

Experimental testing of induction based control strategies for wind farm optimization

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Outline

1. Motivation
2. Methods
3. Theory: *wake control*
4. Results
5. Discussion & future work

Motivation

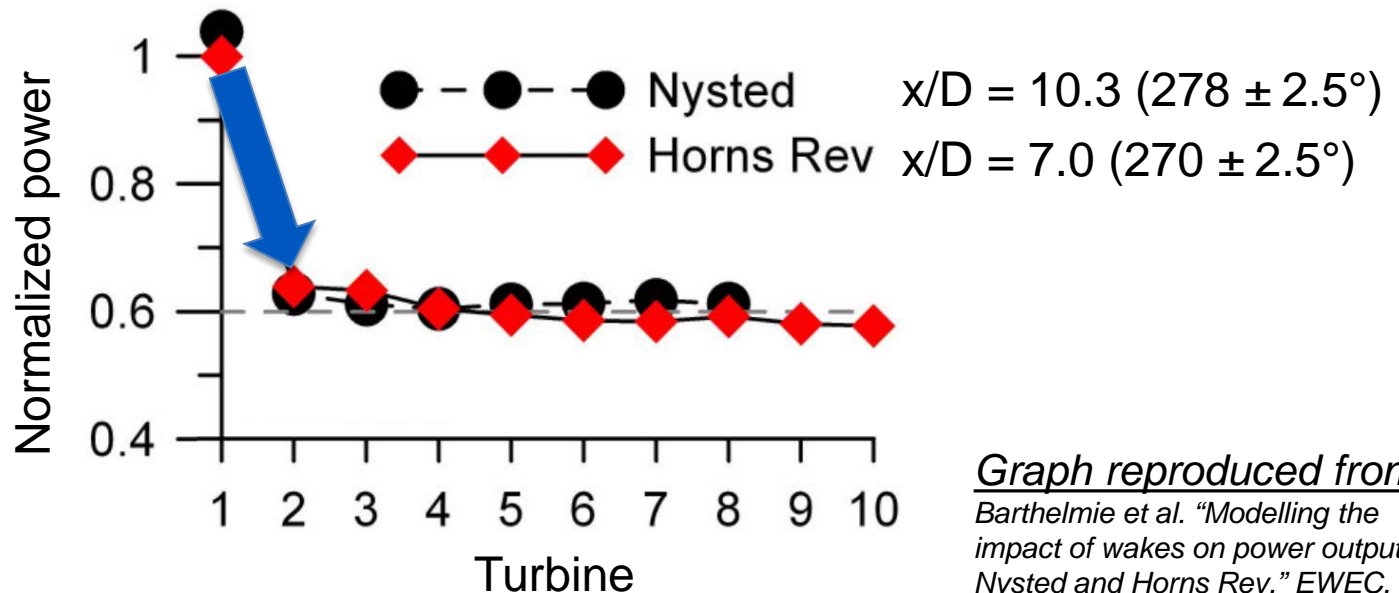
Wake effects in a wind farm



*Picture source: Hasager et al., "Wind Farm Wake: The Horns Rev Photo Case", Energies 2013,
Picture courtesy: Vattenfall*

Motivation

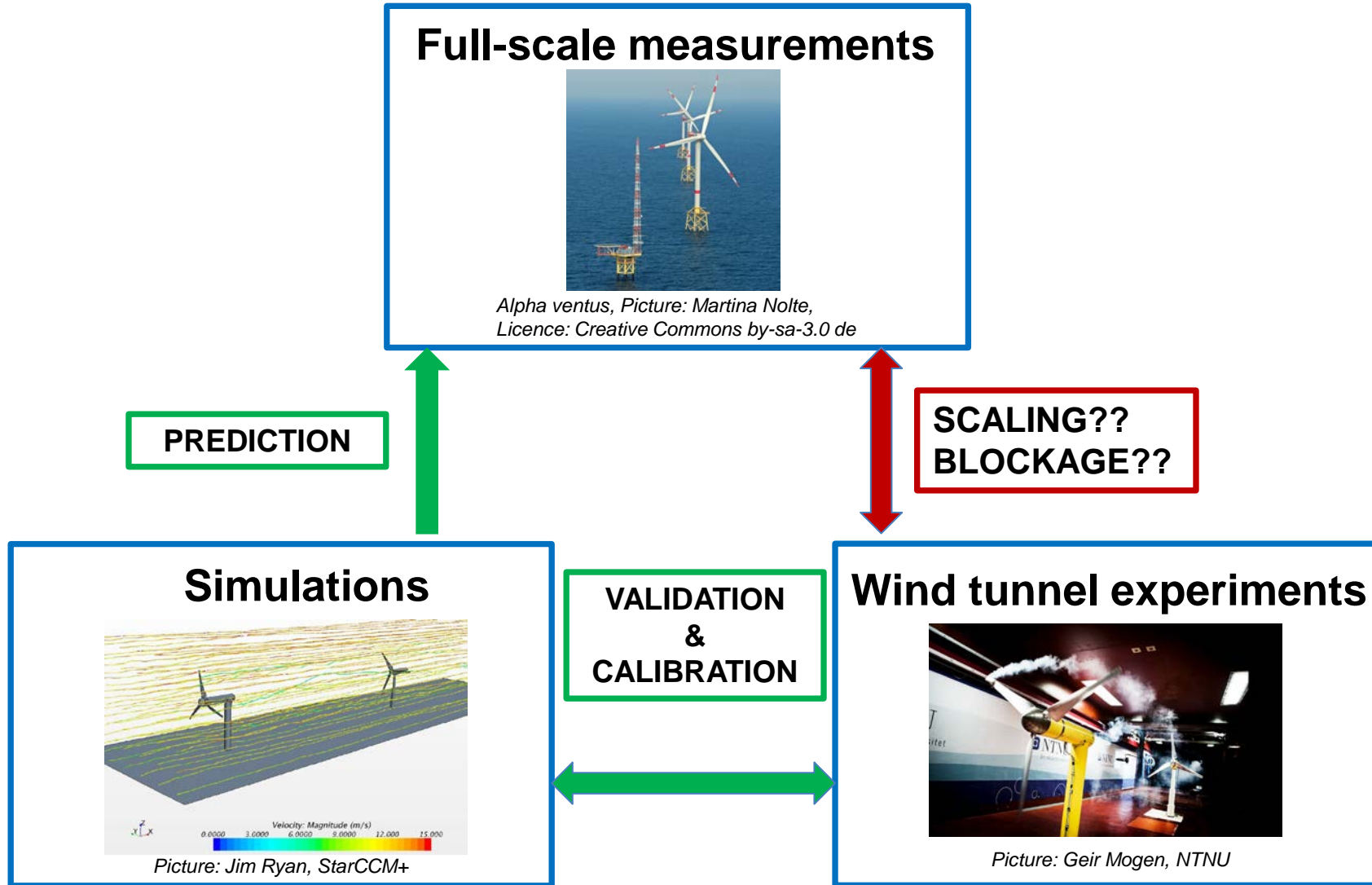
Normalized power at Horns Rev and Nysted for wind directions of full wake interaction



*Graph reproduced from:
 Barthelmie et al. "Modelling the
 impact of wakes on power output at
 Nysted and Horns Rev." EWEC,
 2009.*

⇒ Biggest power drop (~35%) between first and second row

Methods: wind tunnel experiments



Low speed wind tunnel at NTNU



Picture credit: Geir Mogen/NTNU

Grid generated inlet turbulence

Simulation of background turbulence

TI \approx 10% at upstream turbine, TI \approx 5% at downstream turbine



Background

Basic strategies for wake control

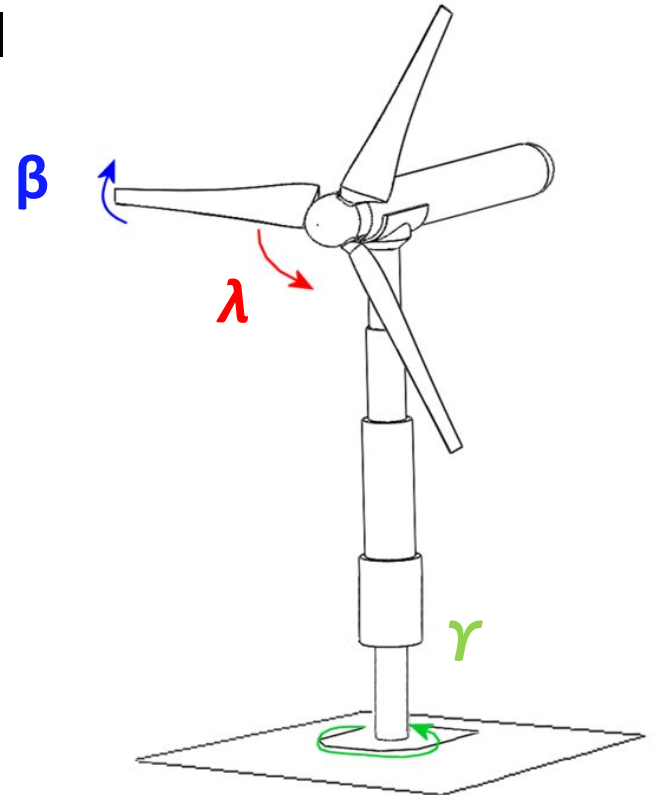
Axial induction based control

λ : torque (TSR) control

β : blade pitch angle control

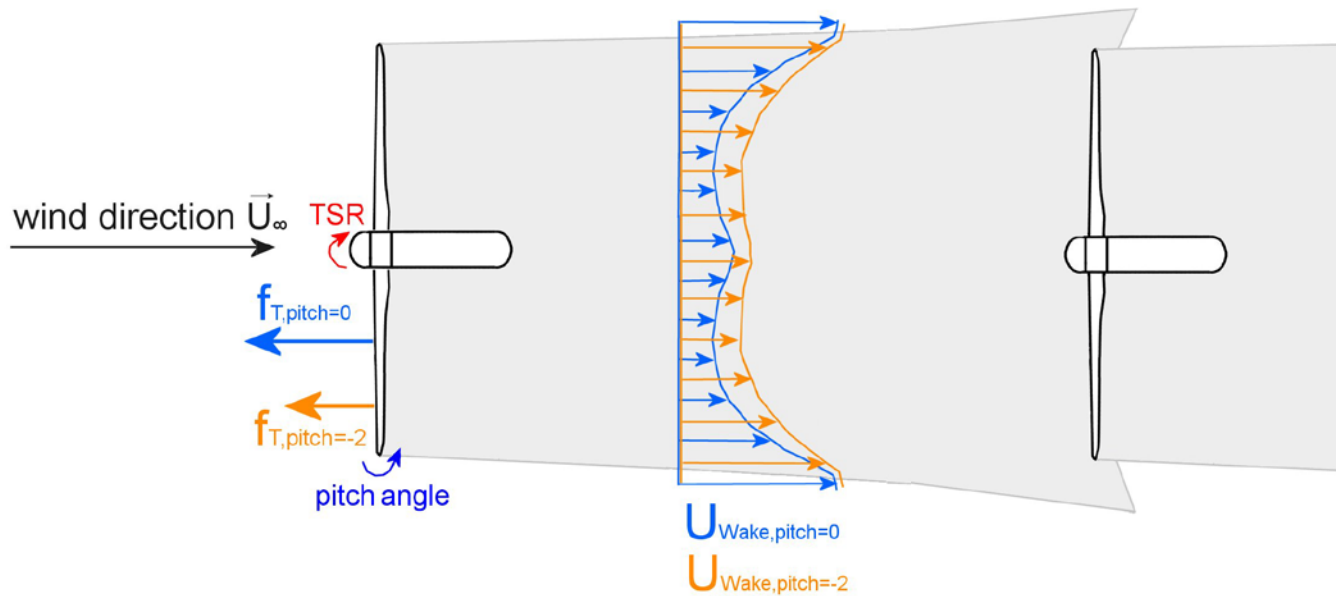
Wake deflection control

γ : turbine yaw angle control



\Rightarrow *Reduce energy capture of upstream turbine to the benefit of the downstream turbines*

