Technische Universität München
Wind Energy Institute

Application of a Reduced Order Wind Farm Model on a Scaled Wind Farm

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Outline

- Motivation
- Reduced Order Wind Farm Model (ROWFM)
- Scaled Wind Farm Experiments
- Wake Position Observer
- Conclusions and Outlook

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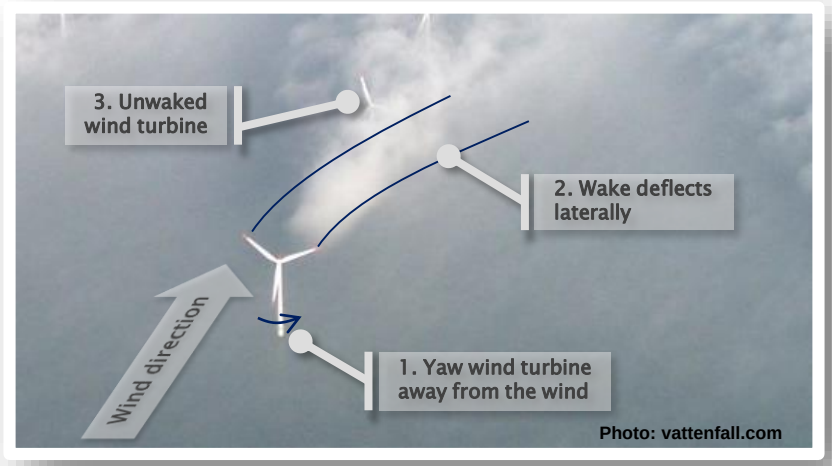
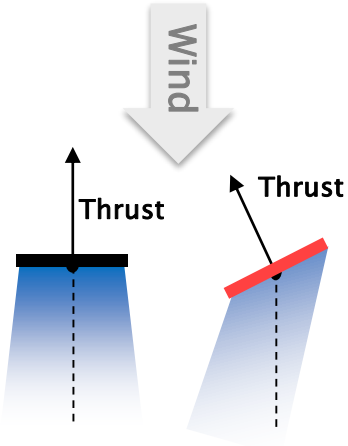
Motivation

Wind Farm Control:



Wake steering/deflection:

Yawing a wind turbine out of the wind, deflects the wake.



non-yawed and yawed wind turbine ▶

How to find the optimum yaw configuration for a wind farm?

- Engineering wake models (based on operating conditions, wind speed, turbulence and direction)

How to deal with model mismatch and disturbance?

- Wind observer and wake detectors (based on turbine rotor loads)

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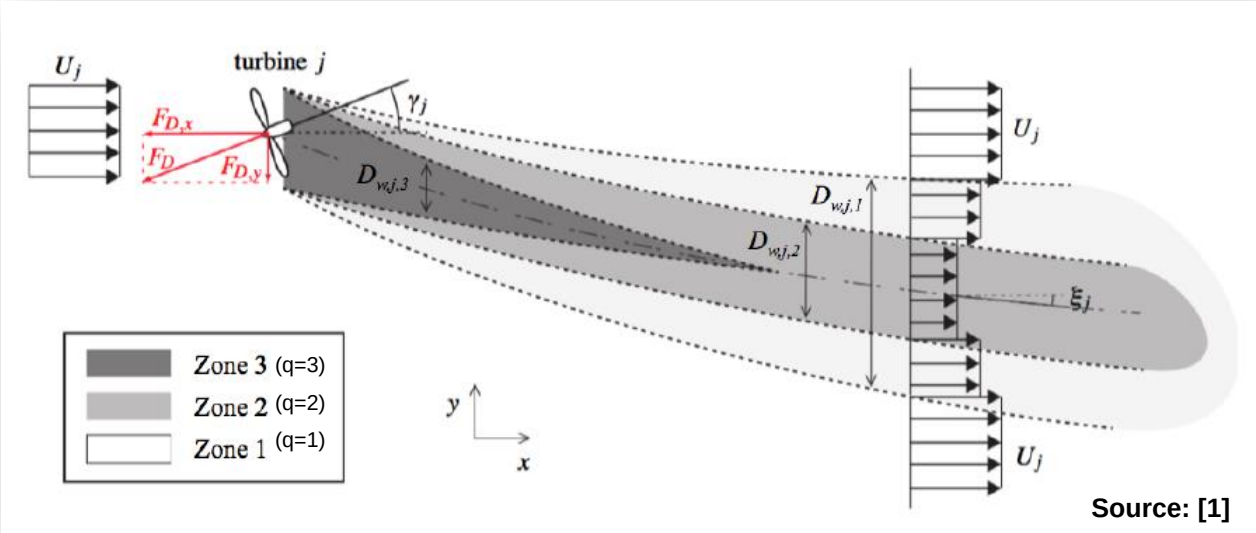
ROWFM

Reduced order wind farm model (ROWFM), FLORIS-like [1]

11 independent parameters to model:

- Reduction
- Expansion
- Deflection



Source: [1]

Reduction

- Jensen Wake Model like
- Small asymmetric effect due to yawing
- k_e as parameter to be changed for different TI

$$\mathrm{U}_{\mathrm{w,q}}(x) = U_\infty(1-r)$$

$$r = 2a\left(\frac{D}{D + 2k_e\Delta x\dfrac{m_{U,q}}{\cos(a_U + b_U\gamma)}}\right)^2$$

Reduction Identified Parameter	
k_e	0.6
$m_{U,1}$	0.1894
$m_{U,2}$	0.3603
$m_{U,3}$	0.0978
a_U	0.9631°
b_U	2.0105

[1] P. M. Gebraad, F.W. Teeuwisse, J.W. van Wingerden, P. A. Fleming, S. D. Ruben, J. R. Marden, and L. Y. Pao, "A data-driven model for wind plant power optimization by yaw control," 2014.

