Design and Evaluation of a Wind Speed Estimator for Hub Height and Shear Components

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Outline

• Introduction to wind speed estimation
  – Why estimate wind speed?
  – Traditional estimation techniques

• Hub height and shear component wind field model

• Kalman filter wind speed estimator design

• Wind speed estimator performance
  – With and without measurement noise
Effective Wind Speed

Rotor Effective Wind Speed

- The equivalent uniform wind speed that would produce the same turbine response as the actual spatial distribution of wind speeds

\[ P = \frac{1}{2} \rho \pi R^2 C_P (\lambda, \beta) u_{eff}^3 \]
Why Estimate Effective Wind Speed?

- Gain scheduling for control (Østergaard, 2007)
- Active power control for grid ancillary services (Aho, Buckspan, 2013)
Why Estimate Effective Wind Speed?

- Gain scheduling for control (Østergaard, 2007)
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- Control using estimated wind speed as a feedforward input (van der Hooft, 2004)
Why Estimate Effective Wind Speed?

- Gain scheduling for control (Østergaard, 2007)
- Active power control for grid ancillary services (Aho, Buckspan, 2013)
- Control using estimated wind speed as a feedforward input (van der Hooft, 2004)
- Optimal filtering of lidar measurements for feedforward control with preview (Schlipf, 2012; Simley, 2013)

Nacelle anemometer provides poor estimate of rotor effective wind speed
  
  - Point measurement
  - Flow affected by rotor

Image courtesy of U.S. Dept. of Energy
Methods for Estimating Effective Wind Speed

- **Power balance method:**
  \[ \tau_g \omega_g = \frac{1}{2} \rho \pi R^2 C_P (\lambda, \beta) u_{eff}^3 \]

- **Torque balance method:**
  \[ J \dot{\omega}_g = \frac{\tau_r}{N_g} - \tau_g \]
  \[ \tau_r = \frac{\rho \pi R^2 C_P (\lambda, \beta) u_{eff}^3}{2\omega_r} \]

- **Kalman filtering (Ma, 1995; Bottasso 2010; Knudsen, 2011)**
  - Includes linearized turbine dynamics
  - Accounts for measurement noise
  - Uses wind speed statistics to improve performance

Fig. 1. Mechanical scheme of the wind turbine transmission system. Figure from Soltani, et al., “Estimation of Rotor Effective Wind Speed: A Comparison,” IEEE TCST, 2013.
The instantaneous wind field can be described as a combination of:

- Horizontal hub height wind speed \( u_{hh} \)
- Horizontal wind direction \( \delta \)
- Vertical wind speed \( w \)
- Linear horizontal wind shear \( \Delta_h \)
- Power law vertical wind shear \( \alpha \)
- Linear vertical wind shear \( \Delta_v \)

Three linear “blade effective wind speeds” can be equivalently described as hub height and shear terms

\[
u_i = f(u_{hh}, \Delta_h, \Delta_v, \psi_i)\]
Wind Field Disturbance Model

From “blade effective wind speeds” to hub height and linear shear components

$$
\begin{bmatrix}
  u_{hh} \\
  \Delta_h \\
  \Delta_v
\end{bmatrix} = T_{MBC}(\psi)
\begin{bmatrix}
  u_1 \\
  u_2 \\
  u_3
\end{bmatrix}
$$
Kalman Filter Design

• Linear state-space turbine model:

  – State update: \[ x(k+1) = Ax(k) + B \begin{bmatrix} \tau_g(k) \\ \beta(k) \end{bmatrix} + B_d \begin{bmatrix} u_{hh}(k) \\ \Delta_h(k) \\ \Delta_v(k) \end{bmatrix} \]

  – Output: \[ y(k) = Cx(k) + D \begin{bmatrix} \tau_g(k) \\ \beta(k) \end{bmatrix} + D_d \begin{bmatrix} u_{hh}(k) \\ \Delta_h(k) \\ \Delta_v(k) \end{bmatrix} \]

• Examples of states:
  – Generator speed
  – Tower deflection
  – Blade deflection

Control input
Wind disturbance
Kalman Filter Design

- Linear state-space turbine model:
  
  - State update:
    \[
    \begin{bmatrix}
    x(k + 1) \\
    u_{hh}(k + 1) \\
    \Delta_h(k + 1) \\
    \Delta_v(k + 1)
    \end{bmatrix}
    =
    \begin{bmatrix}
    A & B_{d,u_{hh}} & B_{d,\Delta_h} & B_{d,\Delta_v} \\
    0 & 1 & 0 & 0 \\
    0 & 0 & 1 & 0 \\
    0 & 0 & 0 & 1
    \end{bmatrix}
    \begin{bmatrix}
    x(k) \\
    u_{hh}(k) \\
    \Delta_h(k) \\
    \Delta_v(k)
    \end{bmatrix}
    +
    \begin{bmatrix}
    B \\
    0 \\
    0 \\
    0
    \end{bmatrix}
    \begin{bmatrix}
    \tau_g(k) \\
    \beta(k)
    \end{bmatrix}
    \]

  - Output:
    \[
    y(k) =
    \begin{bmatrix}
    C & D_{d,u_{hh}} & D_{d,\Delta_h} & D_{d,\Delta_v}
    \end{bmatrix}
    \begin{bmatrix}
    x(k) \\
    u_{hh}(k) \\
    \Delta_h(k) \\
    \Delta_v(k)
    \end{bmatrix}
    +
    \begin{bmatrix}
    \tau_g(k) \\
    \beta(k)
    \end{bmatrix}
    \]

