Parameter Uncertainty Reduction of the Re-calibrated Larsen Wake Model

Tuhfe Göçmen
Juan Pablo Murcia Leon
Gregor Giebel

DTU Wind Energy
Department of Wind Energy
Real-Time Wake Modelling – using turbine data

- Although uncertain could be used for
  - Estimating the real-time (or higher fidelity) reserve / available (or possible) power
  - Implementing into the active model based wind farm control algorithms, built on the operational data
UQ, propagation and reduction techniques

• Focus on implementation in the WF flow models
  ➢ Input uncertainty
    • SCADA $\rightarrow$ $\theta$, $\omega$, $P$ (temp & pressure) $\rightarrow U_{eff}$, WD
  ➢ Documented & Experienced Input uncertainty in SCADA (IEC Standards [1,2])
    • Pitch, $\theta$ $\rightarrow$ 10% (data acquisition & Type B sensitivity)
    • Rotational Speed, $\omega$ $\rightarrow$ 10% (data acquisition, & Type B sensitivity)
    • Temperature, $T$ $\rightarrow$ $\approx$ 2°C
    • Active Power $\rightarrow$ $\approx$ 1%


Estimation of the $U_{eff}$

Comparison of the expected values

Pt-wise measurements vs. rotor averaged

“Siemens WS” signal uses the ‘real’ $C_p(\theta, \lambda)$

- Also uncertain

Still compares well with Siemens WS

- The max. error < 5%
Uncertainty in the $U_{eff}$

- **Uncertainty Propagation**
  - Input uncertainty
  - Combined with $C_p$ uncertainty
Uncertainty in the $U_{eff}$

- Time (or operation) dependent uncertainty
- Increases closer to the rated region
Uncertainty in the Ueff

- Uncertainty significantly decreases during down-regulation
  - Where pitch is “controlled”
Real-time Larsen – LSE fit

\[ u_x(x, r) = -\frac{U_\infty}{9} \left( c_T A(x_0 + \Delta x)^{-2} \right)^{\frac{1}{3}} \left( \frac{3}{r^2} \left( 3 c_1^2 c_T A(x_0 + \Delta x) \right)^{-\frac{1}{2}} - \left( \frac{35}{2\pi} \right)^{\frac{3}{10}} \left( 3 c_1^2 \right)^{-\frac{1}{5}} \right)^2 \]

- 2 variables to adjust:

\[ x_0 = p_1 \cdot c_T^{p_2} + p_3 \cdot TI \]

\[ c_1 = p_4 \cdot c_T^{p_5} + p_6 \cdot TI \]

- Calibrated using 1-sec data from Thanet (normal operation)

- Thanet data fit – single wake (7h, September, daytime, 2014)

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\[ R^2 = 0.914 \quad RMSE = 0.718 \text{ m/s} \]
Real-Time Larsen
Single Wake Results – Re-calibrated Model in Horns Rev-I

- Better recovery with the re-calibration – NO UNCERTAINTY CONSIDERED!
Uncertainty Propagation in Real-time Larsen

- **Uncertainty in Wind Direction**
  - A research topic on its own 😊
  - According to IEC
    - In-situ calibration & signal resolution & d.a.
    - Combined $\approx 3^\circ$
Uncertainty in the wake
Real-time Larsen

• Essentially added on top of the $U_{eff}$ uncertainty
  ➢ Minimum around $\pm 0.5\text{m/s}$!
Uncertainty in PossPOW
how to make it better

• Input uncertainty will always be there... But the parameters?
  – The uncertainty in $C_p$ can be reduced by demanding / using the manufacturer $C_p(θ,λ)$ surface
    • The ideal would be to run the blades in our aero-elastic codes taking uncertainty into account
  – Reducing the uncertainty through re-calibration
    • Bayesian calibration
Uncertainty in the wake
how to make it better

Figure 5.2: Model calibration example with low input uncertainty case (left) Observed pairs, bin averaged observed pairs with their corresponding standard error of the mean (SEM) and true model. (right) Model calibration results.

Figure 5.3: Model calibration example with large input uncertainty case (left) Observed pairs, bin averaged observed pairs with their corresponding standard error of the mean (SEM) and true model. (right) Model calibration results.
Uncertainty in PossPOW
how to make it better

- Input uncertainty will always be there... But the parameters?
  - The uncertainty in $C_p$ can be reduced by demanding / using the manufacturer $C_p(\theta, \lambda)$ surface
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  - Reducing the uncertainty through re-calibration
    - Bayesian calibration
      - Does it perform as good in real data?
        » True values are unknown
      - Need a good prior
        » Re-calibration of the re-calibration
        » Re-Re-Calibration 😊
        » 6 parameters in the real-time wake model to play with...
Uncertainty in PossPOW
how to make it better

Pdf for param #1

Pdf for param #2

Pdf for param #3

Pdf for param #4

Pdf for param #5

Pdf for param #6
To Do List & Challenges

• **Reduction of the uncertainty?**
  - Input uncertainty will always be there... but the parameters?
  - Re-Re-Calibration
    - Bayesian seems promising
    - How “real-time” do we need? What is the “ideal” time interval?

• **There will always be Uncertainty in (any) models-based-control**
  - How to come up with smarter algorithms to take that into account?
    - “learning here and now” models?
    - Investigate how independent uncertainties compensate each other and optimize accordingly?