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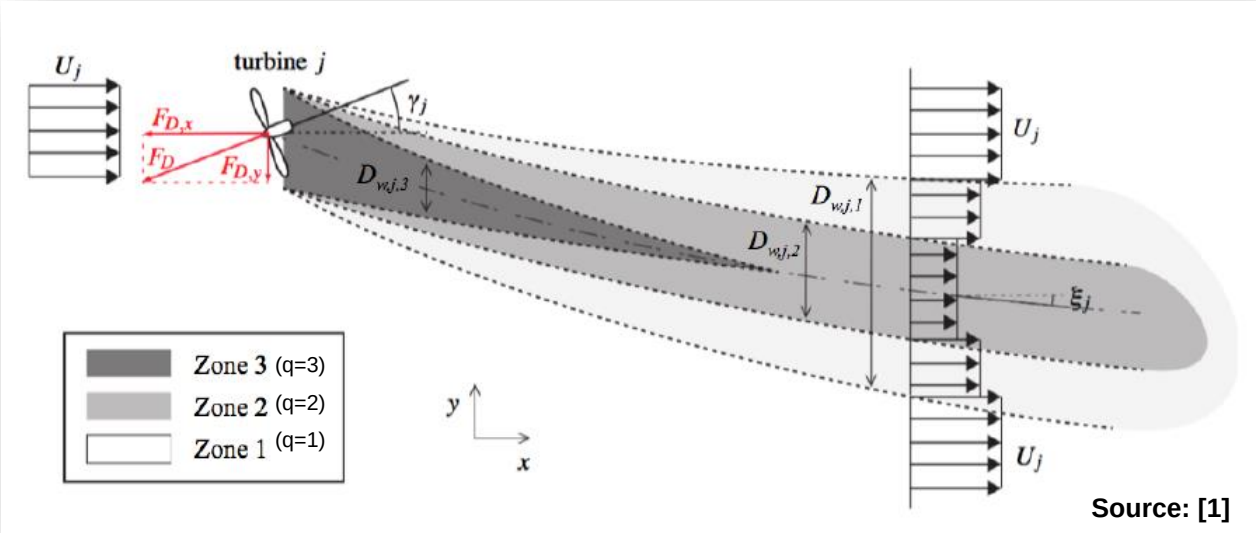

Source: [1]

Expansion

- Jensen Wake Model like
- Linear
- Negative coefficient in inner wake zone (near wake)
- k_e as parameter to be changed for different TI

Expansion Identified Parameter	
k_e	0.6
$m_{e,1}$	0.0040
$m_{e,2}$	0.0374
$m_{e,3}$	-0.0549

$$D_{w,q}(x) = 2k_e m_{e,q} \Delta x$$

[1] P. M. Gebraad, F.W. Teeuwisse, J.W. van Wingerden, P. A. Fleming, S. D. Ruben, J. R. Marden, and L. Y. Pao, "A data-driven model for wind plant power optimization by yaw control," 2014.

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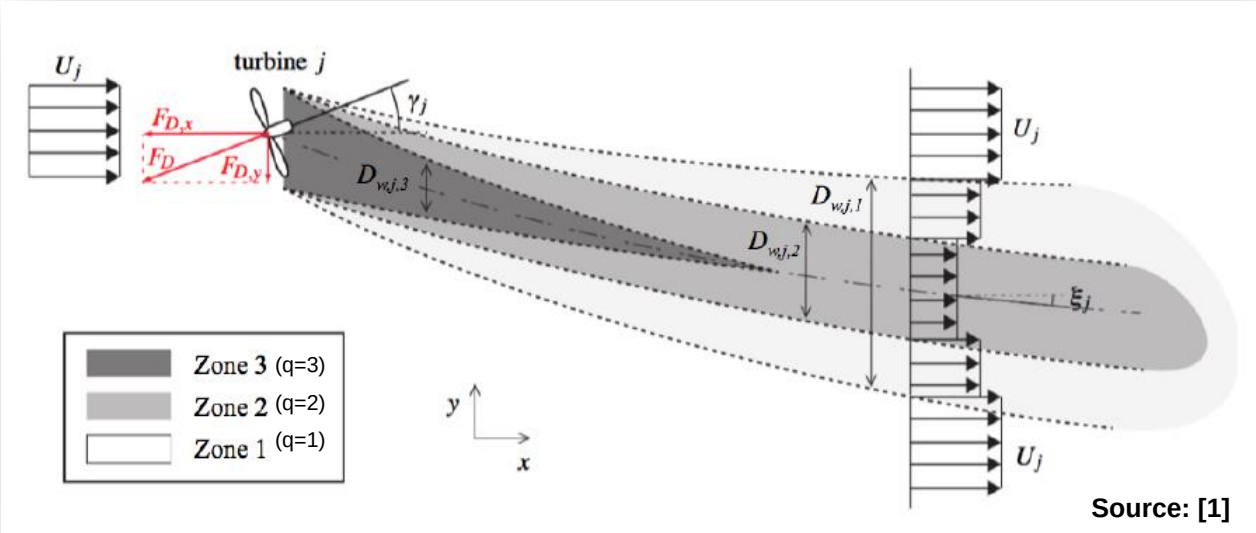


Source: [1]

Deflection

- Wake rotation induced (linear)
- Yaw induced (Jiménez et al.)