Axial induction based wake control

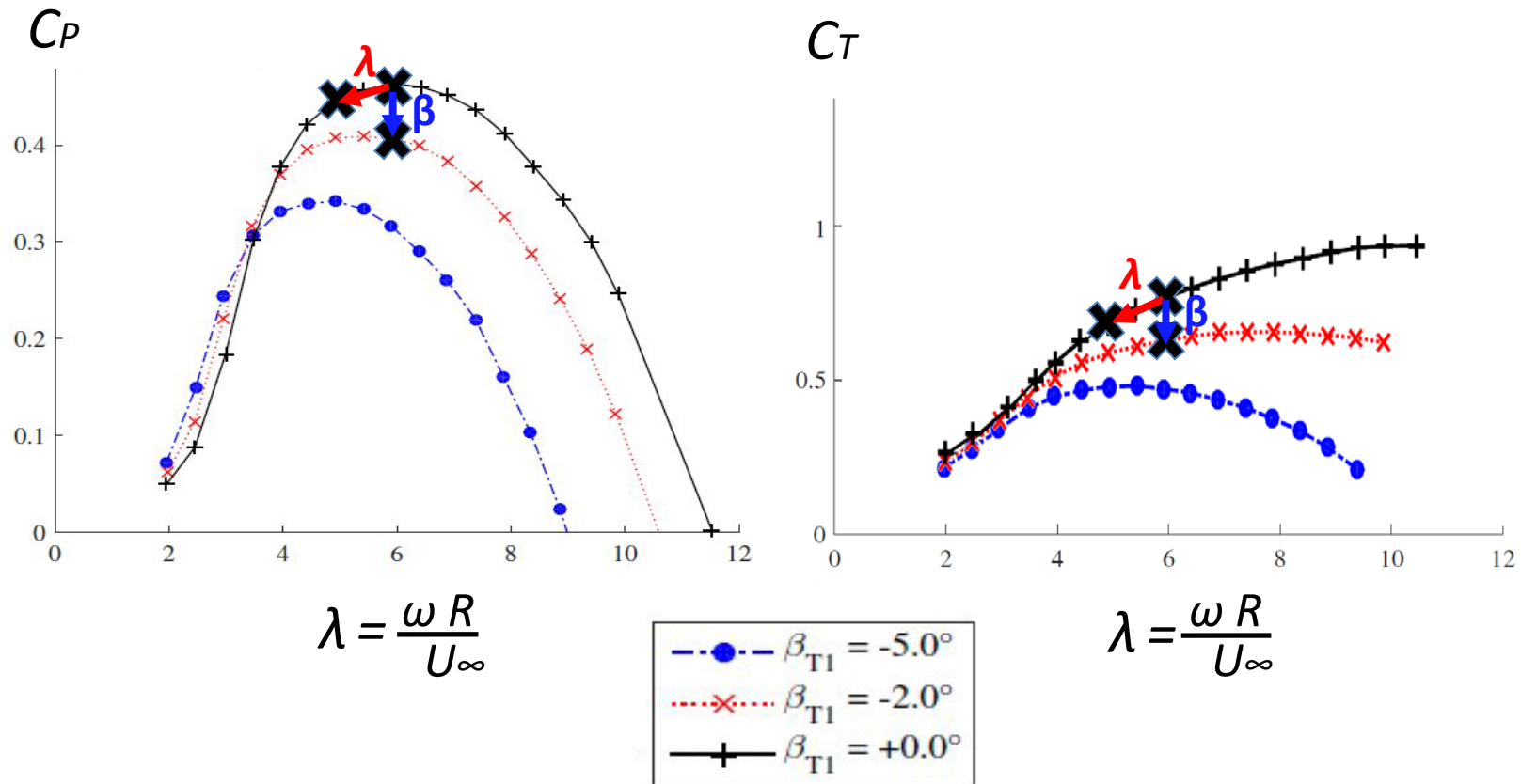


Variation of upstream **turbine tip speed ratio λ** or **pitch angle β**

⇒ assessment of mean and turbulent wake flow

⇒ assessment of downstream turbine performance (C_P , C_T)

Axial induction based wake control



Results

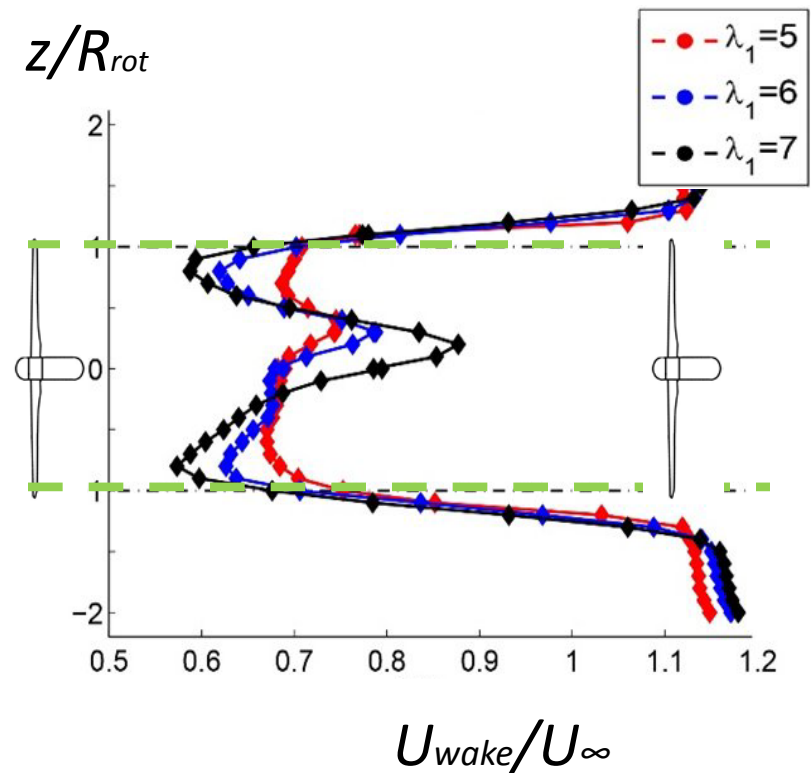
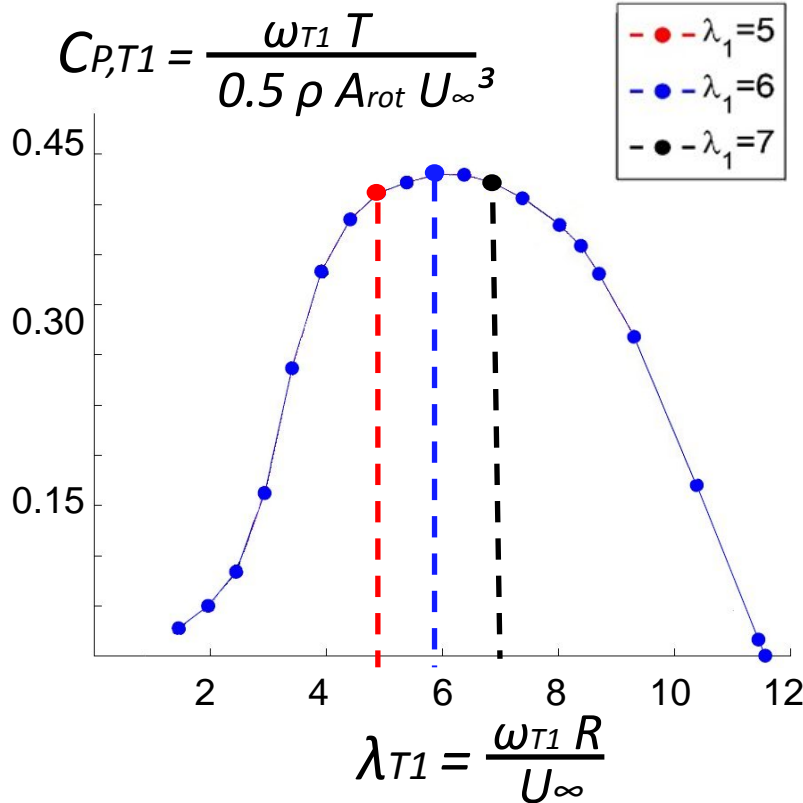
λ -variations:

Selected results of Master thesis by
C. Ceccotti, A. Spiga, P. Wiklak and S. Luczynski

