Wind Farm Effects

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Lecture #12
Controller Design for
Wind Turbines and Wind Farms

Hochschule Flensburg
University of Applied Sciences

SWE Stuttgart Wind Energy
@ Institute of Aircraft Design

Wind Energy Technology Institute

Schedule

02.09.	1	Controller Design Objectives and Modeling
03.09.	2	Baseline Generator Torque Controller
04.09.	3	Collective Pitch Controller
05.09.	4	Filter Design
06.09.	7	Wind Field Generation
09.09.	10	Lidar-Assisted Control I
10.09.	11	Lidar-Assisted Control II
11.09.	5	Tower Damper
12.09.	6	Advanced Torque Controller
12.09.	8	Steady State Calculations
16.09.	9	Individual Pitch Control
17.09.	12	Wind Farm Effects
18.09.	13	Wind Farm Control
19.09.	14	Floating Wind Control I
20.09.	15	Floating Wind Control II

Wind farms

Horns Rev wind farm.
Photo by C. Steiness.

“...a humid and warm air mass was advected from the southwest over cold sea and the dew-point temperature was such that cold-water advection fog formed in a shallow layer...The condensation appears to take place primarily in the wake regions with relatively high axial wind speed and high turbulent kinetic energy.”[1]

Motivation wind farms

- Costs of the grid connection $\searrow$
- Maintenance costs $\searrow$
- Land pollution $\searrow$

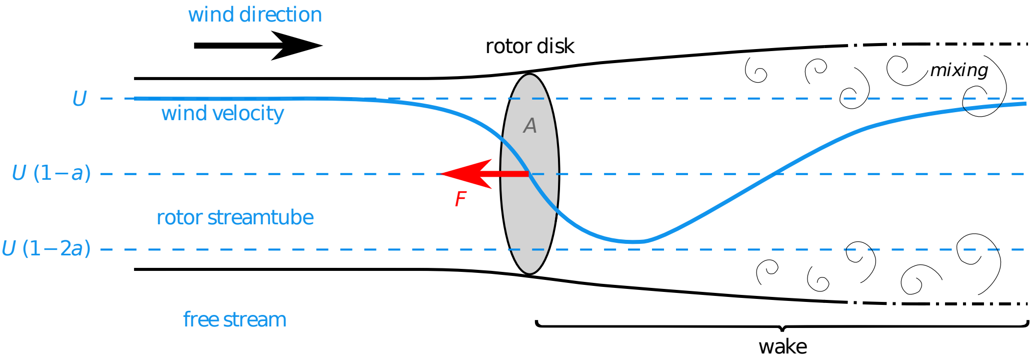
Motivation wind farm control

- Energy production $\nearrow$
- Structural loading $\searrow$
- Energy quality $\nearrow$

Main questions

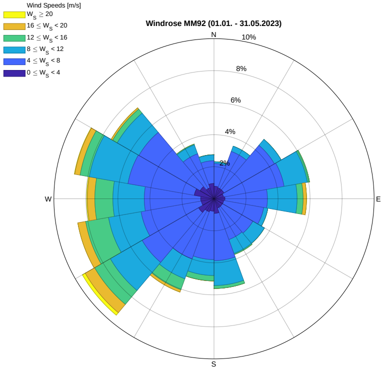
- How can we optimize wind farm operation?
- What are current challenges?

Wind turbine wakes



Simplified representation of a wake [2].

Yaw control



based on [Daniel Pereira (2022)]

Motivation yaw control

- Wind direction is usually not constant
- Upwind turbines usually better aerodynamics, no tower shadow
- Active yaw control is necessary

Main questions

- How is a yaw controller for wind turbines implemented?
- Can we improve yaw control with Lidar?

Learning objectives

After this lectures you should be able to...