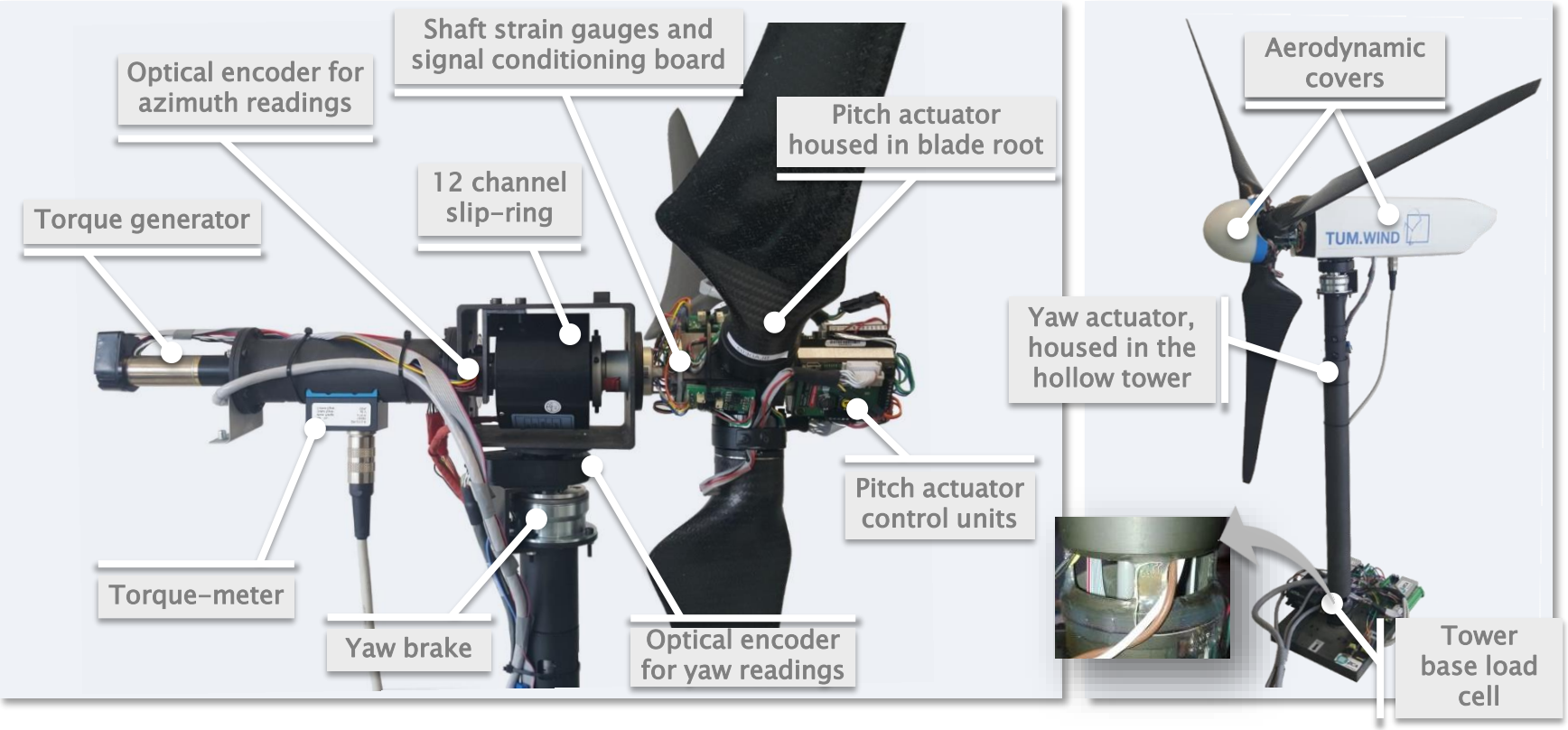
Deflection Identified Parameter	
k_d	0.1280
a_d	0.0108
b_d	-0.0036

$$y_w(c) = \delta_{w,rot}(x) + \delta_{w,yaw}(x)$$

$$\delta_{w,rot}(x) = a_d + b_d \Delta x$$
$$\delta_{w,yaw}(x) = f(\gamma, a, C_T, k_d)$$

[1] P. M. Gebraad, F.W. Teeuwisse, J.W. van Wingerden, P. A. Fleming, S. D. Ruben, J. R. Marden, and L. Y. Pao, "A data-driven model for wind plant power optimization by yaw control," 2014.