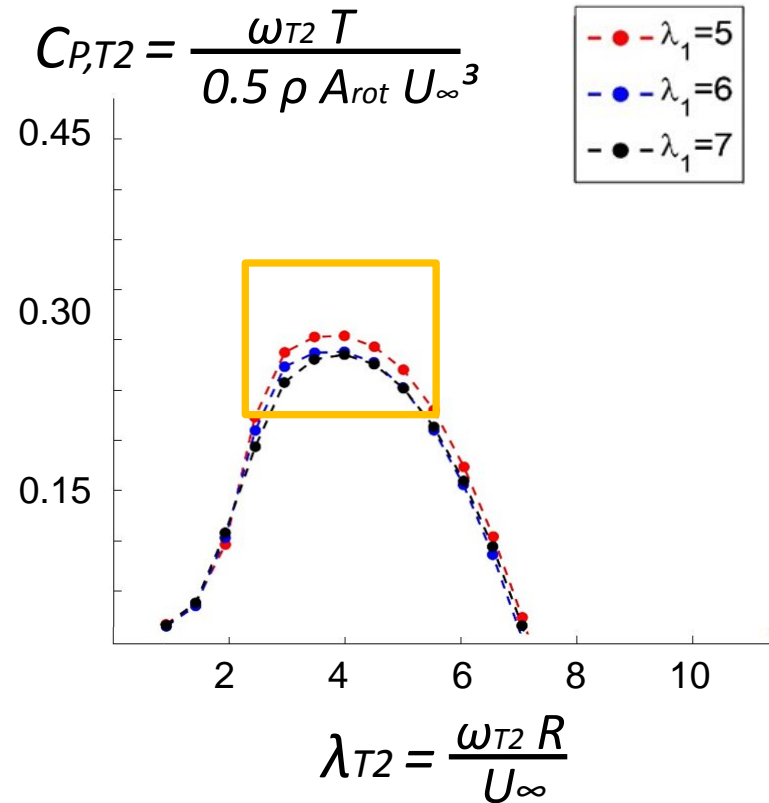
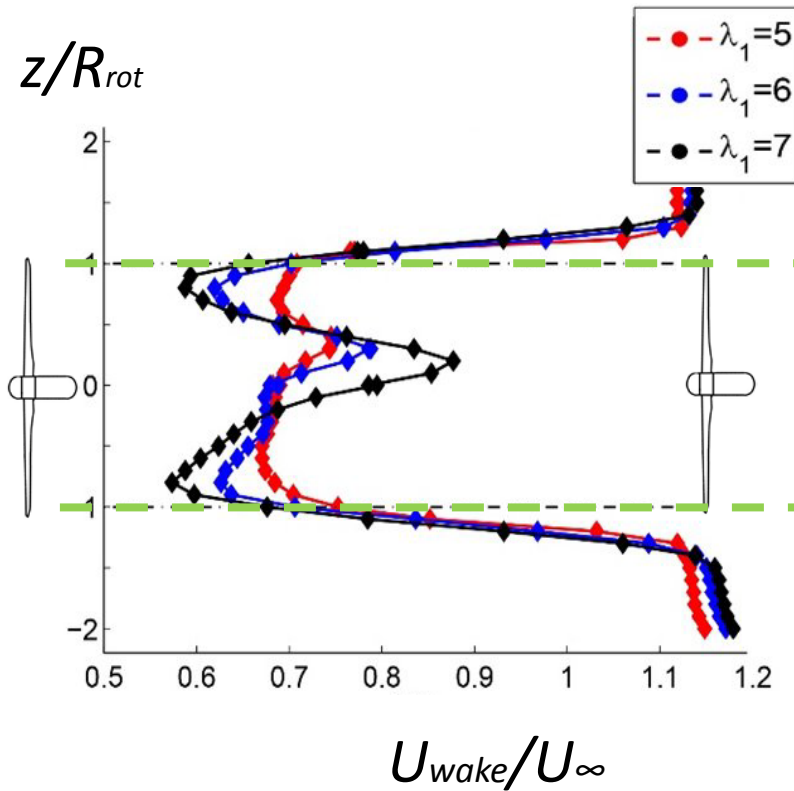
β -variations

Selected results of Master thesis by *M. Löther*

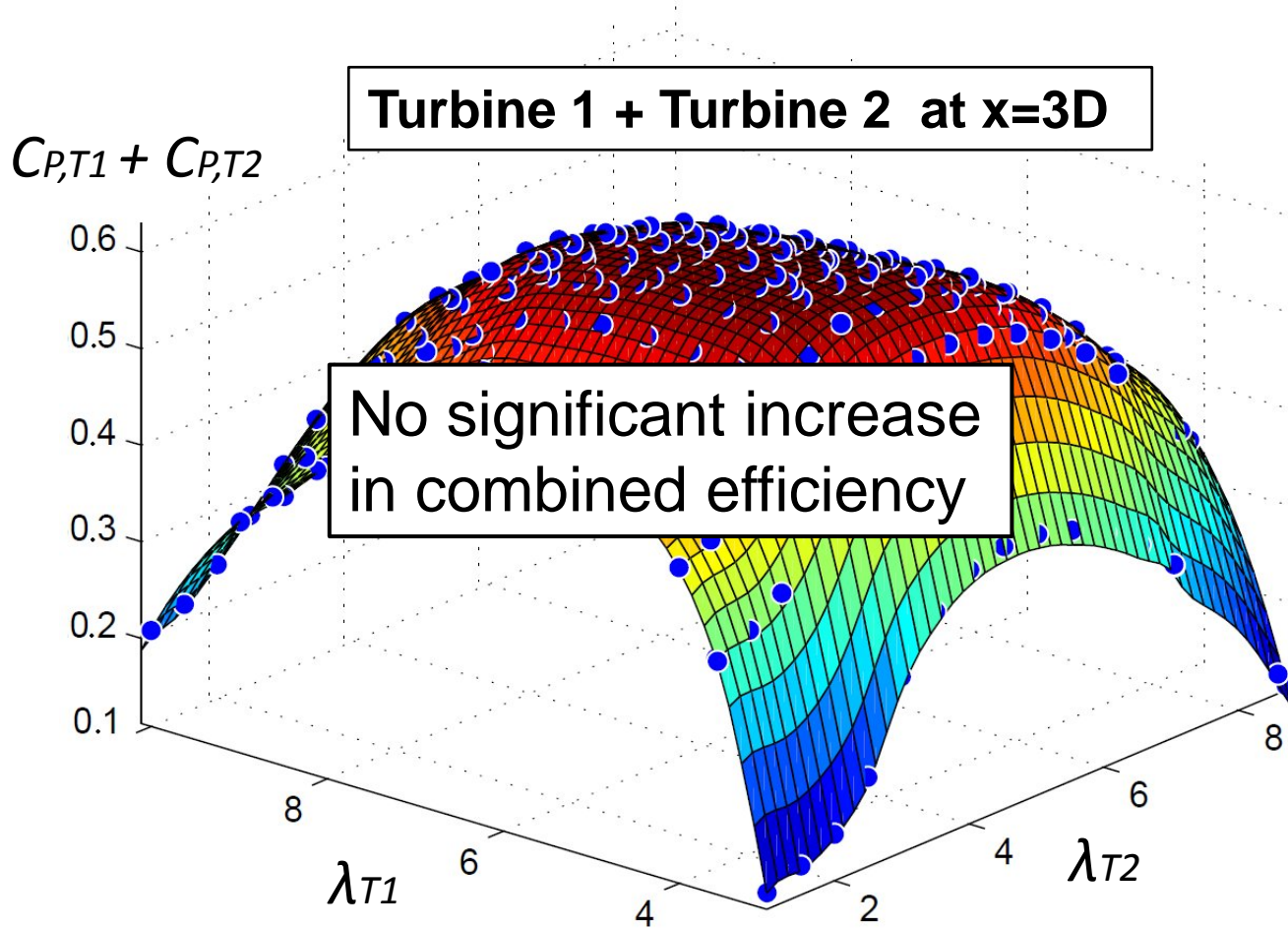
Results: λ -control of upstream turbine



Results: λ -control of upstream turbine

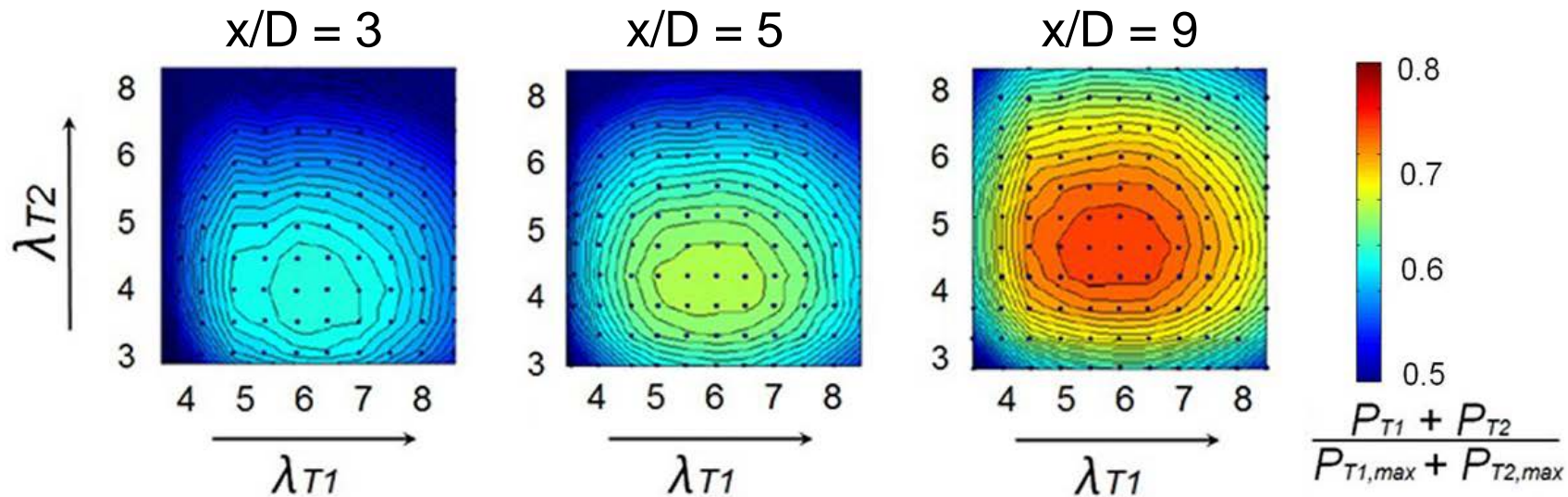


Results: λ -control of upstream turbine



Results: λ -control of upstream turbine

Effect of turbine separation distance x/D



For increasing downstream distance x/D

⇒ more energy is recovered from T2

⇒ λ -control has less influence on wake recovery

More information:

Poster by Clio Ceccotti and Andrea Spiga

Upstream turbine effect on downstream turbine performance

Upstream turbine effect on the downstream turbine performance: a wind farm case optimization

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INTRODUCTION

In a wind farm, wakes interact with each other and directly affect the downstream turbine performances. In this context, a wind tunnel turbine wake study and an analysis of the combined power output of a 2-turbine array are studied. The wake analysis is focused on the description of the wake development at different downstream stations for different turbine operating conditions and flow regimes. The performances of a turbine operating in the wake are analyzed for different configurations focusing on the 2-turbine array power output; moreover a wake-wake interaction is attempted. The array overall efficiency is found to increase by moving the second turbine further downstream, with an increased background turbulence level and by choosing a suitable operating point for each turbine.

METHODS

The experimental analysis is carried out at NTNU aerodynamic labs and the measurement set up is shown in Fig. 1. The reference wind speed is $U_{ref} = 11.5$ [m/s] (Eq. 1) and 2 model wind turbines of $D = 0.9$ [m] [1] are used for the investigations. The turbines operating points are set by handling the rotor speed via a frequency converter. No variations in blade pitch angle are contemplated.

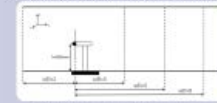


Figure 1: First turbine setup: wake measurements.