- explain the measurement principle of different sensors for yaw control
- explain how yaw control works
- calculate the wake losses using the Jensen wake model
- name and explain the three main concepts of wind farm control
- explain the main challenges in wind farm control

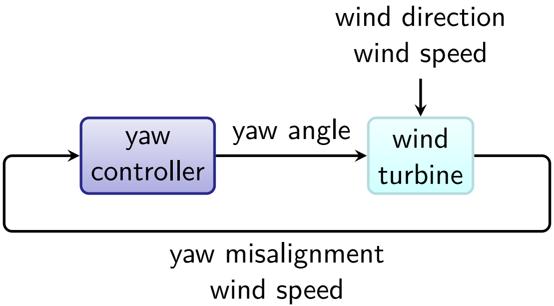
Contents

1. Yaw Control

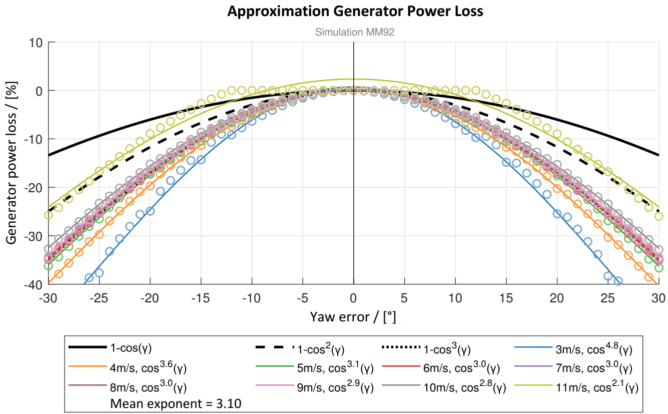
2. Wind Farm Modelling

3. Conclusion

Yaw control loop



Simplified approximation of losses due to yaw missalignment



[own calculations]

$P(\gamma) = P_{\max} \cos^n(\gamma)$ with BEM $n = 3$, from simulations and measurements $n = 1.88$ to 5.14, mostly around 2 to 3.

Conventional sensors for yaw control

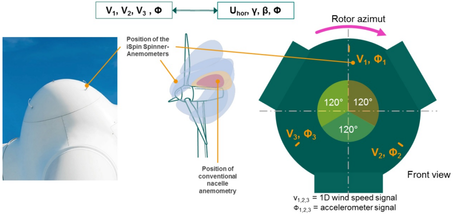
[Thies]

Combined wind vane and cup anemometer

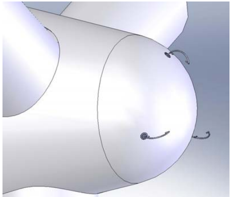
[Lufft]

Heated ultra sonic anemometer

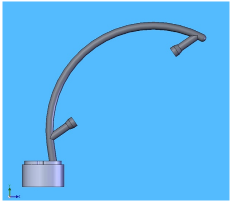
New sensors for yaw control



[ROMO Wind]



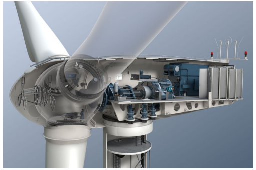
[Pedersen, T.F. (2010)]



[Pedersen, T.F. (2010)]

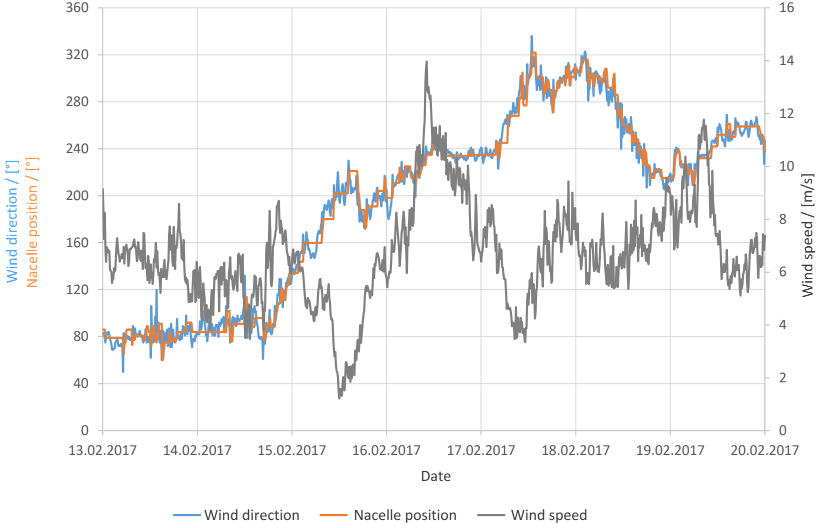
iSpin Spinner Anemometer Technology allows measurement of wind quantities like wind speed and yaw misalignment at the spinner using ultrasonic anemometer

