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

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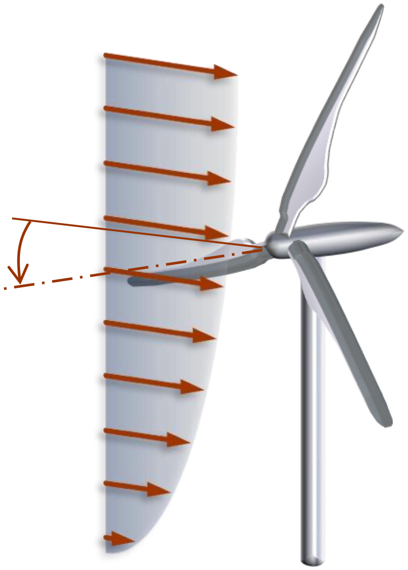
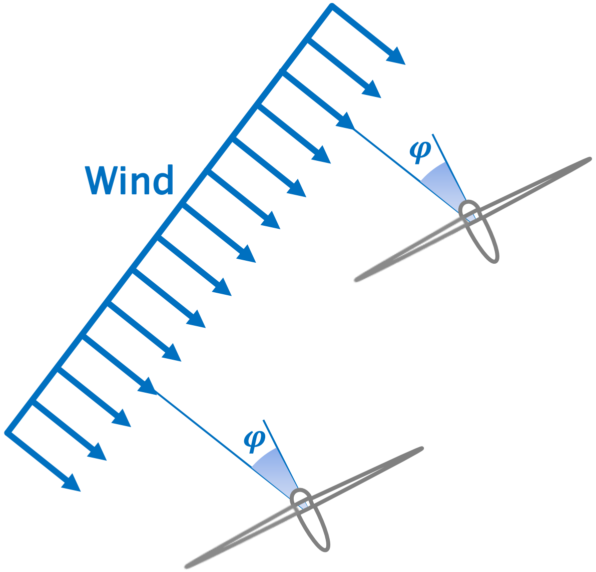


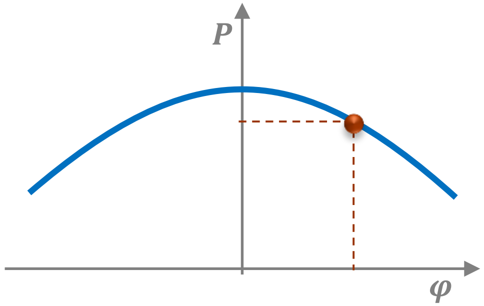
4th MSE colloquium
München, Germany, July 3, 2014

Motivation



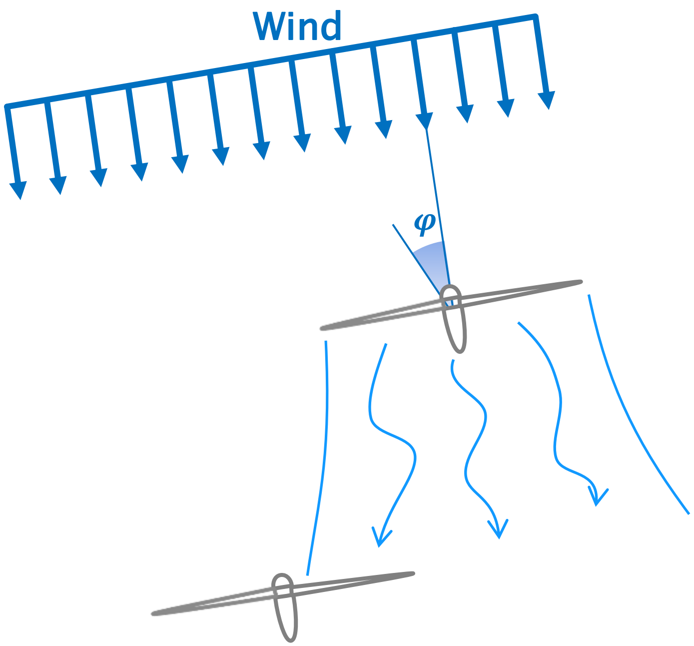
Operating in **yawed conditions**:

- **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:

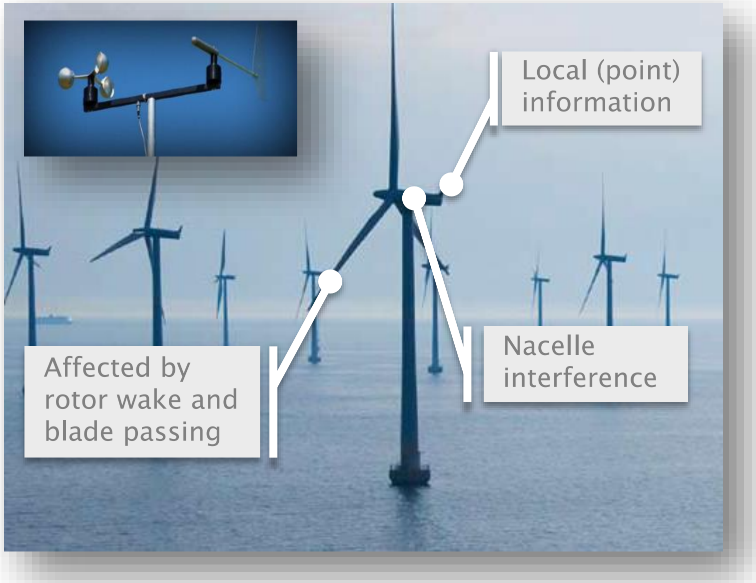
- Lower **mean wind speed** over the rotor disk (**less power available**)
- Higher **turbulence intensity** and periodic loads (**fatigue** problems)
- **Performance degradations** (e.g., dynamic stall)

One could yaw a turbine to **improve performances** of **downstream turbines**

Motivation

Reliable yaw measurements are **difficult** to obtain.