In both conditions turbine horizontal wakes behind a single turbine are measured using a hot wire anemometer. Relative velocity (U_{rel} , Eq. 1) and turbulence intensity (TI [%], Eq. 4) are analysed at 3D, 5D and 9D behind the turbine. The second turbine is located in the tunnel (Fig. 2) and for each tip speed ratio configuration (λ_1, λ_2) the array efficiency E [%] (Eq. 5) is obtained.

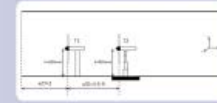


Figure 2: Two turbine array: array efficiency optimization.

$$U_{rel} = U_{ref} \left(1 - \frac{D}{x} \right) \quad (1)$$

$$C_p = \frac{P_{mech}}{\frac{1}{2} \rho U_{ref}^3} \quad (2)$$

$$TSR = \frac{\omega \times R}{U_{ref}} \quad (3)$$

$$TI [\%] = \frac{\sigma}{U_{ref}} \times 100 \quad (4)$$

$$E = \frac{C_{pT1} + C_{pT2}}{C_{pT1} + C_{pT2} + C_{pT3}} \times 100 \quad (5)$$

RESULTS

Single turbine wake development

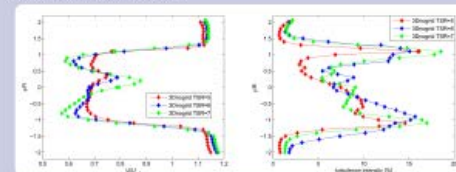


Figure 3: Relative flow velocity, 3D distance behind the turbine working at $\lambda_1 = 5.67$.

Figure 4: TI, 3D distance behind the turbine working at $\lambda_1 = 5.67$.

- No λ dependency on radial expansion is noticed neither at 3D nor at 9D.
- At 3D (Near wake), by varying λ , the rotor inner sections feed momentum into the wake (Fig. 3) and produce big variations in TI (Fig. 4).
- At 9D (Far wake) behind the rotor, almost no difference is visible with λ variations (Fig. 5, 6).
- Generally, by increasing λ , wakes TI increases, since higher thrusts on the turbine induces strongest mean velocity gradients. Tip peaks and turbulence overall level monotonically increase.

References

- [1] Per-Åke Krøglund and Pål Egil Eriksen. "Wind-tow" calculations of the performance and wake development for a model wind turbine. *Renewable Energy*, 50(0):325–333, February 2013.
- [2] Jan-Ale Dalsberg. Assessment of the hill-gated wind farm power performance wake effects. *Intenjonal Vindloggi 48*, 6. *IGP Pilot Report*, 2009.

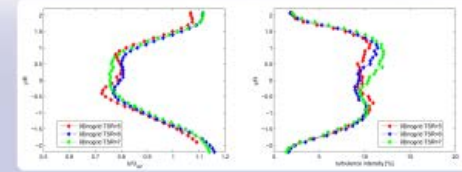


Figure 5: Relative flow velocity, 9D distance behind the turbine working at $\lambda_1 = 5.67$.

Figure 6: TI, 9D distance behind the turbine working at $\lambda_1 = 5.67$.

Correlation between wake behind the first turbine and the power output of the second turbine

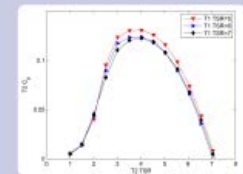
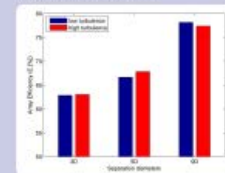


Figure 7: T2 C_p with $\lambda_1 = 5.67$.

At 3D separations even small variations in turbine λ , strongly affect the velocity deficit in the wake (Fig. 3) resulting in a detectable C_p variation for T2 (Fig. 7). Velocity deficit peaks become deeper in the outermost regions ($0.5 < y/R < 1$) leading to less T2 energy extraction.

Two turbine array case study



Configuration	Max array efficiency [%]	λ_1	λ_2
0.23%, 3D	62.8	5	4
0.23%, 5D	66.5	5.5	4
0.23%, 9D	78	5	5
10%, 3D	63	5.5	4
10%, 5D	67.5	6	4.5
10%, 9D	77	6	5

Table 1: Max array efficiency for λ_1, λ_2 operating conditions, near-TI and separation configurations.

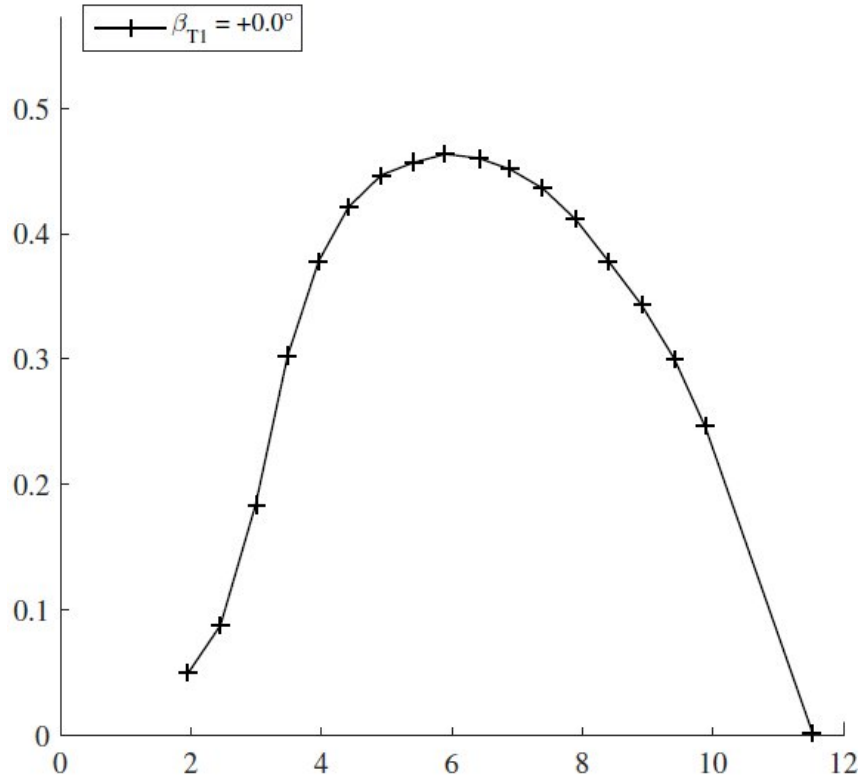
Figure 8: Max array efficiency achievable in each configuration.

- Higher turbulence induced by the grid accelerates the velocity deficit recovery until the grid effect is distinct (SD); at 9D the turbulence induced is negligible.
- A slight λ dependency on E is found. A bigger amount of energy is available for T2 (E_2), is slightly decreased from optimum, resulting in a higher E (Tab. 1).
- A constant impact of approximately 2.5% wind farm overall efficiency recovery is found for every additional diameter separation distance between the turbines.

CONCLUSIONS

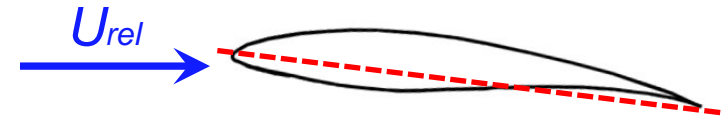
- The parametric study points out a strong array efficiency dependency on:
- INFLOW TURBULENCE LEVEL: the higher the turbulence, the faster the velocity recovery, the bigger the array efficiency. High turbulence wind tunnel results are better matching the full scale reality (atmospheric inflow) [2].
 - Turbine TSRs: best results of array efficiency are found with the 1st turbine running at λ slightly lower than the optimum operating point, especially for small separation distances.
 - Turbine SEPARATION DISTANCE: +2.5% of array efficiency for every additional separation diameter. Accurate management of all the parameters is advised.

Results: β -control of upstream turbine

 $C_{P,T1}$


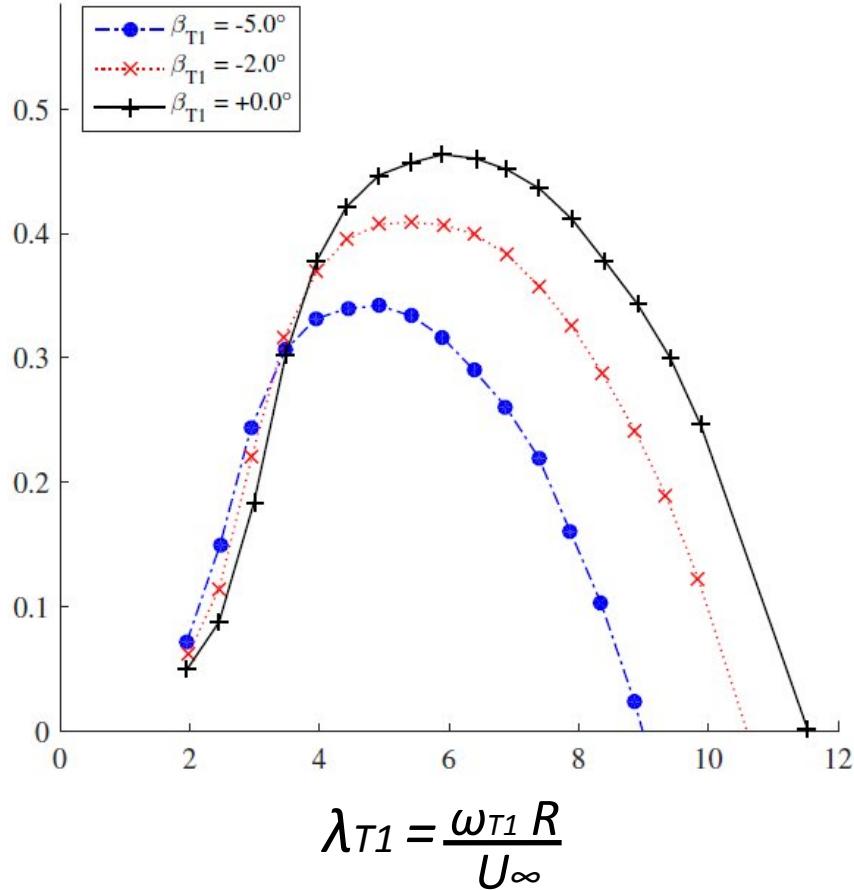
$$\lambda_{T1} = \frac{\omega_{T1} R}{U_\infty}$$

