IMPROVED KNOWLEDGE OF WIND CONDITIONS FOR WIND TURBINE AND WIND FARM CONTROL

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Motivation

Operating in **yawed conditions**:

- **Reduces power** as $\cos^3(\text{yaw})$
- Causes **vibrations** and excites low-damped side-side modes
- Changes airfoil AoA, possible **performance degradations** (e.g., dynamic stall)
Motivation

Sometimes yawing a machine is helpful:

Due to the presence of the wake of the first turbine, the downstream turbine feels:

- Lower mean wind speed over the rotor disk (less power available)
- Higher turbulence intensity and periodic loads (fatigue problems)
- Performance degradations (e.g., dynamic stall)

One could yaw a turbine to improve performances of downstream turbines
Reliable yaw measurements are **difficult** to obtain.

- **Nacelle anemometer**
  - Local (point) information
  - Affected by rotor wake and blade passing
  - Nacelle interference

- **Lidar** (lased doppler anemometer)
  - Promising solution but
    - Costly
    - “Cyclops effect”
    - Unfrozen turbulence
The Concept in a Nutshell

Any **anisotropy** of the wind generates **periodic loads**

By interpreting the rotor response, one can infer desired wind states (here: direction $\varphi$ and vertical shear $\kappa$)

**Advantages**: rotor–effective non–local estimates

The rotor is the **ultimate anemometer**

Wind profile described as a power law curve with exponent $\kappa$
Outline

• Formulation of a general observation model
  – Model structure from an analytical blade response model
  – Observer synthesis by identification
  – Implementation

• Results
  – Testing in a high-fidelity simulation environment
  – Testing with an aeroelastically-scaled wind tunnel model
  – Field testing on NREL CART3 wind turbine

• Conclusions and outlook
Inspired by rigid flapping blade (Eggleston & Stoddard 1987):

• Assume 1P harmonic solution
  \[ \beta = \beta_0 + \beta_{1s}\sin\psi + \beta_{1c}\cos\psi \]

• Insert into blade dynamics, drop h.o.t.’s
• Solve for wind misalignment and shear
  (compute misalignment and shear from 1P periodic terms)

Remarks:

• Linear relationship between misalignment/shear and blade 1P
• Misalignment and shear are independent and observable
• Wind-dependent coefficients
• Gyroscopic effects during yawing (to be considered)

Not useful for practical applications, due to limitations/simplifications of flapping blade model problem
A General Observation Model

Linear input–output wind–scheduled model:

\[
\begin{bmatrix}
\varphi \\
\kappa
\end{bmatrix}
= A(V) m + b(V)
\]

Driving input (blade root loads):

\[
\tilde{m} = (m_{1c}^{OP}/m_{0}^{OP}, m_{1s}^{OP}/m_{0}^{OP}, m_{1c}^{IP}/m_{0}^{IP}, m_{1s}^{IP}/m_{0}^{IP})^T
\]


1P load harmonics by multiblade Coleman–Feingold transformation:

\[
\begin{bmatrix}
m_0 \\
m_{1c} \\
m_{1s}
\end{bmatrix}
= \frac{1}{3}
\begin{bmatrix}
1 & 1 & 1 \\
2 \cos \psi_1 & 2 \cos \psi_2 & 2 \cos \psi_3 \\
2 \sin \psi_1 & 2 \sin \psi_2 & 2 \sin \psi_3
\end{bmatrix}
\begin{bmatrix}
m_1 \\
m_2 \\
m_3
\end{bmatrix}
\]
Model Identification

$N$ observations of wind parameters/associated blade response harmonics:

$$W = T(V)M$$

where

$$W = \begin{bmatrix} \{ \varphi_1 \} \\ \{ \kappa_1 \} \end{bmatrix}, \begin{bmatrix} \varphi_2 \\ \kappa_2 \end{bmatrix}, \ldots, \begin{bmatrix} \varphi_N \\ \kappa_N \end{bmatrix}$$

$$M = \begin{bmatrix} \{ m_1 \} \\ 1 \end{bmatrix}, \begin{bmatrix} m_2 \\ 1 \end{bmatrix}, \ldots, \begin{bmatrix} m_N \\ 1 \end{bmatrix}$$

$$T(V) = [A(V), b(V)]$$

Compute unknown model coefficients by least-squares:

$$T(V) = WM^T(MMM^T)^{-1}$$

Wind scheduling: identify observation model at different wind speeds $V_k$ to cover entire operating envelope of the wind turbine

Linearly interpolate at run time: $T(V) = (1 - \xi)T(V_k) + \xi T(V_{k+1})$
Testing in a Simulation Environment

3MW high-fidelity HAWT model

Cp-Lambda highlights:
- Geometrically exact composite-ready beam models
- Generic topology (Cartesian coordinates + Lagrange multipliers)
- Dynamic wake model (Peters-He, yawed flow conditions)
- Efficient large-scale DAE solver
- Non-linearly stable time integrator
- Fully IEC 61400 compliant (DLCs, wind models)
Verification of Observability

▲ OP and IP loads

▼ OP loads only
Estimation of Wind Properties for Wind Farm Control

Yaw Observation with Varying Shear

Graph showing time series data for different variables:
- $V_0$ [m/sec]
- $\varphi$ [deg]
- $K_1$
- $\bar{U}_0$
- $\tilde{m}_1$

Legend:
- Real averaged
- Observed

Time [sec]
Estimation of Wind Properties for Wind Farm Control

Yaw Observation with 10% Turbulence and Varying Mean Wind Speed
Wind Tunnel Testing

WT²: aeroelastically-scaled wind tunnel model of the Vestas V90 wind turbine with individual blade pitch and torque control

Applications:
• Testing of advanced control laws and supporting technologies
• Testing of extreme operating conditions
• Tuning of mathematical models
• Aeroelasticity and system identification of wind turbines
• Multiple wind turbine interactions
• Off-shore wind turbines (moving platform actuated by hydro-structural model)

4x3.8 m, 55 m/s, aeronautical section:
• Turbulence <0.1%
• Open-closed test section

13.8x3.8 m, 14 m/s, civil section:
• Turbulence <2%
• With turbulence generators = 25%
• 13 m turntable

Aeroelastically scaled blades (70g, 1m)

Pitch actuator:
• Zero backlash gearhead
• Built-in encoder

Main shaft with torque meter

Rotor sensor electronics

Conical spiral gears

Pitch actuator electronics

Slip ring

Torque actuator:
• Planetary gearhead
• Torque and speed control

Civil-Aeronautical Wind Tunnel of the Politecnico di Milano
Wind Tunnel Testing

▲ Verification data set

△ Identification data set
Field Testing

NREL CART3 wind turbine
Model identified from real field measurements (elimination of outliers by RANSAC)

Two typical time histories:

- Black solid: met mast
- Blue dash-dotted: wind vane
- Red dashed: observer

Good match at the low frequencies (what needed for yaw control)
Conclusions

- Successful verification in **simulation**, **wind tunnel** and **field testing**
- Simple **model-free** identification
- Good quality of the estimates, **superior** to on-board wind vanes
- **Negligible computational cost**

**Outlook:**

- Further testing on larger machines, should see even better results
- Field testing of shear observer
- On-board use of observed wind states
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THANK YOU FOR YOUR ATTENTION