based Control
Control Theory in Time Discrete Form

State space model
\[
\begin{align*}
    x(t_{k+1}) &= f(x(t_k), u(t_k)) + w(t_k) \\
    y(t_k) &= g(x(t_k), u(t_k)) + v(t_k)
\end{align*}
\]

State estimator
\[
\begin{align*}
    x(t_k | t_k) &= x(t_k | t_{k-1}) + L \cdot [y(t_k) - g(x(t_k | t_{k-1}), u(t_k))] \\
    x(t_{k+1} | t_k) &= f(x(t_k | t_k), u(t_k))
\end{align*}
\]

State space controller
\[
\begin{align*}
    u(t_k) &= K \cdot x(t_k | t_k) \\
    or \quad u(t_k) &= K \cdot x(t_k | t_{k-1}) \\
    or \quad u(t_k) &= k(x(t_k | t_{k-1})) \\
    or \quad ...
\end{align*}
\]

Disturbances: \( w \) and \( v \)
(Turbulent Wind, Wave forces, ...)
Model-based Control
Control Design Model

• The control design model is a set of linear/nonlinear ordinary differential equations (in state space form), which are “adequately” describing the system to be controlled.

  – “Adequately” means including phenomena of interest (tower DOFs, blade DOFs etc.) in a frequency range of interest.

• The control design model can be obtained from first-principles modeling, system identification (black box), a combination of the two (gray box).

  – A first-principles model of a wind turbine can be obtained from aero-elastic software codes such as Bladed, FAST, HAWCStab2 etc.
Model-based Control
Control Design Model

- Bode plots – From collective blade pitch to generator speed

8 m/s

16 m/s
Model-based Control
Dynamic Inflow
Trailing Edge Flaps
Trailing Edge Flaps

The CRTEF Development

Comsol 2D analyses
two different inflow sensors
Trailing Edge Flaps
Comparison of measurements and model
Trailing Edge Flaps

Test rig

Test rig based on a 100 kW turbine.
Rotation of a 10m long tube with an airfoil section of about 2x1m
Trailing Edge Flaps
Simulation Test Case

• Reference NREL 5 MW turbine

• Adaptive Trailing Edge Flaps
  – All flaps on one blade moved as one

• Sensors:
  – Shaft sp., Blade root b.mom, Tower top acc.

• Simulations with HAWC2
  – Multibody dynamics, includes torsion
  – Unsteady BEM aerodynamics

• IEC conditions: class A. Iref:0.16 (wsp: 18 m/s)

• Focus on blade load alleviation

<table>
<thead>
<tr>
<th>Reference Wind Turbine</th>
<th>Flap Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rat. Power</td>
<td>Chordwise ext. 10%</td>
</tr>
<tr>
<td>Num.Blades</td>
<td>Deflect. limits $\pm 10^\circ$</td>
</tr>
<tr>
<td>Rotor Diam.</td>
<td>Max. $\Delta Cl$ $-0.45 \sim +0.41$</td>
</tr>
<tr>
<td>Blade length</td>
<td>Spanwise length 12.3 m (20% blade length)</td>
</tr>
<tr>
<td>Rat. Rot.Sp.</td>
<td>Spanwise loc. from 47.7 m to 60.0 m span</td>
</tr>
<tr>
<td>Hub height</td>
<td>Max. $\Delta Mx.Bl.Rt$ approx. $\pm 1100$ kNm</td>
</tr>
</tbody>
</table>
Trailing Edge Flaps

Combined IPC and Trailing Edge Flap Control

\[ \Delta \text{DEL Mx.Bl.Rt} [-] \]
LiDAR Enhanced Control
LiDAR Enhanced Control
Types and objectives

• Load alleviation
  – Collective pitch control (CPC)
  – Individual pitch control (IPC)

• Power optimization
  – Tracking optimal operation point
  – Reducing yaw misalignment

• Nacelle mounted (mounted on top of nacelle)

• Spinner/hub mounted

• Blade mounted (instead of pitot-tubes)
LiDAR Enhanced Control
Uncertainties and Limitations

- LiDAR uncertainties
  - Validity of Taylors hypothesis of frozen turbulence
  - Volume average of wind speed measurements
  - Projection error
  - Measurement availability and system reliability
LiDAR Enhanced Control
Collective Pitch Control

- D. Schlipf et al., 2012.
  - Experimental results shows that fatigue loads of CART2 turbine can lowered by introducing LiDAR based feed-forward collective pitch control
- E. Bossanyi et al., 2012

Figure 11: Lifetime fatigue load reductions
LiDAR Enhanced Control
Individual Pitch Control

- K. A. Kragh et al., 2013
  - LiDAR based feed-forward IPC is mainly beneficial in situations with rapid, small scale variations (e.g. changing wind shear).
  - Very sensitive to uncertainties relating to the inflow estimation
Passive vs. Active Control
Passive vs. Active Control
Overview

• Passive control methods
  – Swept blades
  – Bend-twist couplings

• Active control methods
  – Individual pitch control
  – Trailing edge flap control

Figure 2.1: Torsion of a traditional design (left) and bend-twist coupled design (right) wind turbine blade sections
Passive vs. Active Control

Issues

• Many aero-elastic tools need further development to handle complex beam models.

• Can the blades be fabricated such that they behave as predicted by the aero-elastic tools.

• Further development of control methods is needed.

• Developed control methods should be adopted by industry.
Floating Wind Turbines
Floating Wind Turbines
The Hywind Concept
Floating Wind Turbines
Simulations of the Hywind Concept (I)

Wind turbine states
• 1 or 2 tower fore-aft DOF
• 1 or 2 tower side-side DOF
• 2 blade edge-wise DOF pr. blade
• 2 blade flap-wise DOF pr. Blade
• 1 induced wind speed state pr. blade

Disturbance states
• 1 wind speed (2nd order) pr. blade
• 1 fore-aft hydrodynamic force (2nd order)
• 1 side-side hydrodynamic force (2nd order)

Sensors used by the EKF
• Pitch angles of each blade
• Electro magnetic generator torque
• Generator power
• Generator speed
• Rotor speed
• Tower top fore-aft acceleration
• Tower top side-side acceleration
• Flap-wise blade root bending moment at each blade
• Edge-wise blade root bending moment at each blade
Floating Wind Turbines
Simulations of the Hywind Concept (II)

Col. pitch ref. to tower top fore-aft at 8 m/s

Magnitude [dB]

Phase [deg]

Frequency [Hz]
Floating Wind Turbines
Simulations of the Hywind Concept (III)
Floating Wind Turbines
The WindFloat Concept

Levelized Cost of Energy (€*/MWh) evolution per number of built platforms
Industrial/academic Cooperation
Industrial/academic Cooperation

- Foundations for offshore wind turbines (incl. floating concepts)
- Trailing edge flaps
- LiDARs
- Pitch gears
- Drive train gears
- Aerodynamic blade design
- Structural blade design

- Materials research both composites and alloys/metals
- Wind Recourse Assessments

- Measurement campaigns for wind turbines

- High altitude wind energy converters (Kites and lighter than air devices)
Conclusions

• Good mathematical models of systems and components are required both for control design purposes but also for evaluation of performance/behavior.

• Many innovative concepts have been and will be tested and developed, some will mature for commercial success and some will be forgotten, only to be presented as innovations a decade later.

• Cost-of-energy (COE) is ultimately the main driver determining whether or not an innovation will reach a commercial state.

• Academic cooperation is good way to test some of the innovative ideas before spending to much time and money on the idea.
Thank you for your attention!