Nacelle anemometer



Local (point) information

Nacelle interference

Affected by rotor wake and blade passing

Lidar (lased doppler anemometer)

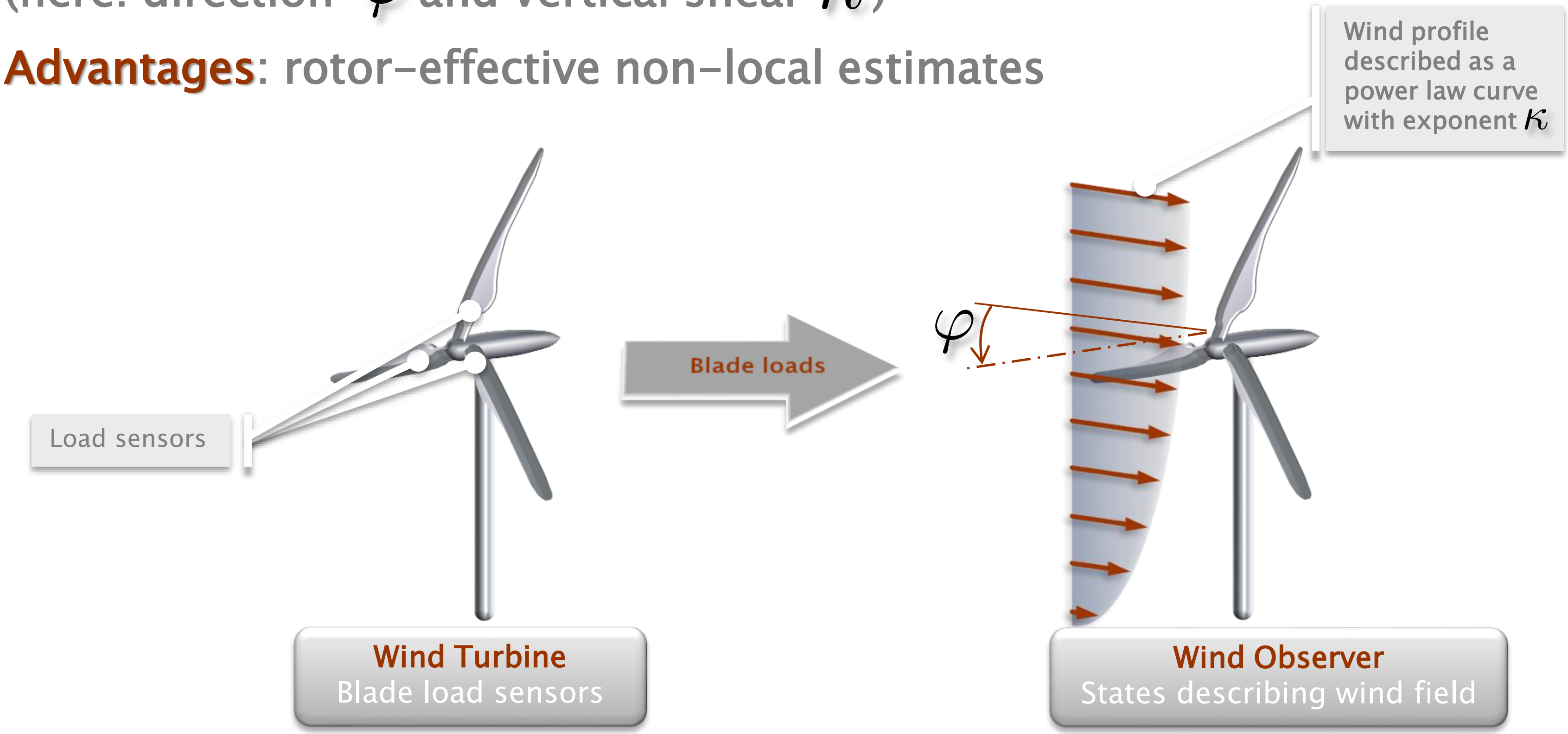
Promising solution but
- Costly
- “Cyclops effect”
- Unfrozen turbulence

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 φ and vertical shear κ)

Advantages: rotor-effective non-local estimates



Load sensors

Blade loads

Wind profile described as a power law curve with exponent κ

φ

Wind Turbine
Blade load sensors

Wind Observer
States describing wind field

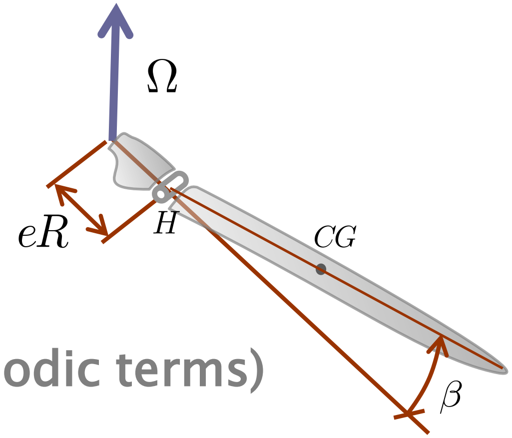
The rotor is the **ultimate anemometer**