Zero pitch:
 all blade elements at
 design angle of attack $\alpha=7^\circ$



Results: β -control of upstream turbine

$C_{P,T1}$

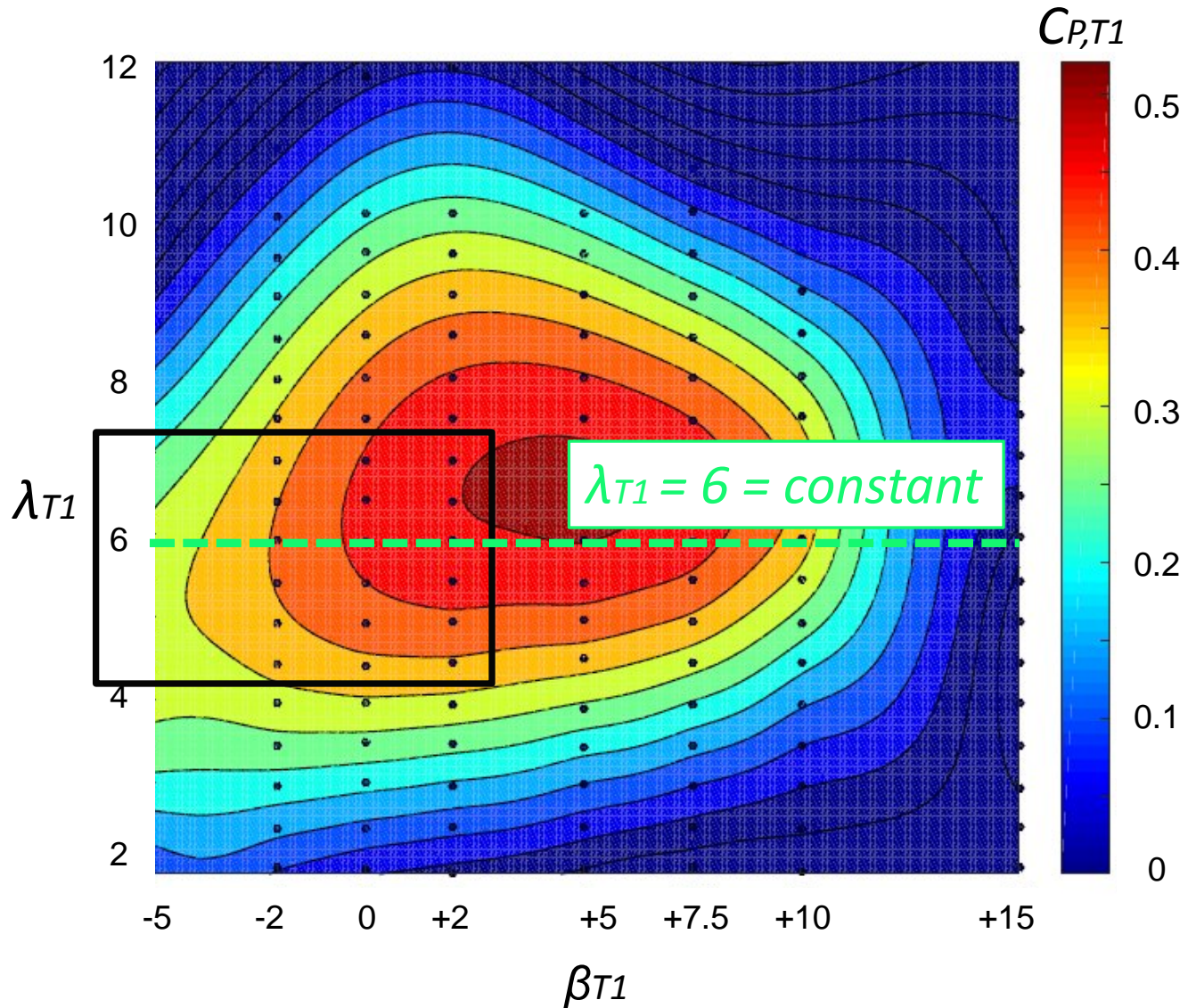


Negative pitch:

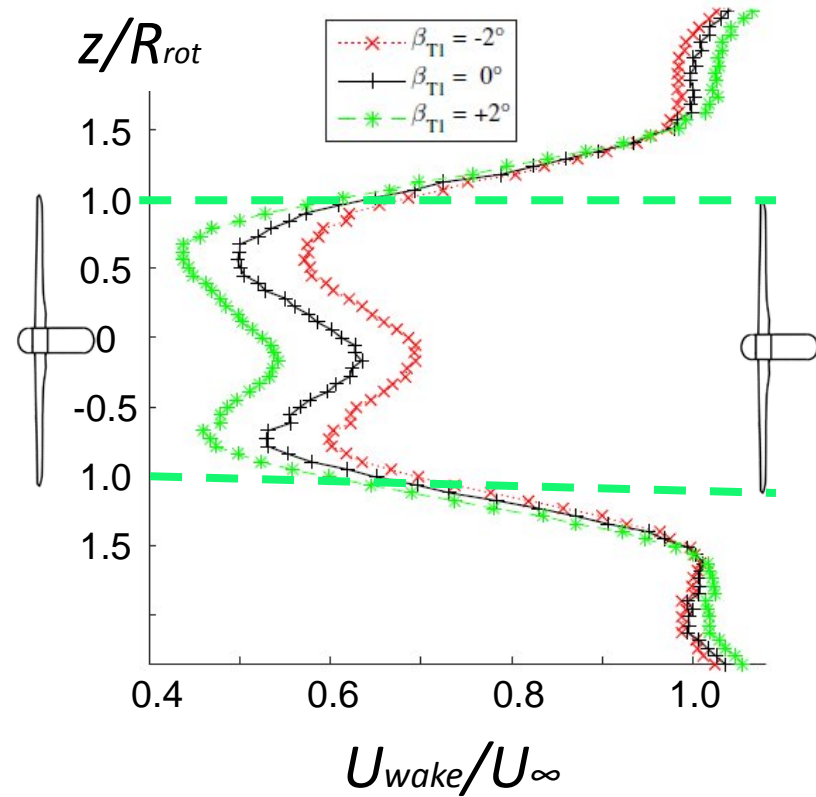
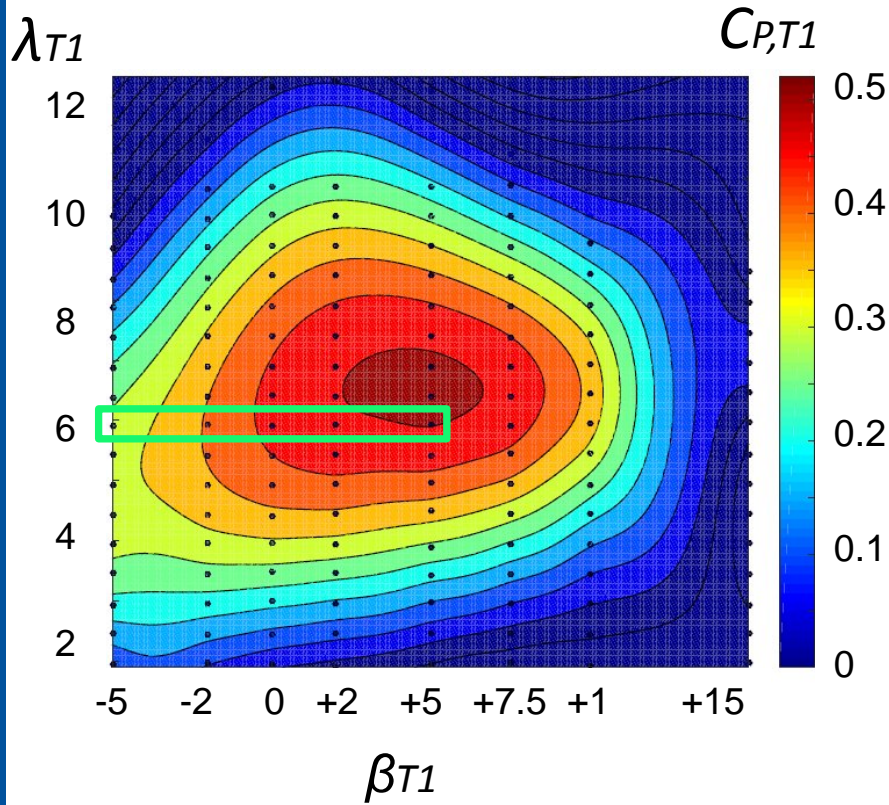
- towards lower α
- towards feather position



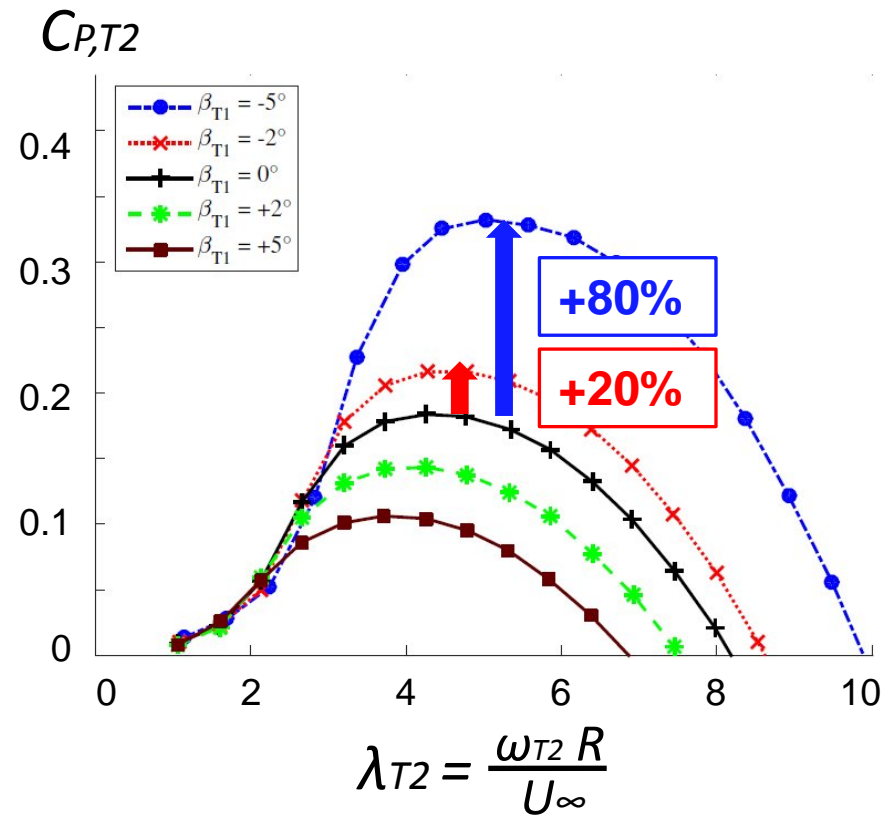
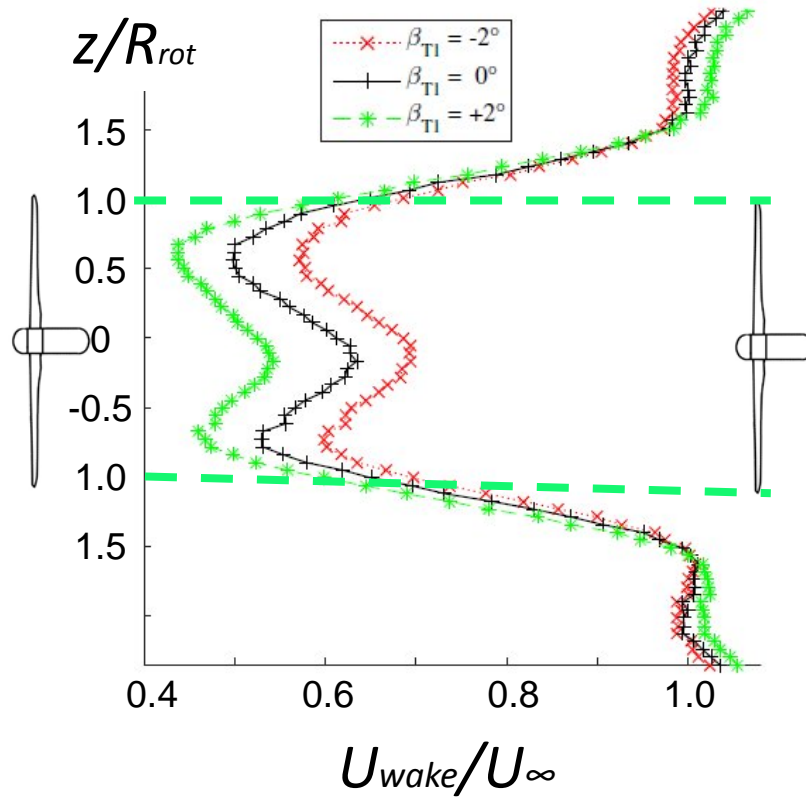
Results: β -control of upstream turbine