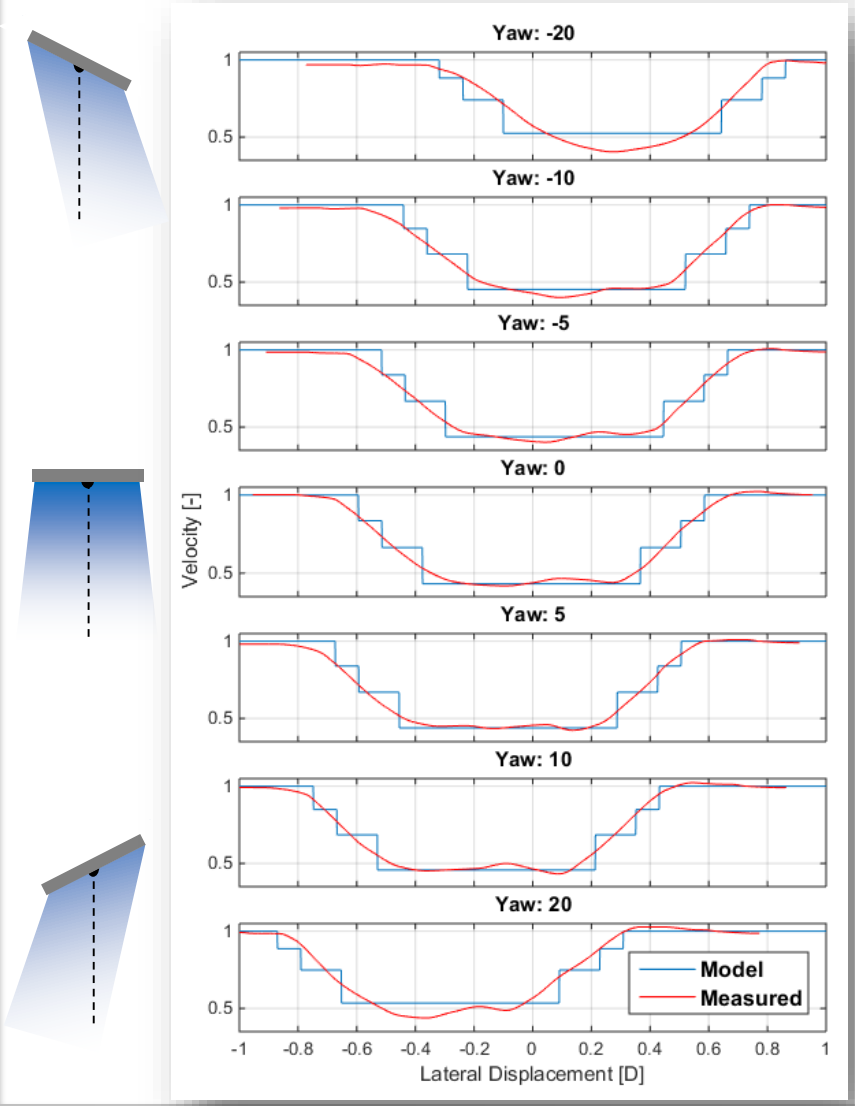
G1 – Generic Scaled Wind Turbine



Rotor diameter:	1.1m	Design TSR:	8
Tower height:	0.8 m	Rated rotor speed:	850 rpm

Campagnolo F, Petrović V, Schreiber J, Nanos E M, Croce A and Bottasso C L 2016 Wind tunnel testing of a closed-loop wake deflection controller for wind farm power maximization *Journal of Physics: Conference Series* **753** 32006

Wake Parameter Identification



Wake measurements

- Hot wire probes
- At hub height of isolated turbine
- Below rated wind speed
- Low TI (<1%)
- Different turbine yawing
- Identification of wake parameters θ by solving:

$$\min_{\theta} \int [V_{measured}(x) - V_{model}(x,\theta)]^2 dx$$

Process:

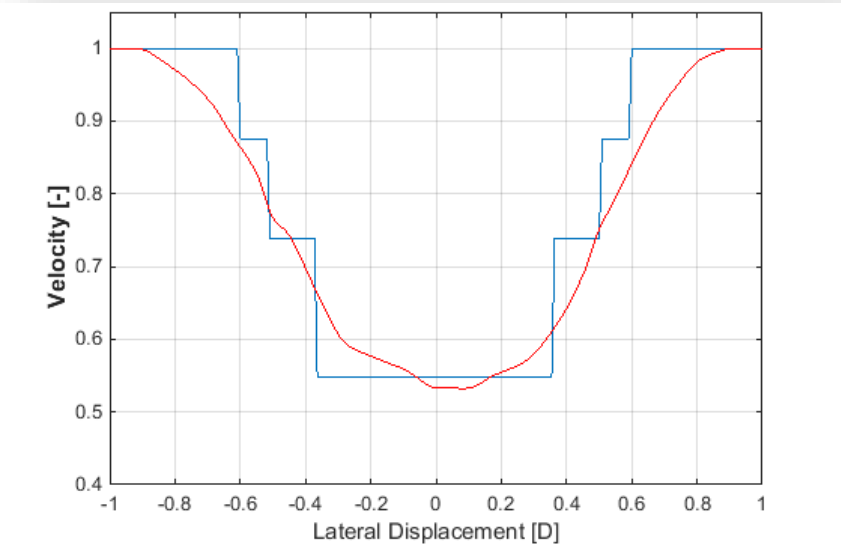
1. Identify linear wake deflection parameters ($\gamma = 0, \Delta x = 4D, 7D, 8D, 11D$)
2. Identify all other parameters ($\gamma = -20° \; to + 20°, \Delta x = 4D$)

◄ Wake at 4D longitudinal distance. Comparison between measurements and identified model for different turbine yawing.

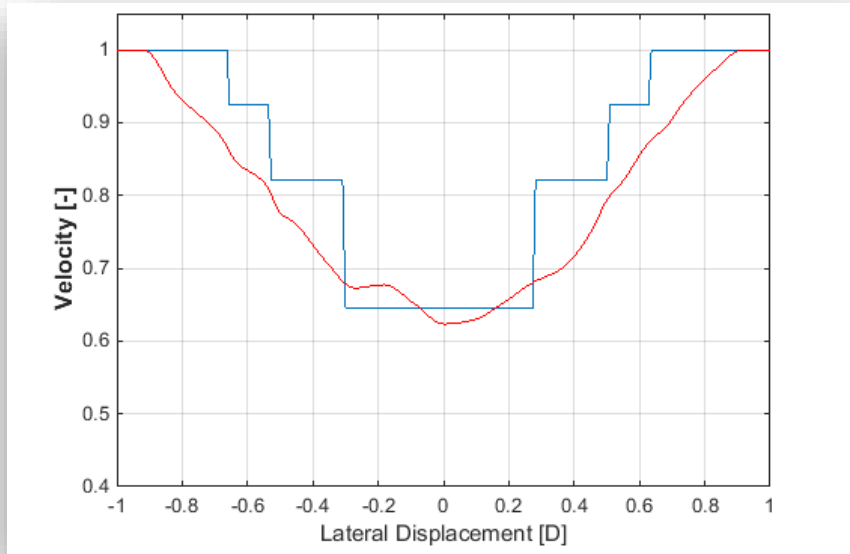
Wake Parameter Identification

Wake measurements at higher TI (~5%)

- k_e re-identification ($\gamma = 0, \Delta x = 4D$)



▲ Wake at 4D longitudinal distance (used for re-identification)



▲ Wake at 6D longitudinal distance

Wake model parameter summary:

- All wake parameter identified at low TI (<1%)
- Only k_e adaped for operation at higher TI (~5%), k_e=0.6549

Power Model

Power Calculation

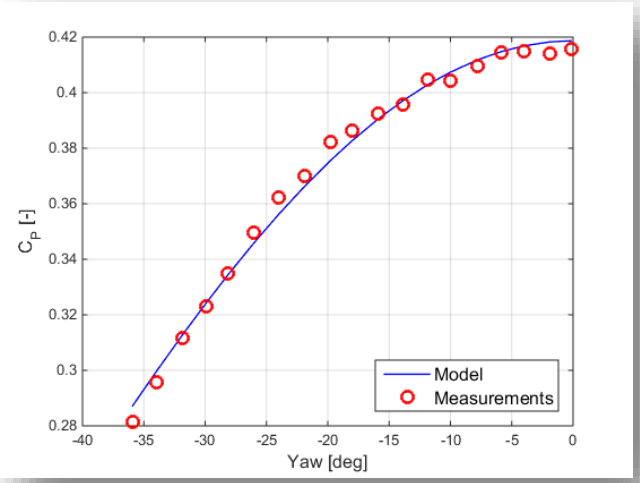
$$P = \frac{1}{2}\rho A V^3 C_P(\gamma)$$

Power Coefficient

$$C_P(\gamma) = C_{P,0}\cos(\gamma)^{p_p}$$

Power Identified Parameter	
p_p	1.787

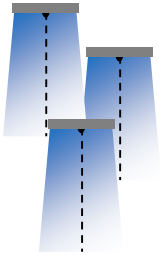
Measured and modeled $C_P(\gamma)$ ►



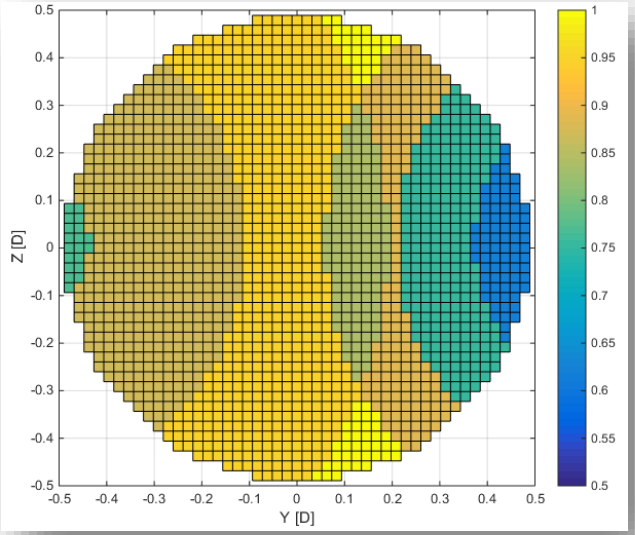
Multiple wake interaction

- Overlapping wakes

$$V = U_\infty \Pi(1 - r_i)$$



Flow at turbine affected by two wakes ►



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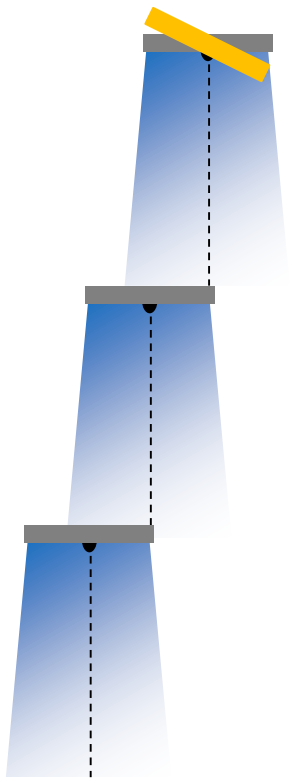
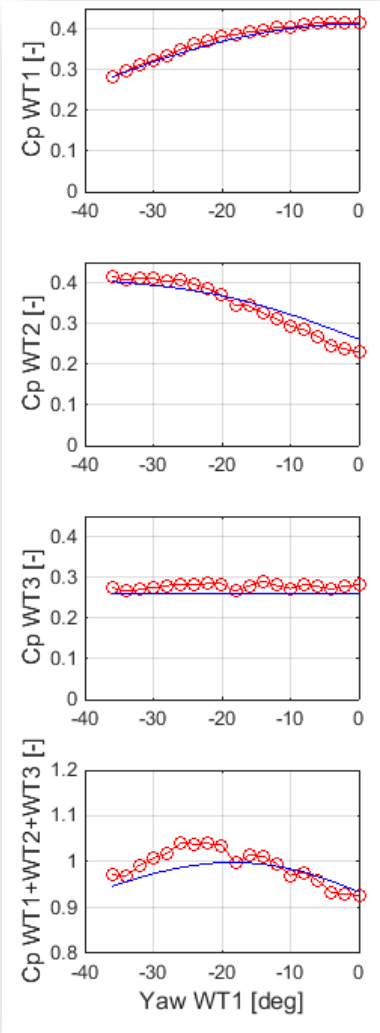
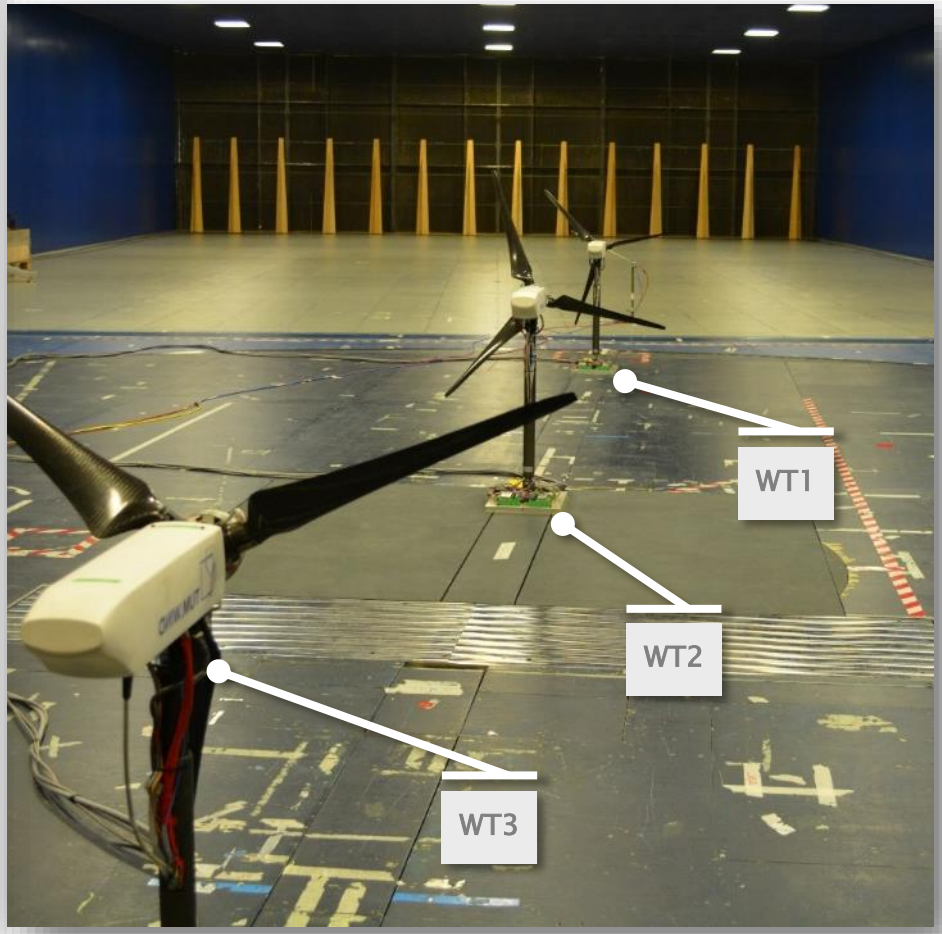
Scaled Experiments – Layout 1