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

Observation Model Structure

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:

$$\begin{Bmatrix} \varphi \\ \kappa \end{Bmatrix} = \boldsymbol{A}(V)\boldsymbol{m} + \boldsymbol{b}(V)$$

Wind-speed-dependent coefficients

Driving input (blade root loads):

$$\bar{\boldsymbol{m}} = \left(m_{1c}^{\mathrm{OP}}/m_0^{\mathrm{OP}}, m_{1s}^{\mathrm{OP}}/m_0^{\mathrm{OP}}, m_{1c}^{\mathrm{IP}}/m_0^{\mathrm{IP}}, m_{1s}^{\mathrm{IP}}/m_0^{\mathrm{IP}}\right)^T$$

OP: out-of-plane, IP: in-plane

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:

$$\boldsymbol{W} = \boldsymbol{T}(V)\boldsymbol{M}$$

where

$$\boldsymbol{W} = \left[\left\{\begin{array}{c}\varphi_1\\ \kappa_1\end{array}\right\}, \left\{\begin{array}{c}\varphi_2\\ \kappa_2\end{array}\right\}, \ldots, \left\{\begin{array}{c}\varphi_N\\ \kappa_N\end{array}\right\}\right]$$

$$\boldsymbol{M} = \left[\left\{\begin{array}{c}\boldsymbol{m}_1\\ 1\end{array}\right\}, \left\{\begin{array}{c}\boldsymbol{m}_2\\ 1\end{array}\right\}, \ldots \left\{\begin{array}{c}\boldsymbol{m}_N\\ 1\end{array}\right\}\right]$$

$$\boldsymbol{T}(V) = [\boldsymbol{A}(V), \boldsymbol{b}(V)]$$

Compute unknown model coefficients by **least-squares**:

$$\boldsymbol{T}(V) = \boldsymbol{W}\boldsymbol{M}^T(\boldsymbol{M}\boldsymbol{M}^T)^{-1}$$

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: $\boldsymbol{T}(V) = (1-\xi)\boldsymbol{T}(V_k) + \xi\boldsymbol{T}(V_{k+1})$

