Wind turbine control applications of turbine-mounted LIDAR

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An independent study

- Much recent interest in LIDAR for wind turbine control
- Some dramatic claims of e.g. increased energy capture
- Potential for reduced loads
- Need for an independent and objective study:
  - Co-funded by GL-GH and two leading LIDAR suppliers
  - Completed Summer 2012

Two key objectives:
- To evaluate the likely benefits of adding LIDAR to the wind turbine controller
- To provide advice to LIDAR manufacturers about the characteristics of LIDAR systems which are most likely to be of value for this application
Project outline

- Develop enhanced simulation modelling capability, covering many LIDAR types
- Develop algorithms for processing the raw LIDAR signals
- Initial screening of many LIDAR configurations by testing their ability to estimate rotor-averaged quantities (wind speed, direction and shear gradients)
- Develop simple control algorithms to make use of a few selected configurations to improve the wind turbine control action
- Evaluate the performance of the LIDAR-assisted controllers using detailed loading simulations carried out in accordance with the IEC Edition 3 standard.
Enhanced simulation modelling capability

- Along-wind decorrelation: abandoning Taylor’s frozen turbulence hypothesis
  - Paper presented at EWEA 2012
  - Avoids ‘cheating’ in simulations

- Many different LIDAR types …
LIDAR types modelled

- CW LIDAR with various focal distances and $\alpha$ values
- Pulsed LIDAR with various numbers of simultaneous focal distances (up to 10)
- Various sampling rates
- Single staring beam
- 2, 3, 4, 6 or 8 fixed beams (pulsed only)
- Simultaneous or sequential switching of focal distances
- Single circular scanning beam with various angles between beam and centreline, and various numbers of samples per scan
- Single beam performing rosette or Lissajous scan
- Nacelle mounted, spinner or blade mounted
Processing the raw LIDAR signals

• LIDAR measures component along the beam-line only ($V_{LOS}$)
• Useful to measure at many points in rotor swept area
• Many possible algorithms to extract rotor-average values from these measurements:
  • Longitudinal wind speed ($U$)
  • Wind direction ($\theta$)
  • Vertical and horizontal shear gradients ($U_Z, U_Y$)
• Least-squares algorithm chosen: assumes uniform $U$, $\theta$, $U_Z$, $U_Y$ and that $\theta$ varies more slowly than $U_Y$
Initial screening of LIDAR configurations

- 10-minute simulation
- 13 m/s with IEC class 1A turbulence
- Superimposed sinusoidal direction transient: $\pm 15^\circ$ over 10 minutes to exercise the direction estimation
- Compared LIDAR estimate against true rotor-averaged quantities
Initial screening: examples

Longitudinal wind speed

Vertical shear gradient

Horizontal shear gradient

Direction
Initial screening: conclusions

- Both CW and pulsed systems can give good results
- Need good coverage of swept area: at least 10 points in 1 second
- Trade-off between no. of points and time taken to scan them all
- No advantage of complex scans over circular scan
- Large beam angle to centreline is better for direction, worse for wind speed & shear; a single configuration won’t be the best for everything
- Sharp focus is not always advantageous
- Spinner mounting is as good as nacelle mounting: can correct for azimuth & tilt, and no blade blockage
- Blade mounting also works well (one example at 70% radius)
- Easy to get good estimate of longitudinal wind speed
- Vertical shear: not bad, assuming mean upflow is known
- Horizontal shear and direction: get reasonable separation if direction is assumed slowly-varying.
Possibilities with LIDAR-assisted control

- **Improved energy capture due to better yaw tracking?**
  - Probably not much – but very useful for wind vane calibration!
  - Yaw control is usually slow (yaw motor duty, gyroscopic loads, etc.)
  - Pay attention to convention yaw tracking strategies first

- **Improved energy capture due to better Cp tracking?**
  - Tiny improvement, outweighed by large power & torque variations

- **Reduced extreme loads due to anticipation of extreme gusts?**
  - Promising but difficult to assess

- **Reduced fatigue loads due to anticipation of approaching wind field?**
  - Improved collective pitch control yields easy benefits
  - More marginal for individual pitch control

Reduced loads implies a potential for re-optimisation of turbine design
→ Improved cost-effectiveness for future designs
Collective pitch control: Very simple feed-forward implementation

LIDAR-based feed-forward control action → Modification to control action

LIDAR measurements → Wind field estimation algorithms

Feedback controller → Bladed simulation (or real turbine)

- Measured generator speed, tower top acceleration, etc.