Actuators for yaw systems

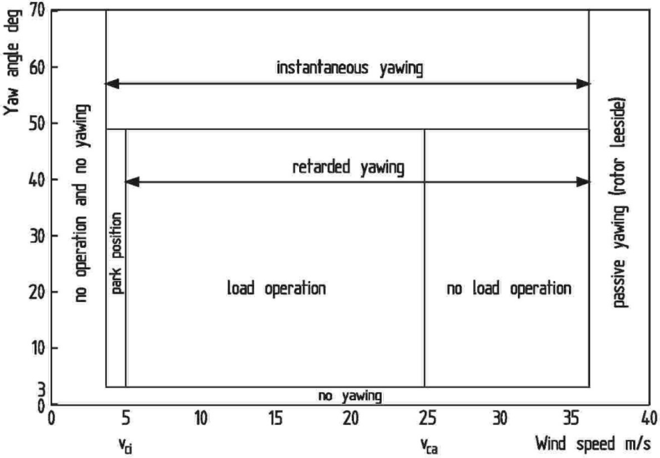


- Mainly electric motors with flange-mounted gears and pinions on the output side
- Brake system consists of several hydraulic brake calipers and a brake disc
- Brake system is always active, adjustment of pressure level depending on operating mode (yawing: low pressure, fixing: higher pressure)
- Nacelle normally has to be turned back after 720°
- Typical adjustment speed approx. $0.5^\circ\,\mathrm{s}^{-1}$

Yaw control at a real wind turbine



Yaw control strategy



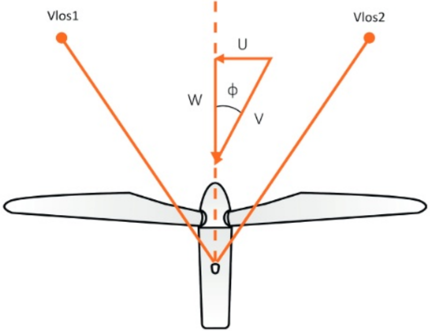
Yaw control example GROWIAN II [3]

Strategy

- Based on averaged signals
- Yaw not activated, if wind speed is too low or high
- Yaw does not change below a certain threshold
- Reaction depends on misalignment

Lidar for yaw control

[Windar]

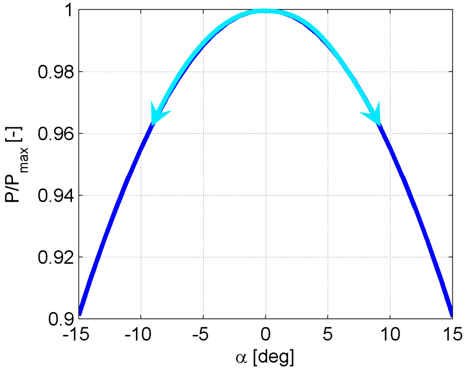


[Windar]

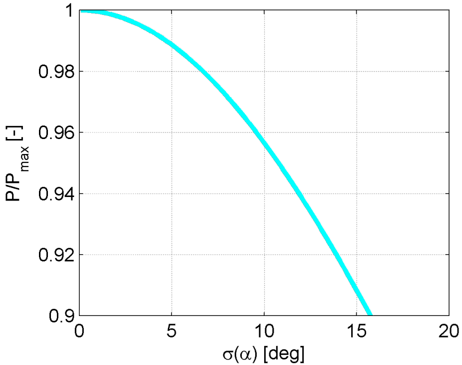
Nacelle-based lidar

Reconstruction of wind direction

Possible improvements with lidar-assisted yaw control [4]

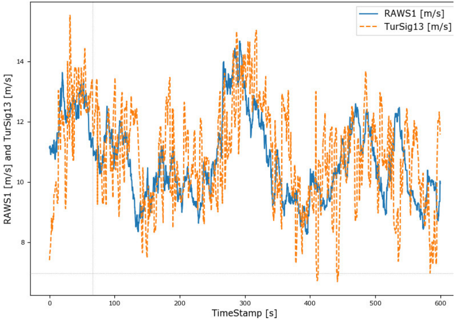


Static yaw misalignment



Dynamic yaw misalignment

Project ABBA (Link to the Project)



