Experimental testing of axial induction based control strategies for wake control and wind farm optimization

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Abstract. In state-of-the-art wind farms each turbine is controlled individually aiming for optimum turbine power not considering wake effects on downstream turbines. Wind farm control concepts aim for optimizing the overall power output of the farm taking wake interactions between the individual turbines into account. This experimental wind tunnel study investigates axial induction based control concepts. It is examined how the total array efficiency of two in-line model turbines is affected when the upstream turbine’s tip speed ratio ($\lambda$-control) or blade pitch angle ($\beta$-control) is modified. The focus is particularly directed on how the wake flow behind the upstream rotor is affected when its axial induction is reduced in order to leave more kinetic energy in the wake to be recovered by a downstream turbine. It is shown that the radial distribution of kinetic energy in the wake area can be controlled by modifying the upstream turbine’s tip speed ratio. By pitching out the upstream turbine’s blades, however, the available kinetic energy in the wake is increased at an equal rate over the entire blade span. Furthermore, the total array efficiency of the two turbine setup is mapped depending on the upstream turbines tip speed ratio and pitch angle. For a small turbine separation distance of $x/D=3$ the downstream turbine is able to recover the major part of the power lost on the upstream turbine. However, no significant increase in the two-turbine array efficiency is achieved by altering the upstream turbine’s operation point away from its optimum.

1. Introduction

Due to limited spacing in offshore wind farms, wake interactions between the single turbines cause significant power losses on the downstream turbines. For certain wind directions these power losses are estimated to account for up to 10-20% for large offshore wind farms [1] as the single turbines are controlled for the optimum individual operation condition. In order to reduce these effects and thus optimize the total power output of the farm, a holistic wind farm control approach is needed [2]. One promising control concept is to reduce the induction on the upstream rotors and thus increase the amount of kinetic power available in the wake that can be recovered by the downstream turbines. This can be done by altering the upstream turbine’s tip speed ratio through the turbine’s torque controller as well as varying the blade pitch angle.

Steinbuch et al. [3] addressed the topic of wind farm control already in 1988. They underline the importance of controlling rotor loads through wind farm control methods. Furthermore, they indicate the potential of an increase in overall energy capture by downrating the upstream turbines. A
Theoretical optimization study of an array of eight aligned wind turbines is presented by Horvat et al [4]. Applying a simple engineering wake model they calculate a total gain in wind farm efficiency of 2.85% when the power extraction of the first three turbines is reduced through pitching. Another study of adjusting the blade pitch angle for wind farm power optimization is presented by Lee et al. [5]. Applying an eddy viscosity model for representation of the wake while optimizing the upstream turbines’ pitch angles, they simulate a wind farm efficiency increase by 4.5% for a model of the Horns Rev wind farm layout. Johnson and Fritsch [6] apply an Extremum Seeking Control algorithm to optimize the power of simple wind farm consisting of three aligned turbines. For low atmospheric turbulence inflow conditions they find an increase in combined efficiency when reducing the induction on the first and second turbine. Their algorithm is using the engineering PARK wake model to simulate the aerodynamic interactions between the turbines. A different approach for the power optimization of three in-line turbines is presented by Marden et al [7]. They utilize game theoretic methods for wind farm optimization and show its potential for an efficiency gain. Their model-free approach does not utilize a wake model and is based on some strongly simplified assumptions. González et al. [8] developed another algorithm for optimizing the wind farm efficiency by individual pitch angle and tip speed ratio control of each turbine. The turbine wake flow is for this case simulated by the PARK model. Considering wind directions that results in fully aligned turbine rows, they model a total farm efficiency increase of 7.55%. A recent study by Annoni et al. [9] discusses the potential of induction-based wind farm control techniques. The higher-order wind plant model SOFWA based on Large Eddy Simulations (LES) is compared to a simpler engineering model, showing up discrepancies in the simple wake model. The simulations based on the engineering wake model predict a slight wind farm efficiency increase when pitching or downrating the upstream turbine, whereas the more advanced SOFWA simulations show that the energy lost on the upstream turbine cannot be fully recovered by the downstream turbine.

Full-scale experiments on wind farm control are reported by Wagenaar et al. [10]. In a farm of 10 small wind turbines of a rotor diameter of D=7.6m spaced at 3.7D in one wind direction, the effect of yaw misalignment is studied. No significant overall farm efficiency increase is reported for this test case. In general, wind farm control methods based on wake deflection like yawing or individual pitch control have the big advantage that low kinetic energy fluid in the wake can be deflected away from the center of an aligned downstream rotor. Most of the studies investigating yaw control [11], [12], [13], [14], [15] report an effective deflection of the wake path around 0.6 rotor diameters, implicating an unsteady and a highly asymmetric blade load distribution for an aligned downstream turbine. Axial induction based wind farm control methods as discussed in this paper, are not able to deflect low kinetic energy fluid away from the downstream rotor. However, they have the advantage of being able to control the load distribution for the downstream turbine steadily over the entire rotor swept area of an aligned downstream turbine, implicating a more uniform load distribution for a downstream rotor.