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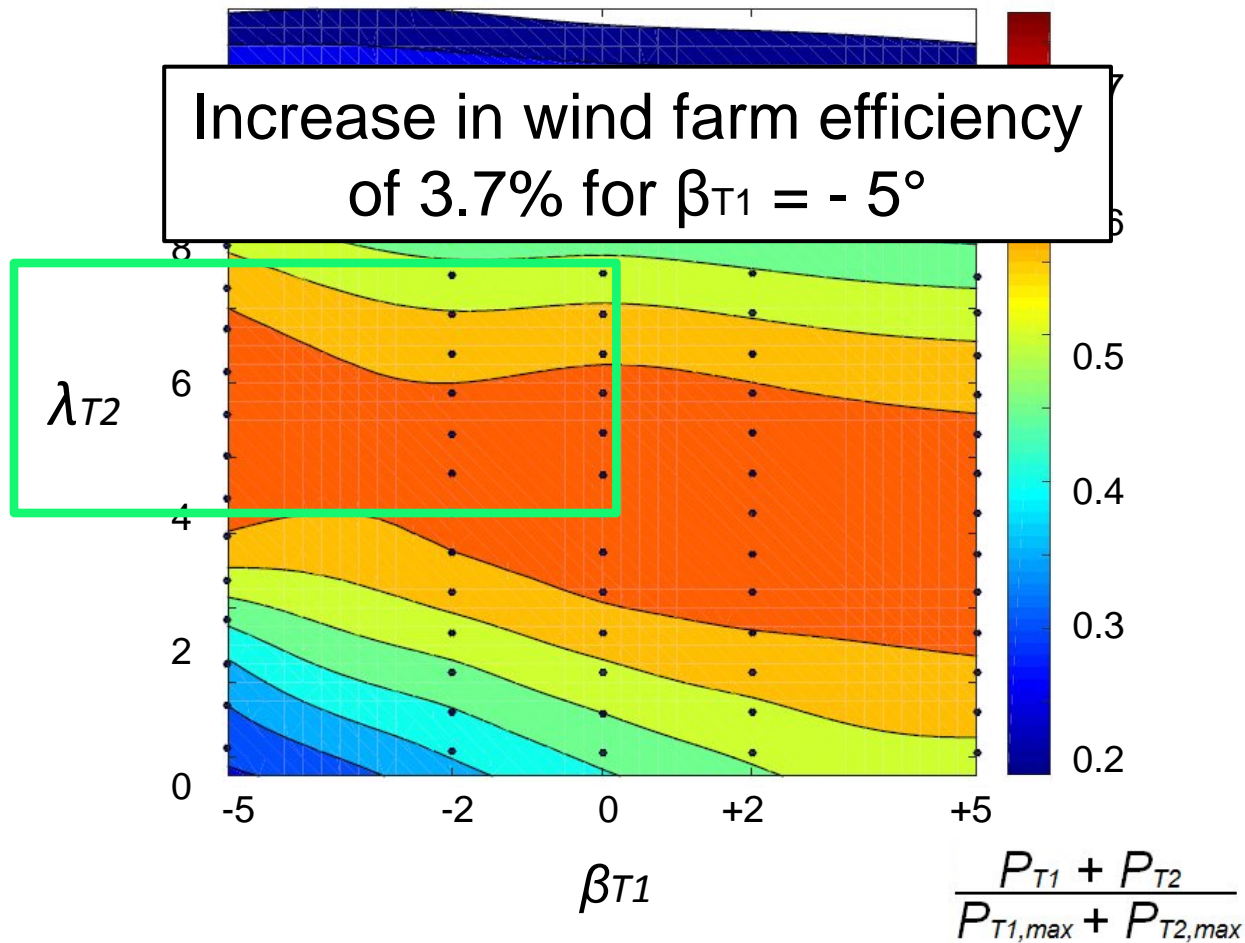


Results: β -control of upstream turbine



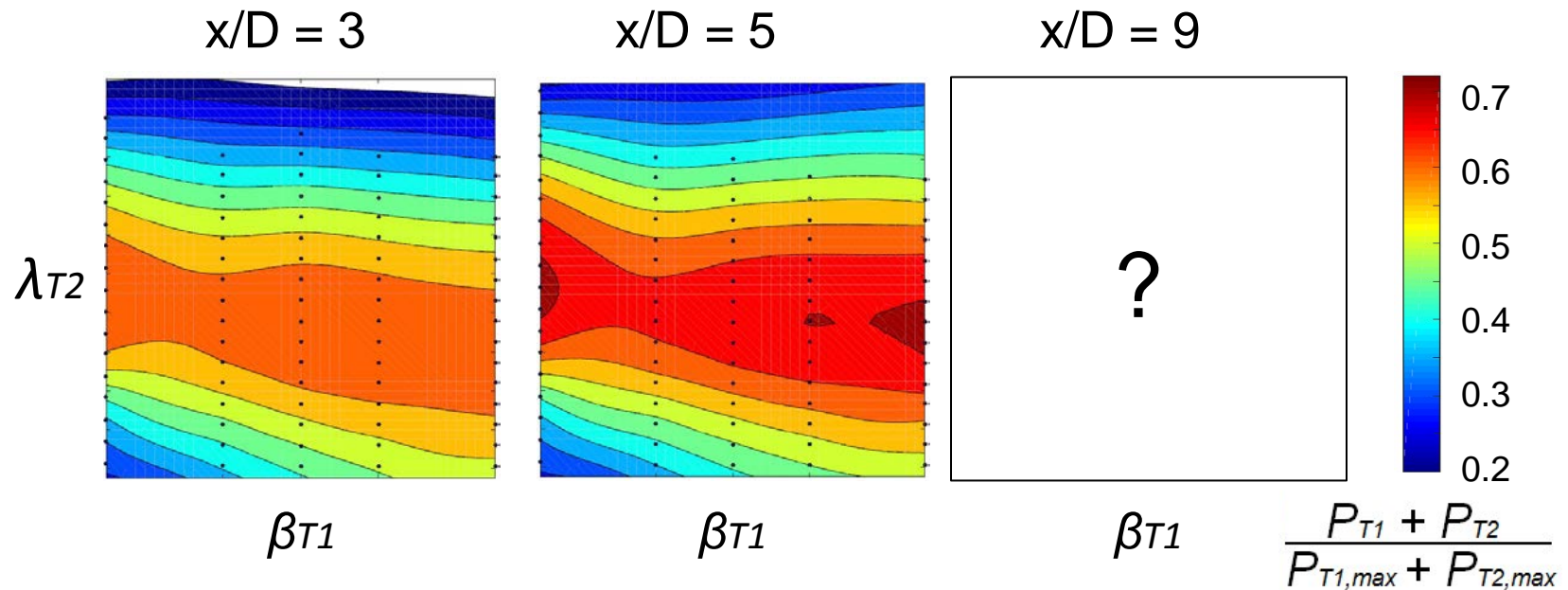
Results: β -control of upstream turbine

Combined wind farm efficiency $P_{T1} + P_{T2}$, $x/D=3$



Results: β -control of upstream turbine

Effect of turbine separation distance x/D

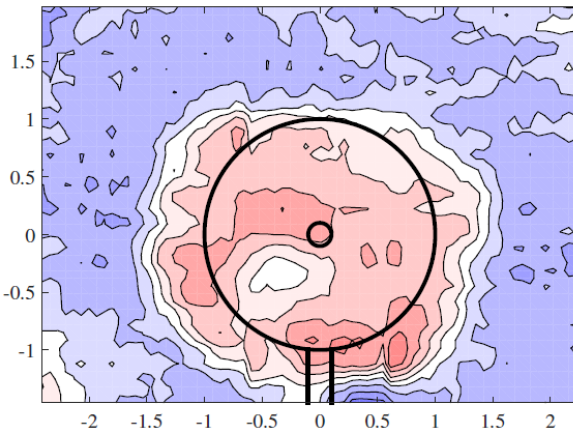


⇒ More energy can be recovered by downstream turbine

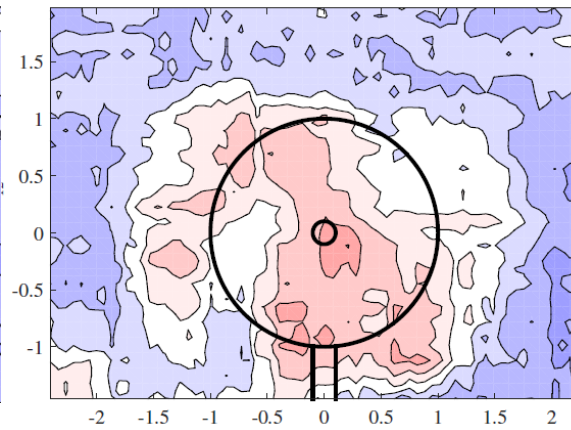
Results: β -control of upstream turbine

Where is the added kinetic energy located in the wake?