Development, evaluation and testing of adaptive operating and control strategies

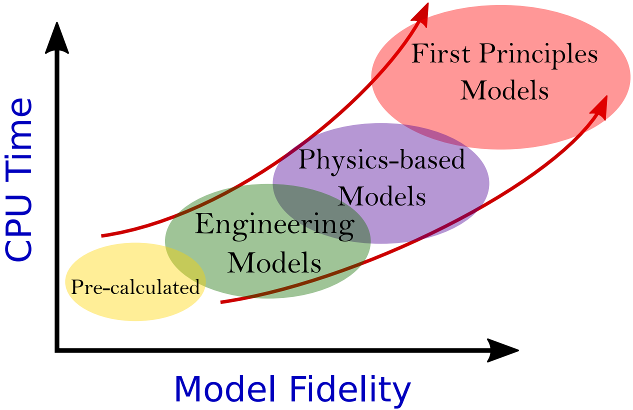
- Integration of energy price, lidar-based wind forecasting and load monitoring
- Lifetime extension and increase of energy yield, reduction of noise emissions and grid support through data-based control

Wind farm models

Components wind farm model

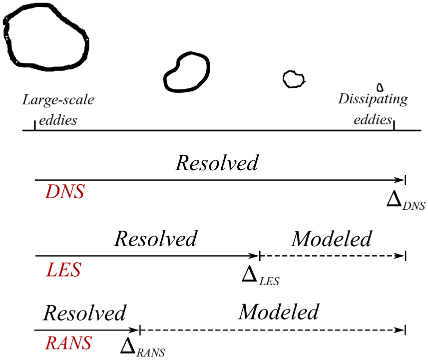
- Rotor model
  - ADM: Actuator Disk Model
  - ADM-R: Rotating Actuator Disk Model
  - ALM: Actuator Line Model
- Turbine model (stiff, elastic (e.g. FAST), ...)
- Flow model (describes wake characteristics)

Fidelity of wind farm models versus CPU time



[An Analysis of Engagement Algorithms for Real-Time Weapons Effects]

High and medium fidelity

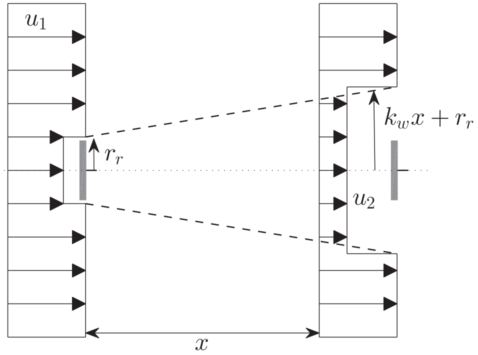


[Lecture slides Dr. A. Bakker]

Methods to solve Navier-Stokes equations

- DNS: Direct Numerical Simulation
- LES: Large Eddies Simulation
- RANS: Reynolds-Averaged Navier-Stokes

Jensen wake model 1/3



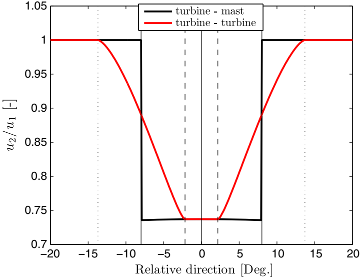
[5]

Reduction of wind speed

$$u_2 = u_1 \left(1 - \frac{1 - \sqrt{1 - c_\mathrm{T}}}{(1 + k_w x / r_r)^2}\right)$$

wake decay coefficient
$k_w = 0.075$ onshore
$k_w = 0.040$ offshore

Jensen wake model 2/3



[5]