Layout 1

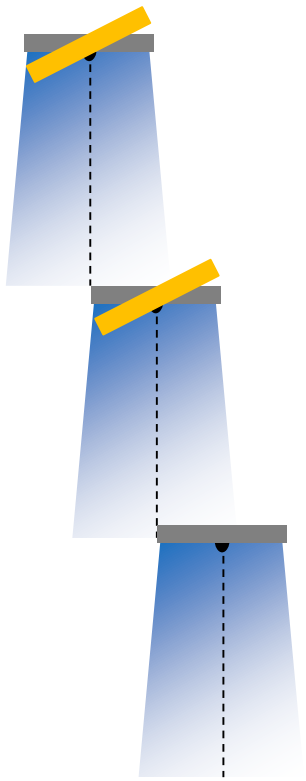


Wind farm with three wind turbines:



▲ Boundary layer wind tunnel at Politecnico di Milano (cross section 14x4m)

Scaled Experiments – Layout 2



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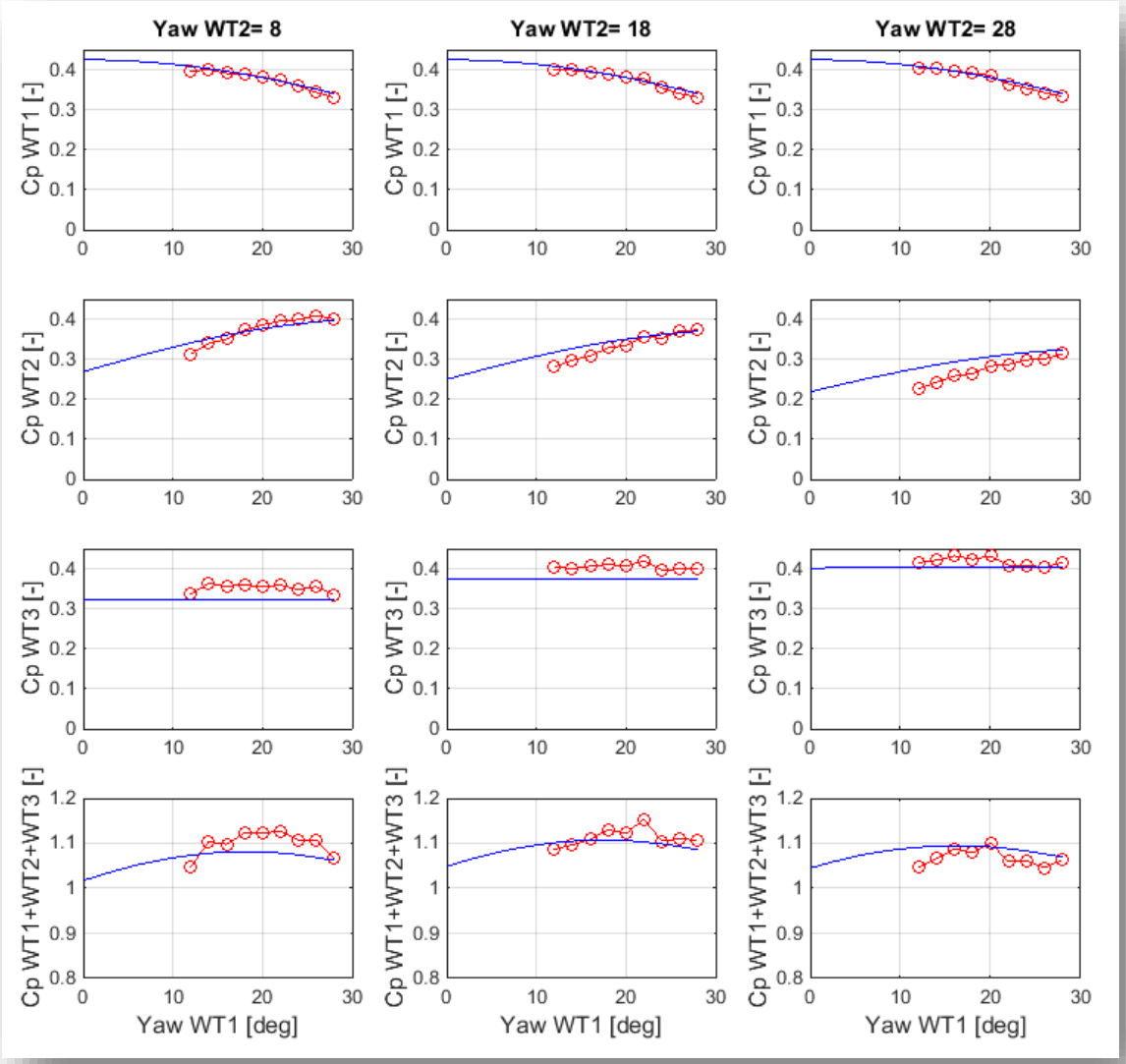