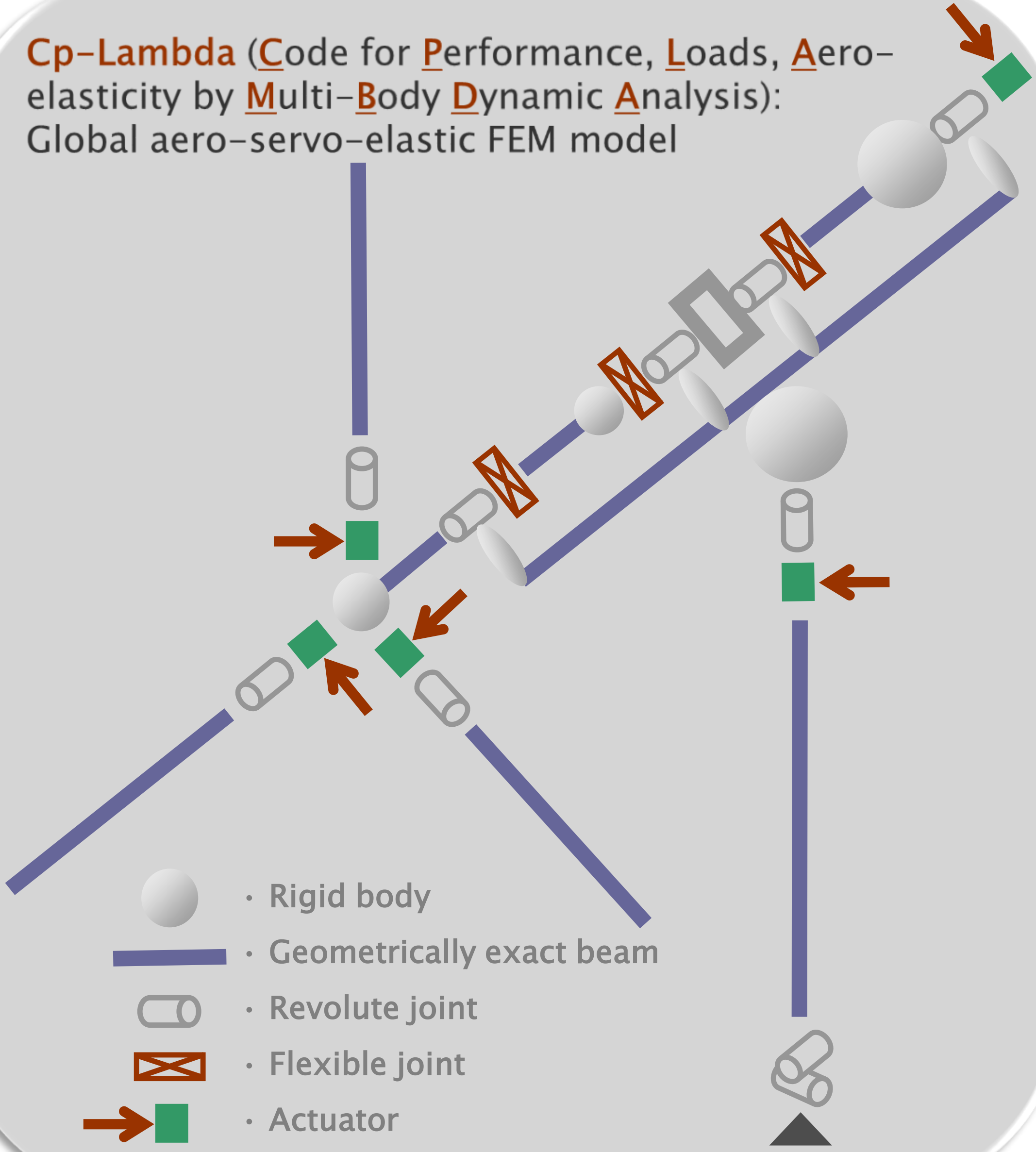
Testing in a Simulation Environment

3MW high-fidelity
HAWT model

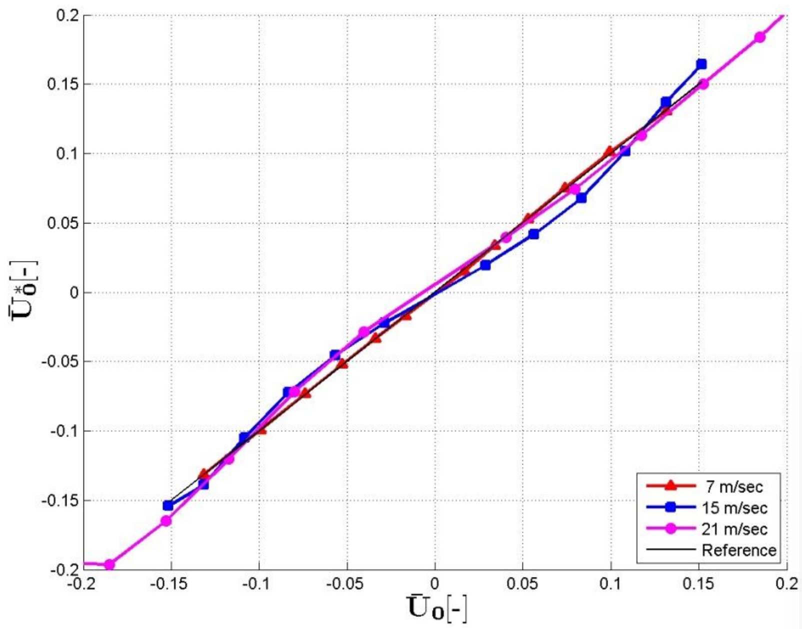
Cp-Lambda highlights:

- 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)

Cp-Lambda (Code for Performance, Loads, Aero-elasticity by Multi-Body Dynamic Analysis):
Global aero-servo-elastic FEM model