Other measured signals → Measured generator speed
Improved collective pitch control with LIDAR

- Immediate improvement in speed regulation
- Take the benefit by reducing control gains
  - Calmer pitch action
  - Lower loads (especially tower bending moments)
Improved collective pitch control with LIDAR

- Re-optimised PI with LIDAR (red line) achieved similar speed control to baseline controller but with lower PI gains
- Pitch movements are reduced
- The pitch controller anticipates the increases in wind speed
- The pitch movements start earlier and so have smaller peaks
Improved collective pitch control with LIDAR

- Reduced pitch movements result in reduction in thrust variation
- Thrust related loads on turbine are reduced, for example: tower base bending moment.
Improved collective pitch control with LIDAR

Even very simple methods achieve significant reduction in thrust-related fatigue loads
- 20% reduction in above-rated wind speeds
- 14% lifetime fatigue load reduction, e.g. tower base bending moment
Improved collective pitch control with LIDAR

Extreme load reduction is much harder to assess:

- Extreme gusts not realistic – and how do they convect and evolve?
- LIDAR must be working at moment of extreme load
  - Affected by meteorological conditions? (Fog, precipitation, lack of aerosols)
- Extreme gusts may not be design drivers

Now more emphasis on extreme turbulence:

- DLC1.1: indicates reduction in extreme tower base overturning moment:
**Improved IPC with LIDAR?**

- LIDAR estimates the vertical & horizontal shear
- Very simple strategy → some reduction of asymmetrical loads (without needing load sensors)
- Not as effective than using load sensors, but more sophisticated strategies would be possible.

![Graph showing decrease in loads or increase in pitch travel (%) for different components: Blade root My moment (steel), Blade root My moment (GRP), Shaft Mz moment (steel), Shaft My moment (steel), Tower top nod moment (steel), Tower top yaw moment (steel). The graph compares Conventional IPC, LIDAR IPC, and Both together.](image-url)
Improved $C_P$-tracking with LIDAR?

😊 Rotor speed tracks wind speed better

 '{$\frown}$ Needs huge power/torque swings to accelerate/decelerate rotor

😃 Tiny fraction of % increase in power production – not worth it!

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Graph showing:
- RPM (No Lidar)
- RPM (Lidar)
- Time [s]
- Rotator average wind speed, m/s

Graph showing:
- Electrical power [MW]
- Time [s]
Improved yaw tracking with LIDAR?

- Probably not much – but could be a very useful commissioning tool for wind vane calibration! (Calibration required as a function of operating point.)
- Yaw control has to be slow (yaw motor duty, gyroscopic loads, etc.)
- Pay more attention to convention yaw tracking strategies first: should not be losing more than 0.5 – 1% of energy compared to ‘ideal’ continuous yawing

10-minute simulation (but really depends on low-frequency variations which are site-dependent)
Conclusions

- Enhanced LIDAR modelling capabilities in *Bladed*
- LIDAR can reduce loads significantly, even with *very simple* control algorithms
- Collective pitch control enhancement: 14% lifetime tower fatigue reduction
- Extreme load reduction, with caveats
- IPC also possible
- $C_p$-tracking and yaw control: benefits much less clear (but LIDAR could certainly be a useful commissioning tool, e.g. for wind vane calibration)
- Both pulsed and CW LIDAR are suitable if configured appropriately
- Need at least ~10 points in swept area, sampled every second, to give a few seconds of look-ahead time
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