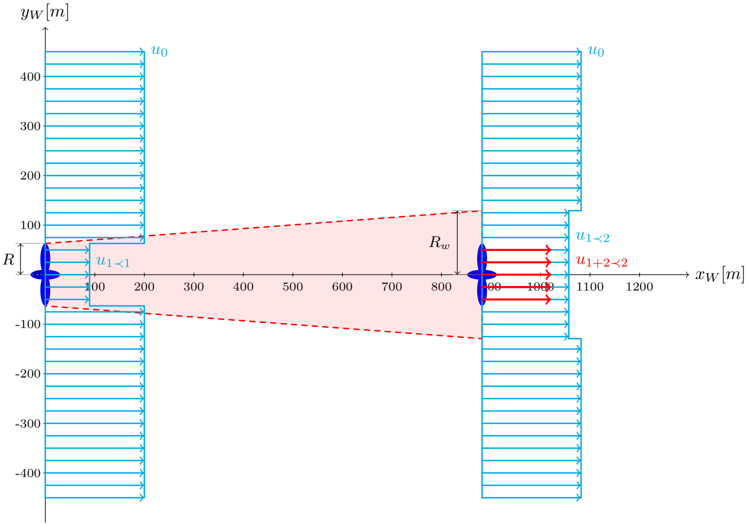
Linear approximation partial wake effect

$$
\begin{aligned}
u_{2p} &= u_2 & \forall |y| \le k_w x\\
u_{2p} &= u_1 & \forall |y| \le k_w x + 2r_r\\
u_{2p} &= f(u_1, u_2, y) & \forall k_w x < |y| < k_w x + 2r_r
\end{aligned}
$$

with f a linear interpolation

$f = \frac{y - k_w x}{2r_r} u_1 + \frac{k_w x + 2r_r - y}{2r_r} u_2$

Jensen wake model 3/3

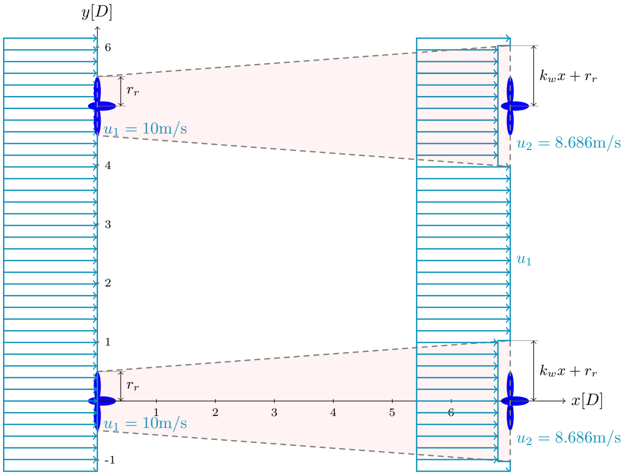


[5]