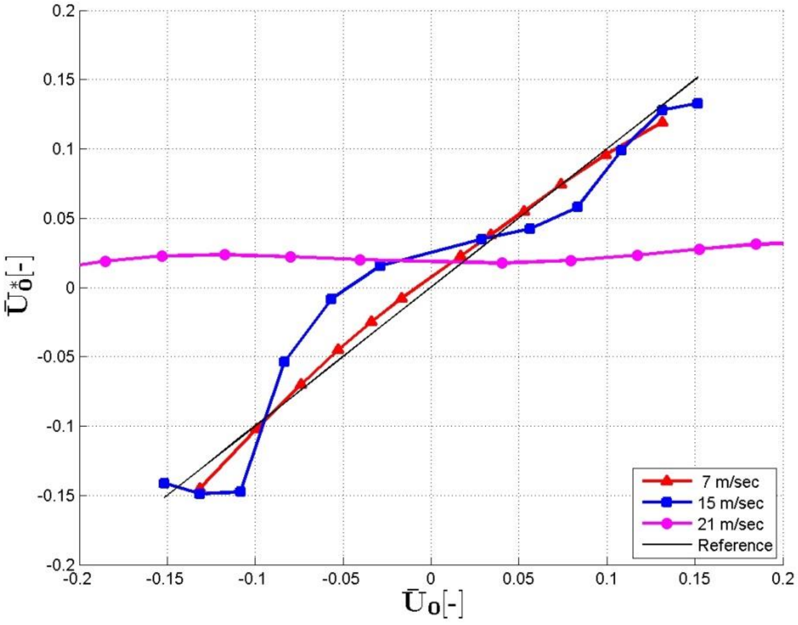


Verification of Observability

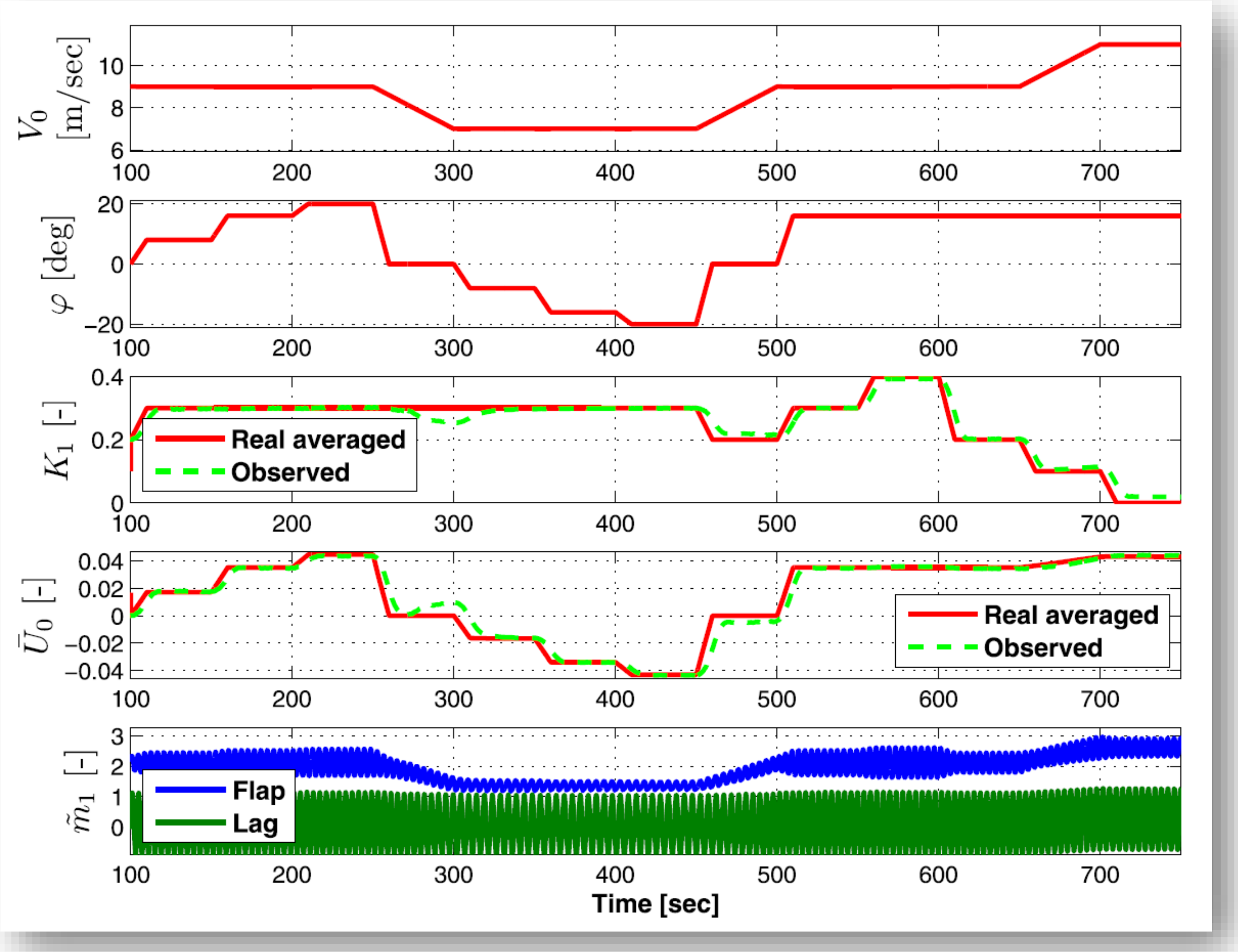


▲ OP and IP loads

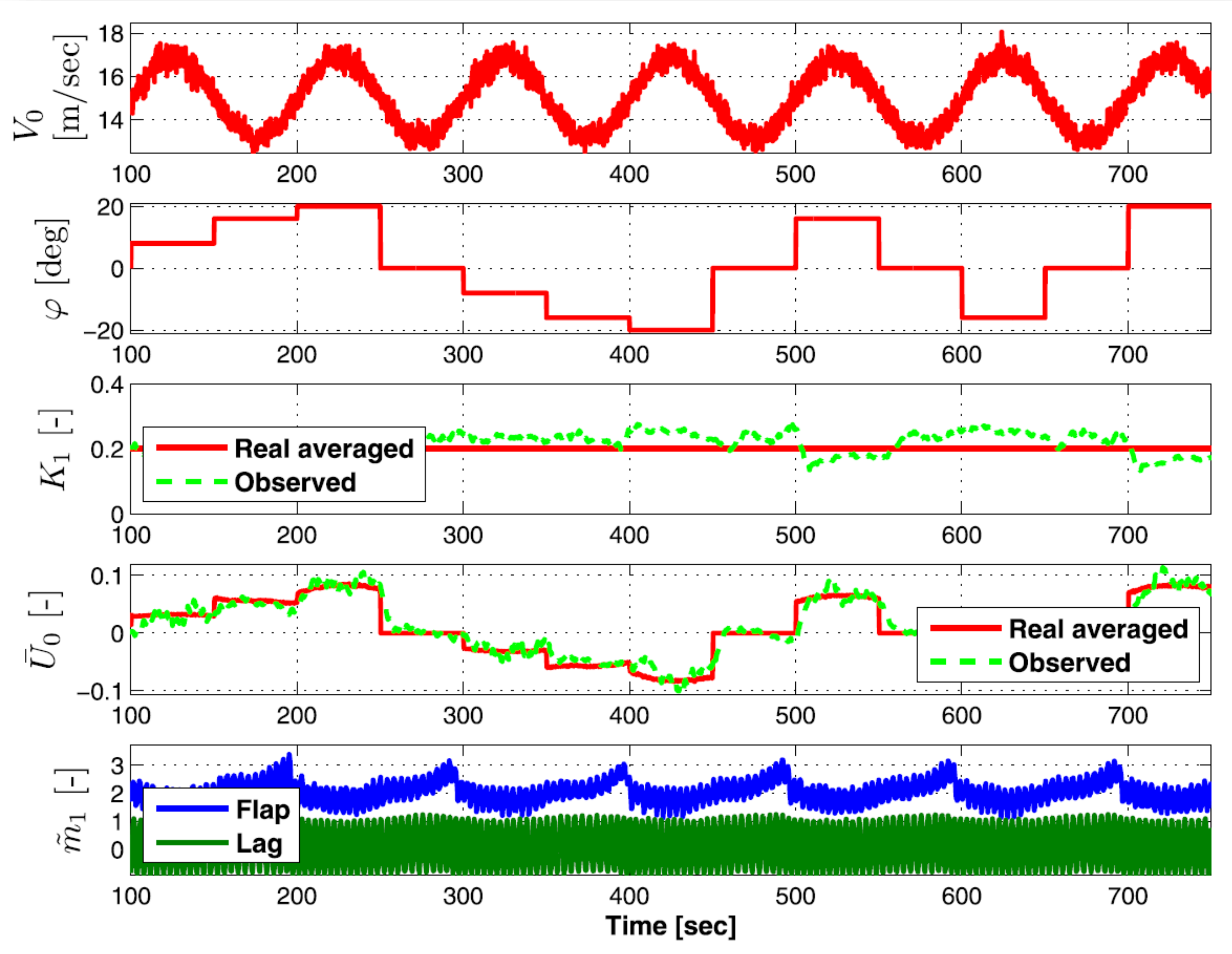
▼ OP loads only



Yaw Observation with Varying Shear



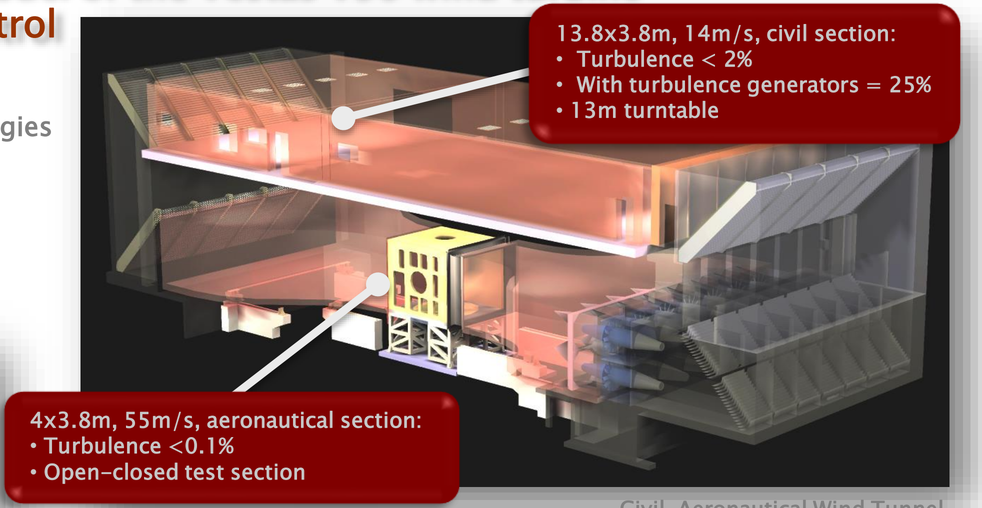
Yaw Observation with 10% Turbulence and Varying Mean Wind Speed



Wind Tunnel Testing

WT^2: aeroelastically-scaled wind tunnel model of the Vestas V90 wind turbine with individual blade pitch and torque control