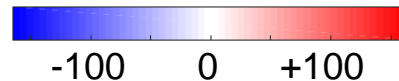
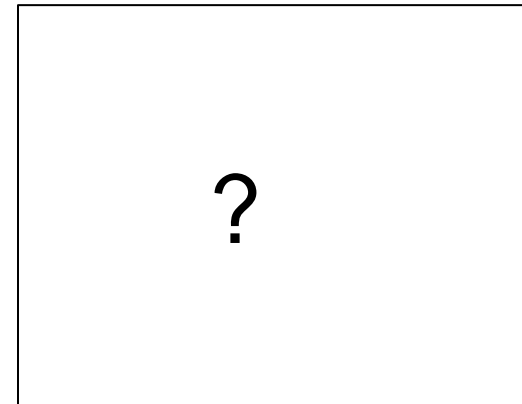
$x/D = 3$



$x/D = 5$



$x/D = 9$



$$\frac{P}{A} = \frac{1}{2} \cdot \rho \cdot U_M^3 \left[\frac{W}{m^2} \right]$$

⇒ Added kinetic energy is diffusing outside the downstream rotor area

Some concluding remarks

λ -control:

- Insignificant effect on total power output from slight variations around the design tip speed ratio
 - power lost on the upstream turbine is recovered by the downstream turbine
- ⇒ total power production is stable around design TSR

β -control:

- Higher potential for wind farm efficiency increase
 - Pitch angle of $\beta = -5^\circ$ gives highest combined efficiency
- ⇒ more pitch angles to be analysed
- ⇒ more thorough wake analysis needed

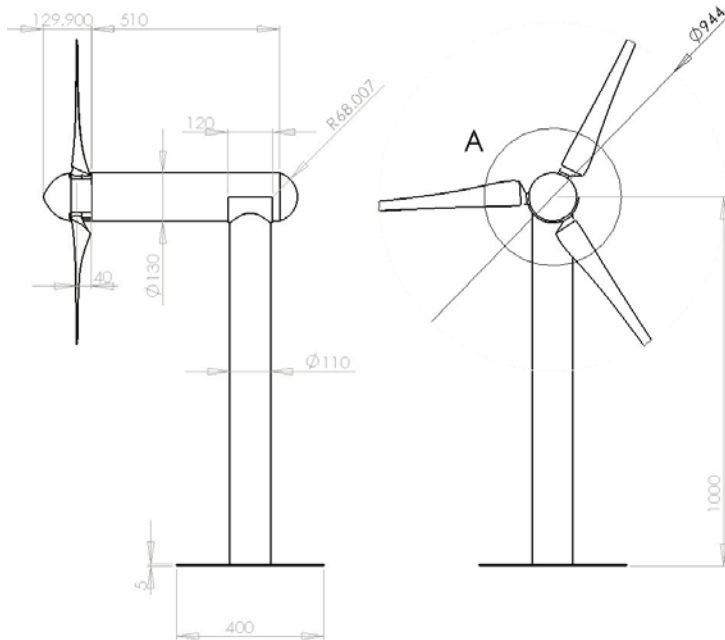
Further work

- Wake analysis for pitch angles β_{T1}
- 3rd turbine?
- γ -control

Thank you for your attention!

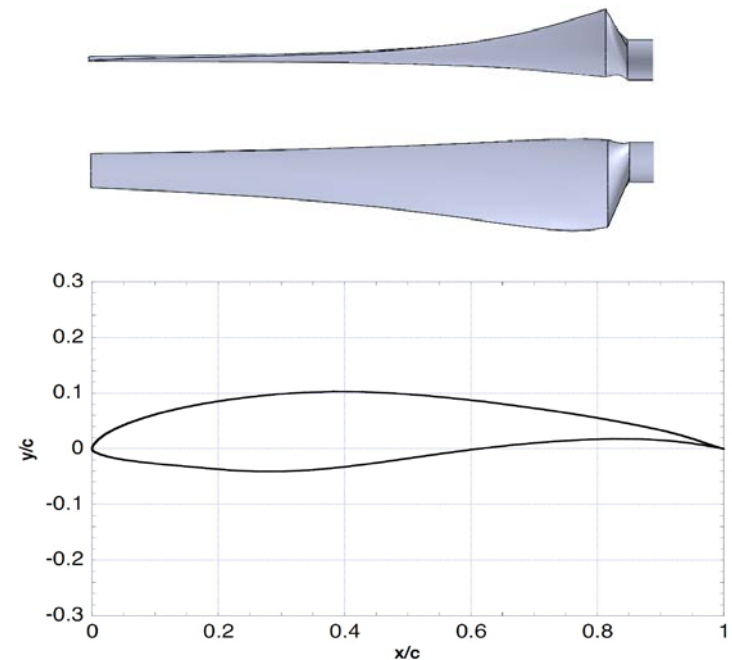
Model wind turbines & blade geometry

Two model turbines



$$D_{\text{Rotor},T1} \approx 0.90 \text{ m}$$

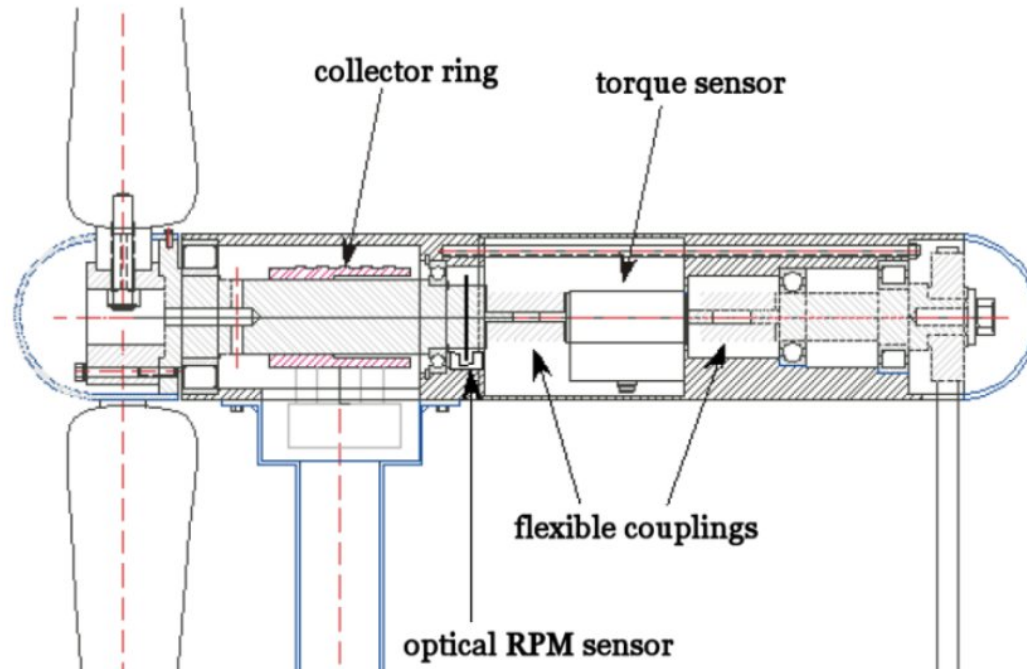
Blade: NREL S826 airfoil



$$\text{Solid blockage } \sigma = \frac{A_{\text{Rotor}}}{A_{\text{Tunnel}}} = 12\%$$

- designed for $Re = 10^6$
- operated at $Re \approx 10^5$

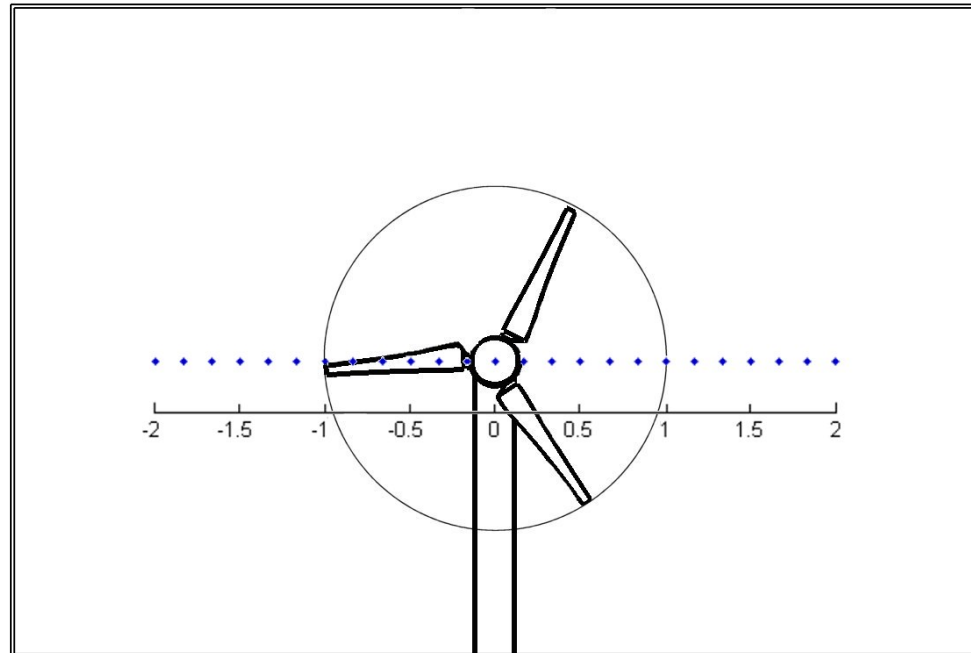
Power measurements



$$P = \omega * T$$

Wake flow measurements

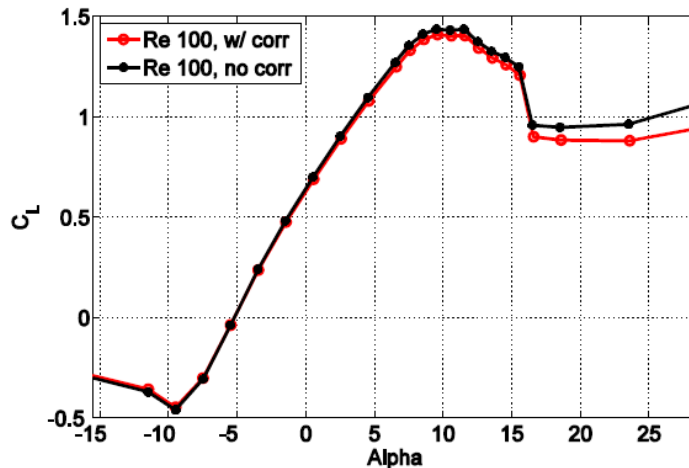
Constant Temperature Anemometry (CTA) Hot-wire



