Overview of Recent Experiments in Wind Farm Control using Scaled Models in a Boundary Layer Wind Tunnel

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WESE Workshop, Pamplona, Spain, 2–3 October 2019
Outline

Scaled wind turbine testing at TUM

Wake deflection control

Experimental results
The Role of Wind Tunnel Testing

Wind tunnel testing:
– Cons:
  • Usually impossible to exactly match all relevant physics due to scaling
+ Pros:
  • Better knowledge/control of conditions/errors/disturbances
  • Due to scaling, time runs faster in the wind tunnel
  • Relatively low cost compared to full scale testing

Contributions of this presentation:
• Wind farm control:
  – What is the effect of model accuracy on WFC performance? Do we need highly accurate models or is a rough one good enough?
  – What are the effects of control parameters (e.g. uncertainty level, actuation frequency/filtering)?
• Model adaption/learning from SCADA data: are we learning correctly?
The Politecnico di Milano Wind Tunnel

- Turn-table
- Turbulence (boundary layer) generators
- Complex terrain modeling
- 16 fans (1.5MW)

Courtesy Dept. Mech. Eng. POLIMI
G1 – Generic Scaled Wind Turbine for Wind Farm Control Applications

- Aerodynamic covers
- Torque meter
- 12 channel slip-ring
- Torque generator
- Optical encoder for azimuth readings
- Shaft strain gauges and signal conditioning board
- Yaw actuator, housed in hollow tower
- Yaw brake
- Pitch actuator housed in blade root
- Pitch actuator control units
- Yaw optical encoder
- Load cell @ tower base
- Optical encoder for azimuth readings
TUM Scaled Wind Farm Facility

Wind farm super-controller

6 G1s (up to 9)

WT controllers
Earlier Experiences in Wake Deflection Wind Farm Control

From 2016: constant mean wind direction, turbulent & sheared flow

Wake visualization with DTU scanning LiDARs:

Without wind farm control

With wind farm control

Unwaked wind turbines

Laterally deflected wakes

Yawing in the right direction triggered by wake-state observer based on rotor loads
First ever closed-loop demonstration of wake deflection control (February 2016):

- Significant power gain for WT3
- WT1 & WT2 yaw out of the wind, loosing power
- >15% power increase

Control algorithm: closed-loop extremum seeking formulation
Variable Wind Direction Experiment

- Reproduced with the **turntable**
- Mimic **full-scale** variability of wind direction, accounting for **scaling** and hardware limitations
Variable Wind Direction Experiment

w/o wind farm control

with wind farm control
Based on LUTs obtained with **three different** static wind farm models:

- **Lower accuracy**: baseline “FLORIS”, tuned with wind tunnel wake data
- **Intermediate accuracy**: “FLORIS-Aug”, with extra error terms for unmodelled effects
- **Higher accuracy**: “Data-Driven” response surface (no modelling)
Baseline FLORIS Model

**Gaussian** wake model, tuned with single G1 wake measurements

**Offshore Inflow Conditions (mod–TI)**

**Onshore Inflow Conditions (high–TI)**
**FLORIS-Aug Model**

**Question**: can we learn from SCADA data, and do we learn the right things?

**Approach**:

1. Augment FLORIS with unmodelled effects:
   - Secondary Steering (SS)
   - Non-uniform speed and direction (orography)
   - Flow acceleration outside of wake


Wind tunnel: power error improvement by machine learning

Field testing: learning of orographic effects (ongoing)

**Driving effect on WT1**: inflow non-uniformity

**Driving effect on WT3**: secondary steering
Very precise representation of wind farm power output
Assumed as ground truth
Model Accuracy Comparison

Increasing model fidelity
What are the Effects of Control Parameters?

Effects of filtering

Wind tunnel experiment:
• Negligible yaw sensor error
• Negligible wind vane error
• Only uncertainty: **effect of wind direction filtering**

Robust LUTs computed according to Rott et al. 2018
Effects of Time Filtering
FLORIS LUTs with $\sigma_\Phi = 0$

- Strong impact on cluster power gain
- Modest effect of filtering on yaw actuator duty cycle

\[ \text{ADC} = \frac{1}{T} \int_0^T \frac{|\dot{\gamma}|}{\dot{\gamma}_{\text{max}}} \, dt \]
Is Model Accuracy Important for WFC?

**Constant wind direction experiments**: apparently not much

- FLORIS: +10.7%
- FLORIS-Aug: +11.5%
- Data-Driven: +11.8%

**Variable wind direction experiments**: yes, model accuracy is important!

**Possible reasons**:
- Direction uncertainties
- Limited yaw rate
- Wake dynamics
Effect of Robust LUTs on ADC

- Robust LUTs mitigate $\Delta ADC_{WF}$ increase
- Modest effect of model used for LUT computation

\[
ADC_{WF} = \frac{1}{3} \sum_{i=1}^{3} \frac{1}{T} \int_{0}^{T} \frac{\left| \dot{\gamma}_i \right|}{\dot{\gamma}_{max}} \, dt
\]
Effects of Model and Robustness on DEL

- Only marginal DELs increase of WT1 for robust LUTs
- Strong reduction of DELs for WT2 and WT3
- A better model implies lower DELs

Note: shaft rotating DELs
Publicly available datasets:

- Single & multiple wake measurements (triple hot wire)
- Broad range of environmental (TI & shear) and wind turbine operating conditions (yaw misalignment & derating)
- Steady and time-varying wind direction

Applications: validation and tuning of CFD, medium-fidelity and engineering wake models

Data available upon request to the CL–Windcon consortium
Validation of LES Digital Copy of Experiments
Concluding Remarks

**Wind tunnel testing:**
- Not a perfect match of reality, but very useful for better understanding
- Fast and relatively inexpensive

**Main conclusions from latest experiments:**
- Better models pay off: improved power capture, reduced loading
- Excessive filtering strongly affects performance
- Recommended recipe: robust LUTs + better models + rapid filtering

**Outlook:**
- Better models by learning from operational data
- Beyond WFC: similar models applicable to lifetime estimation, predictive maintenance, feed–in to digital twins, ...
Acknowledgements

Work in collaboration with:

J. Schreiber, E. Nanos, J. Wang, R. Weber

Work supported in part by European Union’s Horizon 2020 R&I Program under grant agreement No. 727477 (“CL-WINDCON”)