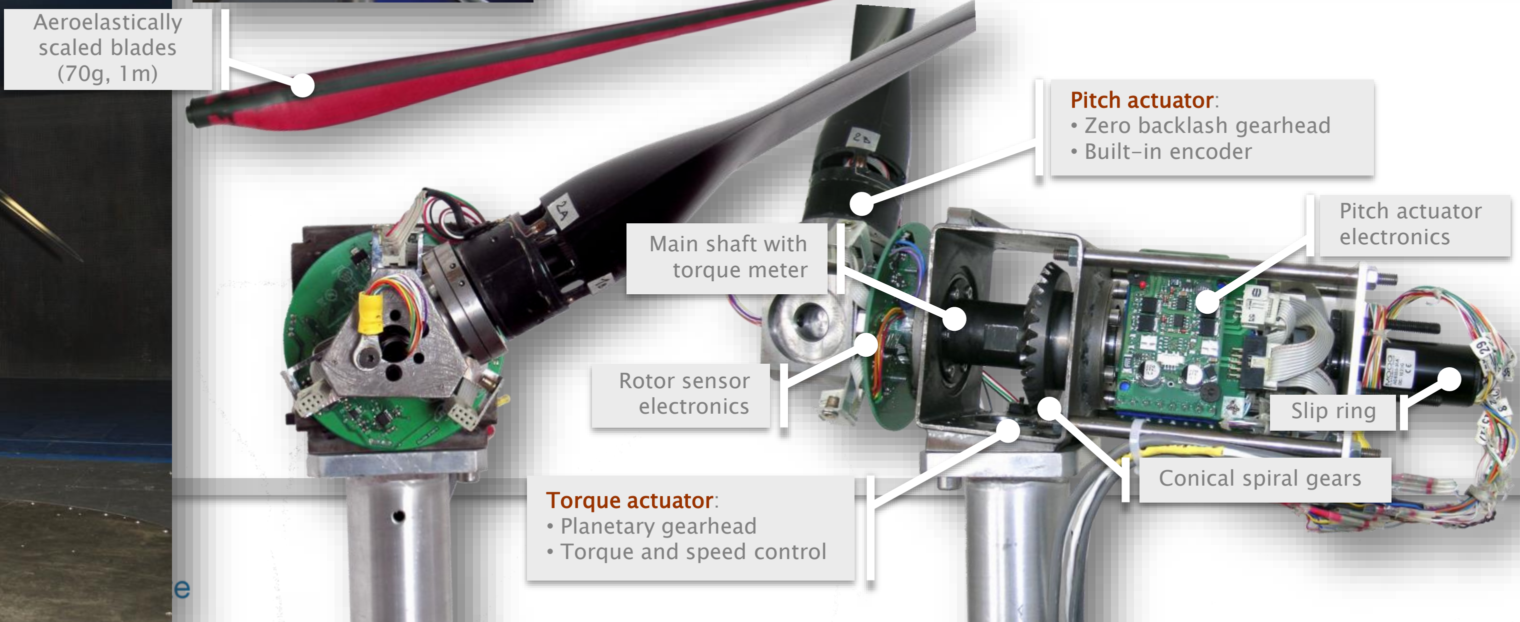
Applications:
- Testing of advanced control laws and supporting technologies
- Testing of extreme operating conditions
- Tuning of mathematical models
- Aeroelasticity and system identification of wind turbines
- Multiple wind turbine interactions
- Off-shore wind turbines (moving platform actuated by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