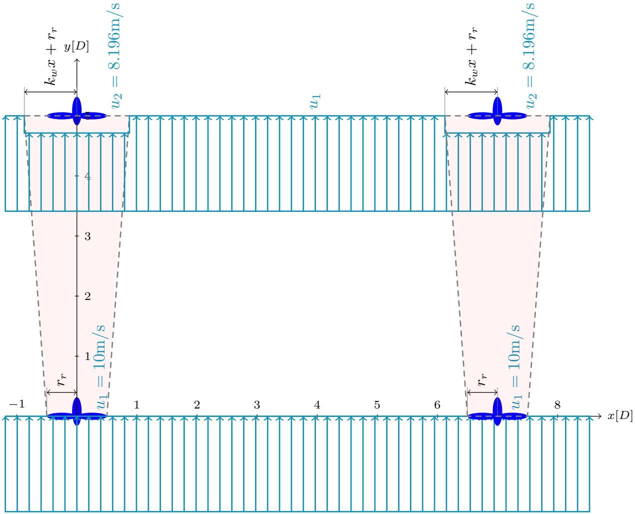
Wake overlap

$$\delta_n = \sqrt{\sum_{i=1}^{n} \delta_i^2}$$

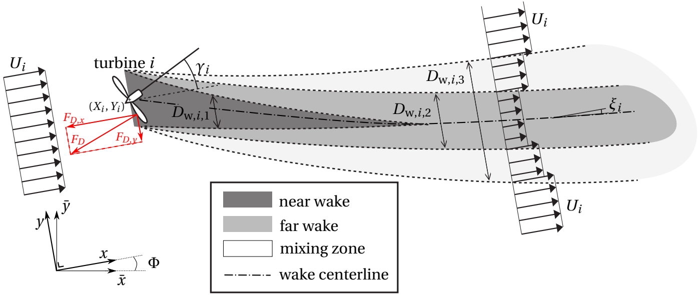
Jensen wake model - case study



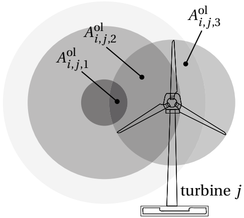
Jensen wake model - case study



FLORIS: FLOw Redirection and Induction in Steady State



(a) Top view



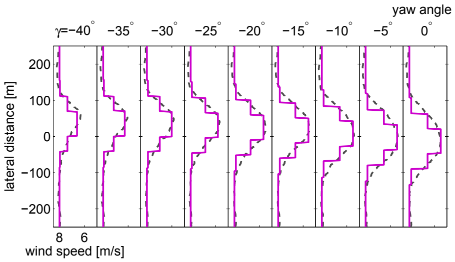
(b) Cut-through at downstream turbine

[6]

Ansatz multi zone model

- Combine effects of yaw control on redirection of wake and velocity in the wake.
- Separate wake into 3 zones: near wake ($q = 1$), far wake ($q = 2$), mixed zone ($q = 3$).
- Identify model parameters from data.

Multi zone model



[6]

Diameter of wake zones

$$D_{w,q}(x) = \max\left(D + w k_e m_{e,q}\left[x - X\right]\right)$$

with D turbine diameter, $x \geq X$ distance in downwind direction and m_e and $k_{e,q}$ fitted to simulation data

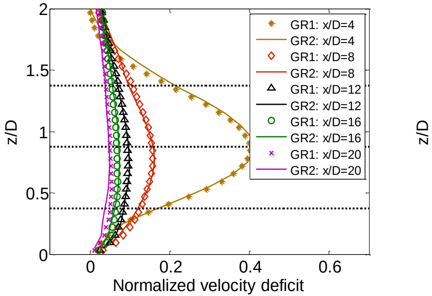
Decay of velocity deficit

$$U_w(x, y) = U\left(1 - 2ac_q(x, y)\right)$$

$$c_q = \left(\frac{D}{D + 2k_e m_{U,q}(\gamma)(x - X)}\right)^2$$

with γ yaw angle and k_e and $m_{U,q}$ fitted to simulation data

Gaussian wake model



[7]

Ansatz Gaussian wake model

- fit continuous Gaussian normal distributions to the velocity deficit
- extension for higher order "Super-Gaussians"

Conclusion

- How is a yaw controller for wind turbines implemented?
- Can we improve yaw control with Lidar?

- slow control loop independent from pitch and torque control
- lidar might help to increase energy, depends on inhomogeneity and control strategy

References

[1] C. B. Hasager, N. G. Nygaard, P. J. H. Volker, I. Karagali, S. J. Andersen, and J. Badger. "Wind Farm Wake: The 2016 Horns Rev Photo Case". In: *Energies* 10.3 (2017), p. 317. DOI: 10.3390/en10030317.

[2] P. M. O. Gebraad. "Data-driven wind plant control". PhD thesis. Delft University of Technology, 2014. DOI: 10.4233/uuid:5c37b2d7-c2da-4457-bff9-f6fd27fe8767.

[3] E. Hau. *Wind Turbines: Fundamentals, Technologies, Application, Economics*. Springer, 2006. ISBN: 978-3-540-29284-5.

[4] D. Schlipf et al. "Prospects of optimization of energy production by LIDAR assisted control of wind turbines". In: *European Wind Energy Association Annual Event*. Brussels, Belgium, Mar. 2011. DOI: 10.18419/opus-3916.

[5] A. Peña, P.-E. Réthoré, and M. P. van der Laan. "On the application of the Jensen wake model using a turbulence-dependent wake decay coefficient: the Sexbierum case". In: *Wind Energy* 19.4 (2016), pp. 763–776. DOI: 10.1002/we.1863.

[6] P. M. O. Gebraad and J. W. van Wingerden. "A control-oriented dynamic model for wakes in wind plants". In: *Journal of Physics: Conference Series* 524.1 (2014), p. 012186. DOI: 10.1088/1742-6596/524/1/012186.

[7] M. Abkar and F. Porté-Agel. "Influence of atmospheric stability on wind-turbine wakes: A large-eddy simulation study". In: *Physics of Fluids* 27.3 (Mar. 2015), p. 035104. DOI: 10.1063/1.4913695.

Please let me know if you have further questions!

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