Field Testing of Feedforward Collective Pitch Control on the CART2 Using a Nacelle-Based Lidar Scanner

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Why should you control a wind turbine with lidar?

- wind is a disturbance
- knowing the disturbance, control can be improved
- used in daily life, e.g. bicycle
- for wind turbines several possibilities

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<th>Benefits</th>
<th>Potential</th>
<th>Complexity</th>
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<td>less loads</td>
<td>+ +</td>
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<td>Direct Speed Control</td>
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<td>Nonlinear Model Predictive Control</td>
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<tr>
<td></td>
<td>less loads</td>
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<td>less loads</td>
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Test the most promising!
Content

- Test Environment
- Controller Design
- Preparation
- Correlation Study
- Results
- Evaluation
- Conclusions and Outlook
Test Environment

scanning lidar on the CART2

CART2
\( D = 42 \, \text{m} \)
\( P = 600 \, \text{kW} \)

commercial lidar on the CART3
[AI AA2013]

met mast
control engineers

National Wind Technology Center
Boulder, Colorado, USA
from March to August 2012

mirror with 2 DOF
Controller Design
Feedforward Controller

Control Goal
minimizing rotor speed variation

Feedforward Controller
- static pitch curve
- prediction time $\tau$

Advantages
- simple update
- guaranteed stability
- 1 design parameter $\tau$
- few model information
Controller Design
Simulated Extreme Loads

- FAST CART2
- perfect lidar measurement
  - only small preview necessary to compensate the pitch actuator
  - reduction overspeed from 2% to 0.02%
  - “side effect”: less loads

But not realistic, because
- wind is much more complex disturbance
- wind cannot be measured perfectly
Controller Design
Feedforward Controller + Adaptive Filter

Control Goal
minimizing rotor speed variation

Feedforward Controller
- static pitch curve
- prediction time $\tau$

Adaptive Filter
- fitted filter $\approx G_{RL}$
- cutoff at maximum coherent wavenumber

Diagram:
- $v_0 L$ input
- $G_{RL}$ filter
- $\theta_{FF}$ output
- $\Omega_{rated}$ input
- $\Omega$ output
- $\hat{k}$ wavenumber
- $\tau$ time
Controller Design
Feedforward Controller + Adaptive Filter + Reconstruction + Timing

Reconstruction
- assuming perfect alignment
- combination to one rotor effective wind speed $v_{0L}$

Timing
- assuming Frozen Turbulence
- considering filter time delay
- buffering remaining time

= Adaptive Feedforward Controller
- depends on mean wind speed
- adjusted by $\tau$ and $\hat{k}$
Preparation

- installation with crane
- real time application
- integration in the control system via Modbus

- customize trajectory with model [ISARS2012]
  - best correlation:
    - circle 6 points
    - \( r = 0.25D \)
    - \( x = 2D \)
Correlation Study
Estimation Rotor Effective Wind Speed from Turbine Data

simple nonlinear estimator:

\[ J \dot{\Omega} = M_a - M_{LSS} \]

\[ \frac{1}{2} \rho \pi R^2 c_p(\lambda, \theta) v_0^3 / \Omega \]

\[ \Omega R / v_0 \]

\[ \nabla \text{lidar better correlated to the turbine than the met mast} \]
Correlation Study
Adjusting the Adaptive Controller - Timing

- timing adjusted by cross correlation $\tau = -0.6s$
- Frozen Turbulence seems to be mostly a good hypothesis
Correlation Study
Adjusting the Adaptive Controller - Filter

- maximum coherent wavenumber mostly detected at \( \hat{k} = 0.06 \text{ rad/m} \)
- but sometimes worse – why?
Correlation Study
Blade Impact and Hard Target Problem

- blade impact not really an issue due to the fast spinning turbine
  - points removed by CNR threshold
- hard targets due to guy wires/met mast
  - cutoff the Doppler spectra
Results
Time Domain

smooth activation

some improvement!

low wind speed
Results

Frequency Domain

data divided in blocks of 32 s

- similar wind distribution
- reduction in standard deviation of the generator speed of 30% at low frequencies
- but increase of 30% before solving the hard target problem
- similar behavior for the tower base bending moment and other loads
- in total only 15 min due to low wind conditions and technical problems
Evaluation - Could we have done it better?

Hybrid Simulations
- feeding $v_0$ into FAST
- using original lidar data and original controller
- brute force optimization (81 x 5 min simulations) comparing to feedback only
  - used parameters close to optimal values
- retuned feedback controller
  - filter design seems to be independent from feedback
  - more load reduction possible
  - higher prediction time benefits load reduction
Conclusions

- first proof of concept on a small turbine: spectra show expected behavior!
- correlation can be used to design a filter to avoid wrong pitch action
- adaptive filter depending on the mean wind speed and current correlation needed
- feedback controller should be retuned to get more load reduction
Outlook

- future campaigns
  - other CART control campaign
  - onshore wind turbine of the MW class
  - offshore wind turbine at alpha ventus (LIDAR II project)

- investigation for floating wind turbines
Thanks for you attention!

Acknowledgement
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