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

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

Civil-Aeronautical Wind Tunnel of the Politecnico di Milano



Aeroelastically scaled blades (70g, 1m)

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

Pitch actuator electronics

Main shaft with torque meter

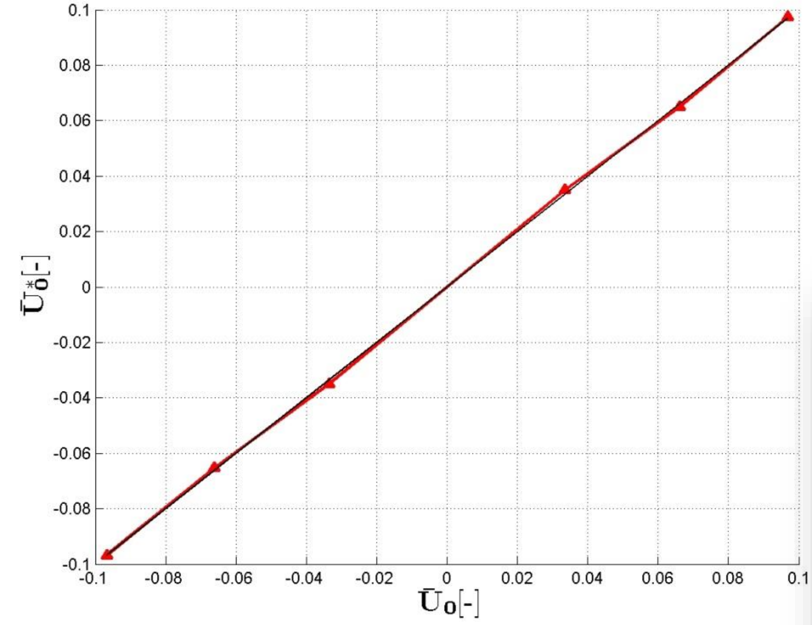
Rotor sensor electronics

Slip ring

Conical spiral gears

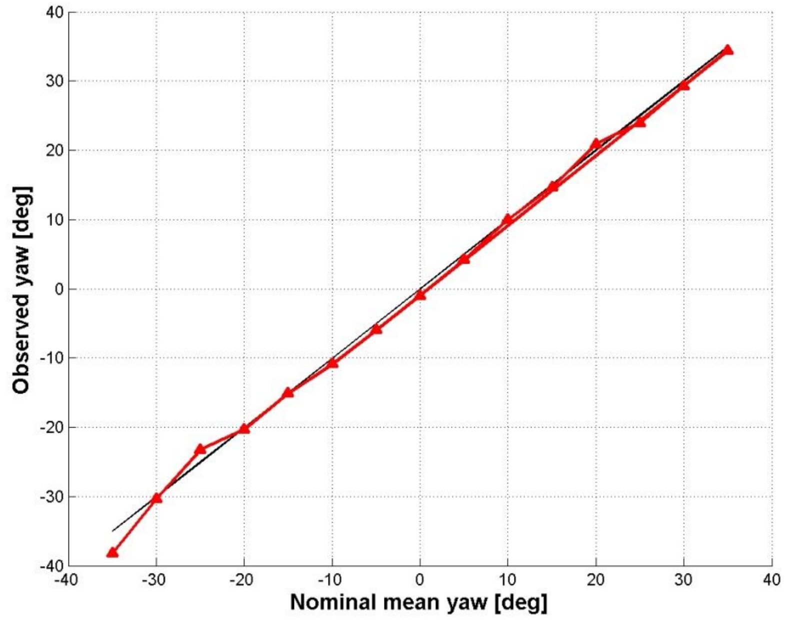
Torque actuator:
- Planetary gearhead
- Torque and speed control