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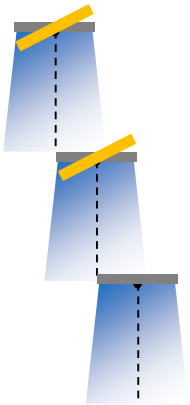

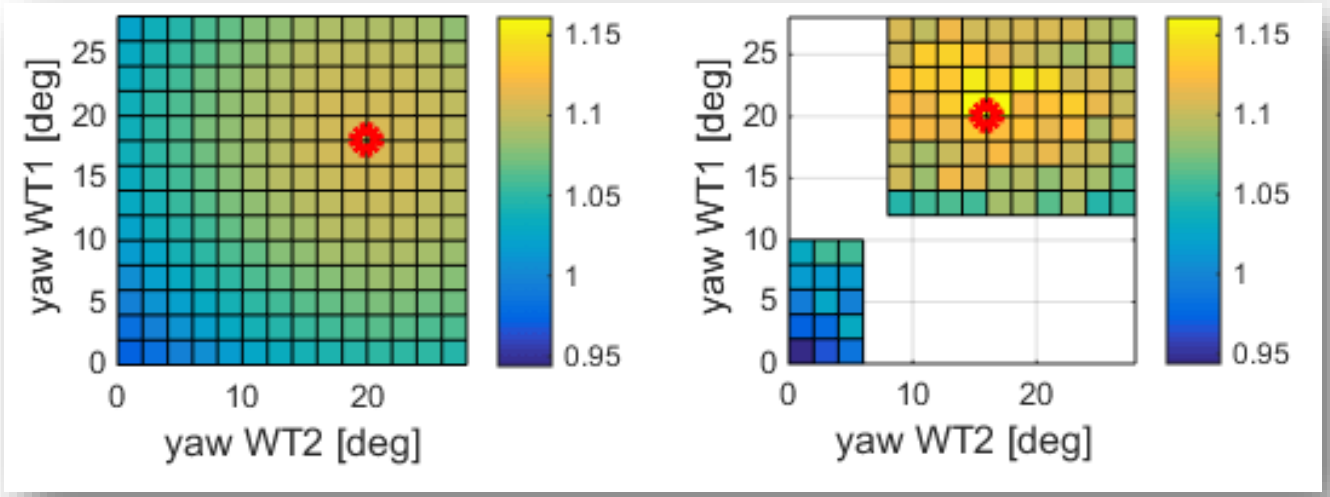

▲ **Model** total WF-Cp ▲ **Experiment** total WF-Cp

- Model determines roughly the optimum yaw configuration:
  - Optimum model: Yaw WT 1: 18° Yaw WT 2: 20°
  - Optimum experiment: Yaw WT 1: 20° Yaw WT 2: 16°
- Both show **power increase > 10%** (w.r.t. not yawing)
- But what happens in case of disturbances (i.e. wrong wind direction as model input)?

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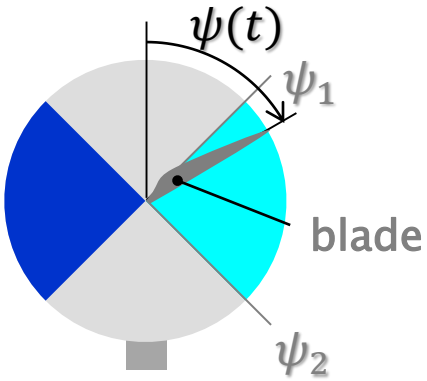
Wake Position Estimation from Rotor Loads

Using blade out of plane loads the **wind speed at each blade position** (blade effective wind speed V_{BE}) can be estimated through the cone-coefficient:

$$C_{m_0}(\lambda_{\mathrm{LE}}, \beta, q) = \frac{m(\psi)}{\frac{1}{2}\rho A R V_{\mathrm{BE}}{}^2}$$



The estimated blade effective wind speed gives velocity at different parts of the rotor disk or the **horizontal wind shear.**

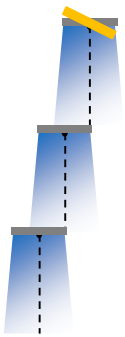
By comparing the

- **observed** horizontal wind shear and rotor speed at a wind turbine and
- **expected** properties (based on a wake deficit model)

one can estimate the wake position.