  - Wind disturbance states
  - Control input
Kalman Filter Design

- Linear state-space turbine model:
  
  - State update:
    
    $$
    \begin{bmatrix}
    x(k+1) \\
    u_{hh}(k+1) \\
    \Delta_h(k+1) \\
    \Delta_v(k+1)
    \end{bmatrix}
    =
    \begin{bmatrix}
    A & B_{d,u_{hh}} & B_{d,\Delta_h} & B_{d,\Delta_v} \\
    0 & 1 & 0 & 0 \\
    0 & 0 & 1 & 0 \\
    0 & 0 & 0 & 1
    \end{bmatrix}
    \begin{bmatrix}
    x(k) \\
    u_{hh}(k) \\
    \Delta_h(k) \\
    \Delta_v(k)
    \end{bmatrix}
    +
    \begin{bmatrix}
    B \\
    0 \\
    0 \\
    0
    \end{bmatrix}
    \begin{bmatrix}
    \tau_g(k) \\
    \beta(k)
    \end{bmatrix}
    +
    \begin{bmatrix}
    0 \\
    n_1(k) \\
    n_2(k) \\
    n_3(k)
    \end{bmatrix}
    $$

  - Output:
    
    $$
    y(k) =
    \begin{bmatrix}
    C & D_{d,u_{hh}} & D_{d,\Delta_h} & D_{d,\Delta_v}
    \end{bmatrix}
    \begin{bmatrix}
    x(k) \\
    u_{hh}(k) \\
    \Delta_h(k) \\
    \Delta_v(k)
    \end{bmatrix}
    +
    D
    \begin{bmatrix}
    \tau_g(k) \\
    \beta(k)
    \end{bmatrix}
    +
    \nu(k)
    $$

  - Wind disturbance states
  - Control input
  - Sensor noise
  - State update noise
Kalman Filter Design

• Linear state-space turbine model:
  • Degrees of freedom
    – Generator
    – First flapwise blade bending mode
    – First tower fore-aft mode
  • Sensors
    – Generator speed
    – Out-of-plane blade root bending moments
    – Nacelle IMU translational acceleration
  • Sensor noise
    – Generator speed, $\sigma = 2\%$ of operating point
    – Strain gages, $\sigma = 2\%$ of RMS value
    – Accelerometer, $\sigma = 4\%$ of RMS value

Simulation Environment

• NREL’s FAST aeroelastic simulator
• NREL 5MW Reference Turbine
  – Baseline collective pitch controller
• Above rated wind speed 13 m/s
• No mean wind shear
• Hub height and shear components modeled using three rotating blade effective wind speeds
  – Von Karman turbulence spectrum
  – 7.7% turbulence intensity

• Want to estimate wind speeds accurately up to ~1Hz (approximate bandwidth of pitch actuators)
Wind Speed Estimator Performance

Hub height component, above rated conditions, w/o tower mode

![Wind Speed vs Time](image)

- True Wind Speed
- Estimated Wind Speed

![Coherence vs Frequency](image)

- Frequency (Hz)

![PSD vs Frequency](image)

- Frequency (Hz)

![Phase vs Frequency](image)

- Frequency (Hz)
Wind Speed Estimator Performance

Hub height component, above rated conditions, w/ tower mode

- True Wind Speed
- Estimated Wind Speed

- Coherence

- Phase (deg)

- PSD (m²/s)
Wind Speed Estimator Performance

Hub height component, below rated conditions

![Graphs showing wind speed and estimates over time and frequency]

- True Wind Speed
- Estimated Wind Speed

![Graphs showing power spectral density (PSD) and phase over frequency]

- Coherence
- Phase (deg)

8/5/2013  E. Simley – NAWEA 2013, Wind Speed Estimation
Wind Speed Estimator Performance

Horizontal shear component, above rated conditions

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**Wind Speed Estimator Performance**

**Horizontal shear component, above rated conditions**

- **Shear Component**
  - Time (s)
  - True Wind Speed
  - Estimated Wind Speed

- **Coherence**
  - Frequency (Hz)
  - 0.0
  - 0.1
  - 1.0

- **PSD (s)**
  - Frequency (Hz)
  - 10^{-1}
  - 10^{0}
  - 10^{-2}

- **Phase (deg)**
  - Frequency (Hz)
  - 10^{-1}
  - 10^{0}

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8/5/2013

E. Simley – NAWEA 2013, Wind Speed Estimation
Wind Speed Estimator Performance

Hub height component, with measurement noise

\[ y(k) = \begin{bmatrix} C & D_{d,u_{hh}} & D_{d,\Delta h} & D_{d,\Delta v} \end{bmatrix} \begin{bmatrix} x(k) \\ u_{hh}(k) \\ \Delta_h (k) \\ \Delta_v (k) \end{bmatrix} + D \begin{bmatrix} \tau_g(k) \\ \beta(k) \end{bmatrix} + \nu(k) \]

Sensor noise variance must be estimated.
Conclusions

• Wind speed estimation has many uses in wind turbine control
• A Kalman filter-based wind speed estimator can estimate hub height and shear components up to 1 Hz bandwidth
  – generator speed, blade root bending moment, and nacelle acceleration measurements
  – Difficult to model closed-loop modes
• Kalman filter accounts for measurement noise and state uncertainty
  – Requires knowledge of measurement noise and wind statistics
• Robust to measurement noise uncertainty up to 1 Hz bandwidth
Future Work

- Improve model of closed-loop system
- Implement a non-causal Kalman filter
  - Fixed estimation lag time
- Analyze performance during operating point transitions
  (time varying mean wind speed and mean shear)
Thank You

Questions?

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