Wind Tunnel Testing

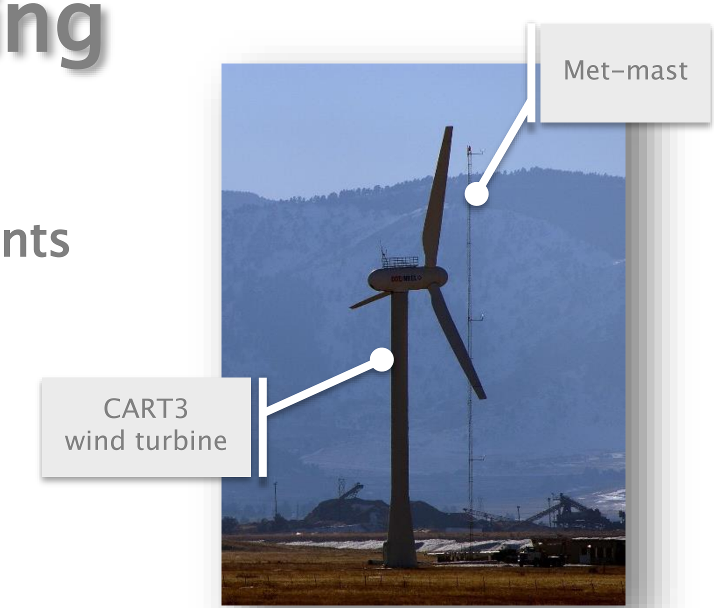


▲ Identification data set

▼ Verification data set



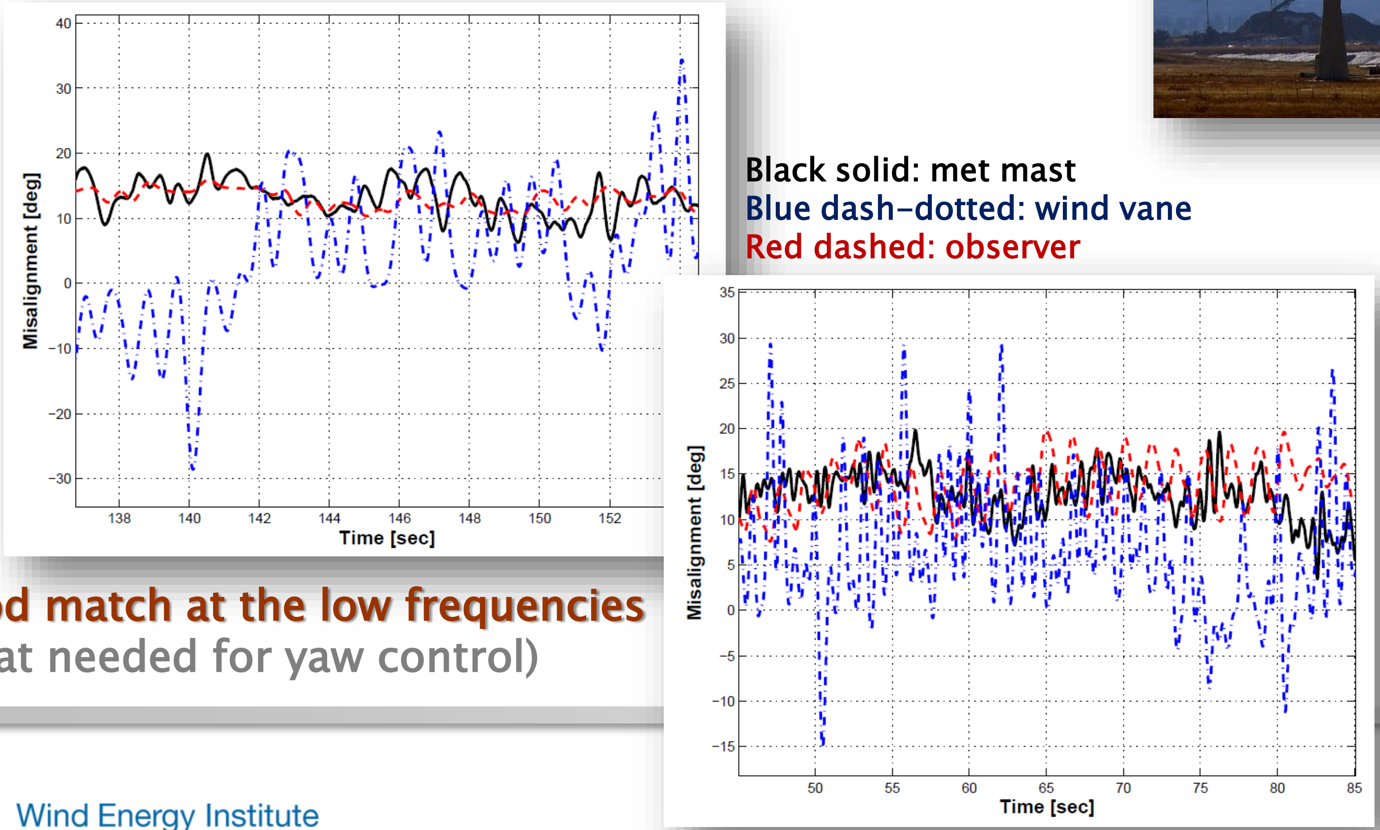
Field Testing



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