41 measurement points in the wake $z/R = -2$ to $z/R = +2$

NREL S826 airfoil characteristics

(a) Lift coefficient



(b) Drag coefficient

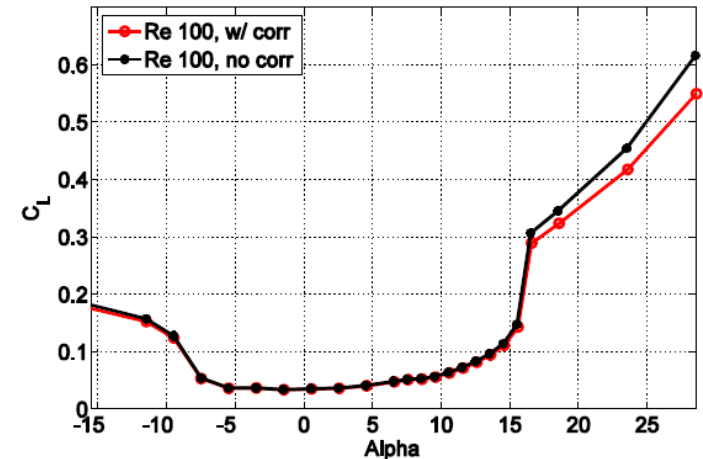
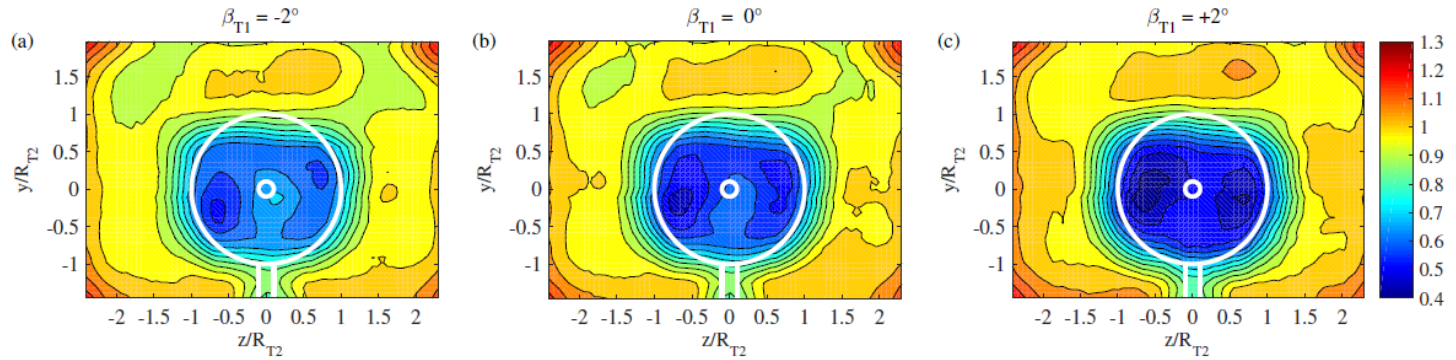


Figure 7 a-b: Lift- and drag measurements corrected for solid blockage, wake blockage and streamline curvatures. $Re = 1.0 \times 10^5$, $TI = 0.71\%$

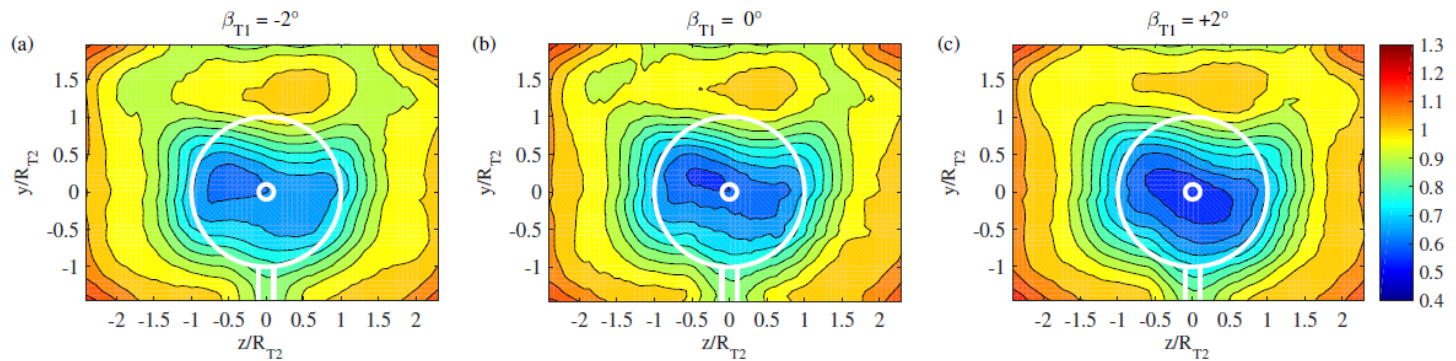
Source: Initial measurements on S826 wing, N.Aksnes & J.Bartl, NTNU

Full-area wake measurements, $\beta = -2, 0, +2$

$x/D=3$

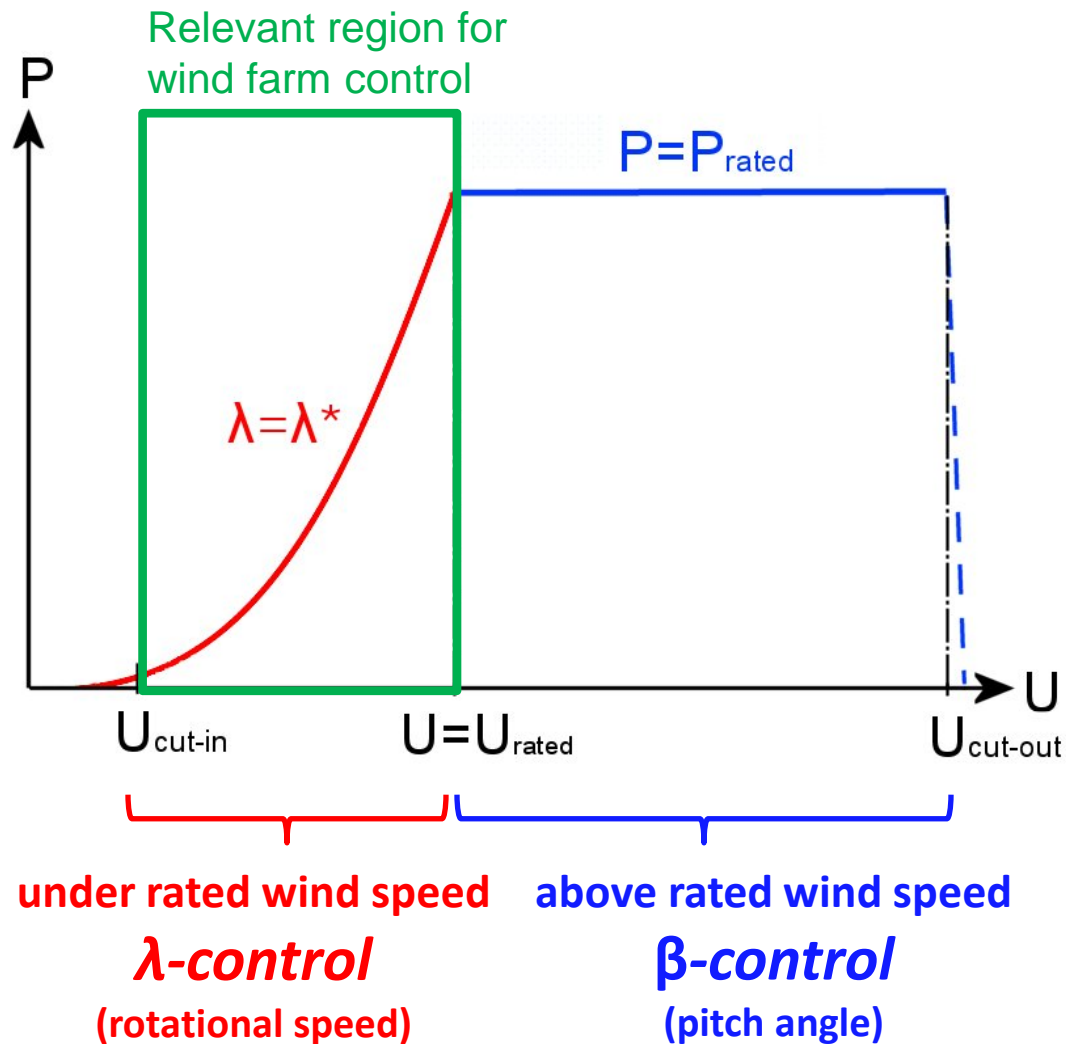


$x/D=5$



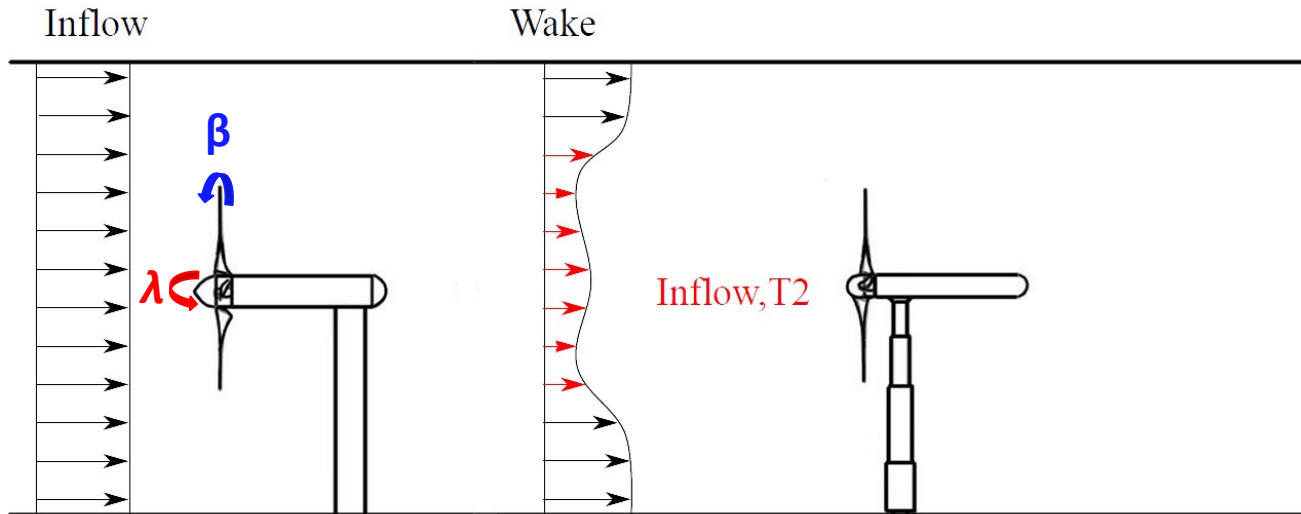
Background

Basic *individual* wind turbine control



Background

Concepts of wind farm control / wake control



➔ Reduce energy capture of upstream turbine to the benefit of the downstream turbines

Background

Further wind turbine control goals

- Fatigue load reduction
- Resonance avoidance
- Gust load alleviation
(extreme loads)
- Periodic disturbance reduction
(wind shear, tower shadow effect)
- Actuator duty cycles reduction
- ...

*(Source: C.L. Bottasso, «Wind turbine control – short course»;
<http://www.aero.polimi.it/~bottasso/DownloadArea.htm>)*