See also: J Schreiber, S Cacciola, F Campagnolo, V Petrović, D Mourembles and C L Bottasso 2016 Wind shear estimation and wake detection by rotor loads — First wind tunnel verification *Journal of Physics: Conference Series* **753** 32027

Wake Position Estimation from Rotor Loads



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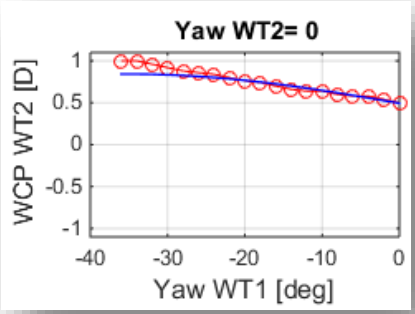
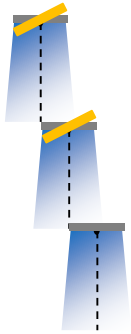
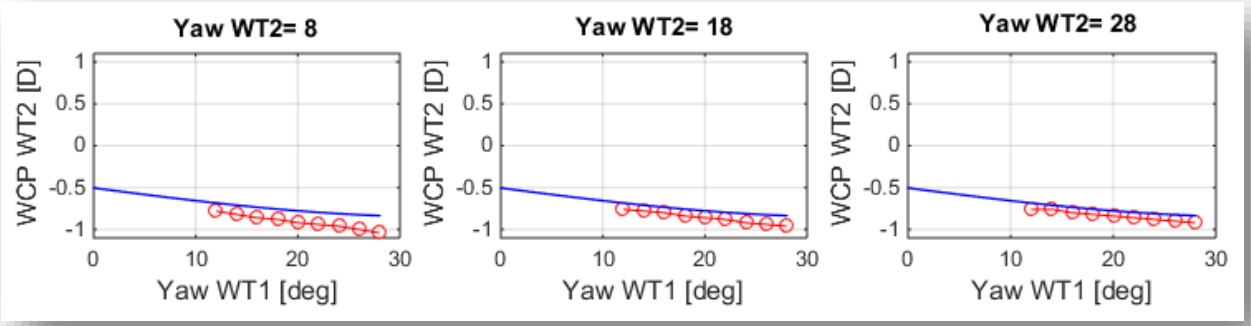


- Difference between modeled and observed wake center position (WCP < 0.2D)
- Modeled wake positions base on isolated wake measurement at low TI
- 0.2D also corresponds to a wrong wind direction of only 3°



Layout 2



Model
Measurements

Wake Position Estimation: An Experiment

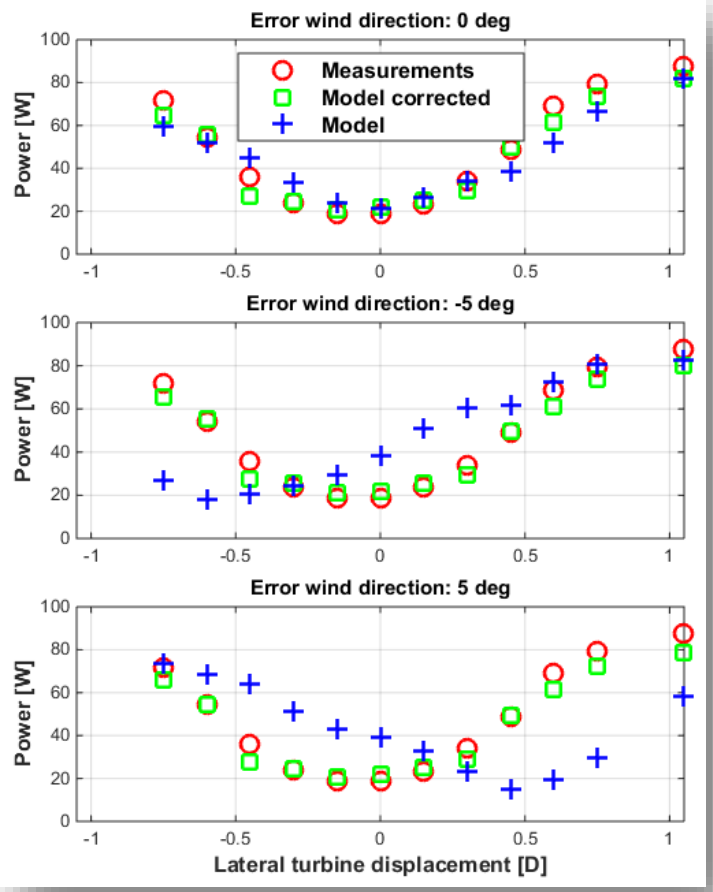
Disturbance in wind direction:

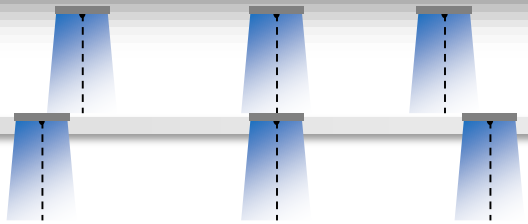
- No error in ROWFM-wind direction: Model predictions are good (upper subplot)
- Error in ROWFM-wind direction: Model predictions fail completely (lower subplots)

Using Wake Position Estimator:

- Instead of ROWFM-wake position, the observed wake position is used in the model (Model corrected)
- Much better power prediction in all cases

Wake position estimation can be valuable information in wind farm control!





Note: A different turbine model (G2) has been used in those experiments.

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Conclusions & Outlook

Conclusions:

- **ROWFM parameter identified** for scaled wind turbine G1 (at low TI)
- Simple (single) parameter adaptation for higher TI
- Sucessful **prediction of approx. optimum yaw configuration** in scaled experiments
- Wake position observer can **improve knowledge on wind farm flow**

Outlook:

- Study of further experiments in additional layouts
- Employ wind observer and/or wake position observer
  - to **improve knowledge of model input** (ambient wind direction)
  - as **feedback in closed loop wind farm control**

Thank you for your attention!