2. Objectives

The objective of this experimental study is to show up the potential of axial-induction based control methods on the total wind farm efficiency. The focus is particularly directed on the mean wake flow affected by the upstream turbine’s operating condition. The distribution of kinetic energy in the wake is directly related to the power output of the downstream turbine. The total wind farm efficiency is mapped in dependency of the operation conditions of the upstream and downstream turbine for three representative turbine separation distances. A study of the wake behind the second turbine, and thus an indication for the available power of a third turbine is given by Bartl et al. [16].

Given the drawbacks of low Reynolds-numbers operation and wind tunnel blockage effects this study does not claim to represent a full-scale situation. Nevertheless, the study consists of a set of well-documented experimental data, which provides a defined test case for calibration and validation of CFD methods. A comparison of wake and performance data of CFD predictions to experimental data from NTNU’s wind tunnel is presented in the so-called Blind test experiments [17], [18], [19], [20].
3. Methods

In this experimental study the characteristics of the axial-induction-based control strategies are assessed for a setup of two in-line model wind turbines. The models have a rotor diameter of about 0.90m and are installed in a closed wind tunnel test section of 2.7m x 1.8m resulting in a solid blockage ratio of 13%. Figure 1 schematically shows the experimental setup, a detailed description of the turbine geometry can be e.g. found in [18]. The turbine blades are based on the NREL S826 airfoil, which is shown to result in Reynolds-number-independent rotor performance for reference wind velocities above $U_{\text{ref}}=11.5$ m/s [21]. The model turbines are equipped with a torque transducer and an optical photo cell making it possible calculating the mechanical power at the rotor shaft. Moreover, the turbines are mounted on a 6-component force balance allowing assessing the thrust force. The axial induction factor over the blade span is calculated by the means of Blade Element Momentum (BEM) method. 30 blade elements are chosen to get an approximation of the blade load distributions. Hot-wire anemometry with a sampling frequency of $f=20$ kHz is used to measure the mean and turbulent streamwise velocity in wake behind the upstream turbine. In order to simulate realistic atmospheric conditions a turbulence grid is set up at the test section inlet generating a background turbulence intensity of $T_l=10.0\%$ at the first rotor plane, decaying to $T_l=5.0\%$ at the position of the second rotor $x/D=3$ rotor diameters downstream of the first rotor.

The random error of the power, thrust and mean velocity measurements are calculated based on a 95% confidence interval. Systematic errors based on a uncertainty analysis of the calibration procedures are taken into account and thus a total error is calculated. Herein, the systematic error of ±1% from the velocity calibration is seen to be the major contributor to the total uncertainty in all presented quantities. The uncertainty in the upstream turbine power coefficient at design conditions is calculated to be within ±3%, while it is lower than ±2% for the thrust coefficient. The total uncertainty in the mean velocities in the wake is calculated to be lower than ±1.5%.

4. Results

4.1. Tip speed ratio variation ($\lambda$-control)

In a first experimental setup the upstream turbine tip speed ratio is varied from its design point at $\lambda_{T1}=6.0$ and the influence on the performance of the downstream turbine assessed. The power coefficient $C_{P,T1}$ and the thrust coefficient $C_{T,T1}$ of the upstream turbine are shown in dependence of the tip speed ratio $\lambda_{T1}$ in Figure 2 (a) and (b).

\begin{align}
C_{P,T1} &= \frac{P_{T1}}{0.5\rho A_{rot1} U_{ref}^3} \\
C_{T,T1} &= \frac{F_{T,T1}}{0.5\rho A_{rot1} U_{ref}^2} \\
\lambda_{T1} &= \frac{\omega R}{U_{ref}}
\end{align}

Figure 1. Schematic of the experimental setup in the wind tunnel. The upstream rotor is set up at $x/D=2$ from the turbulence grid. The downstream rotor is positioned $x/D=3$ behind the upstream rotor.
The upstream turbine power can be reduced by overspeeding the rotor to higher tip speed ratios, which on the other hand increases the total thrust and thus the total axial induction $a_{\text{ind}}$ on the rotor.

$$a_{\text{ind}} = 0.5(1 - \sqrt{1 - C_T}) \quad (4)$$

The induction factor as calculated in from momentum conservation in equation (4) is a global parameter for the entire rotor. In reality, however, the axial induction factor is not distributed evenly over the rotor radius.

This can, for instance, be shown by a simple Blade Element Momentum (BEM) calculation. In Figure 2 (c) the axial induction factor calculated by a BEM code is shown 30 blade elements over the blade root distance $r/R$ for the five investigated tip speed ratios. It is shown that the axial induction is actually reduced in the inner part of the rotor up to about 0.4 times the blade span, and increased for the outer blade elements in case the rotor is overspeeded.

This non-uniform change of the induction over the blade radius directly affects the wake flow behind the turbine. As presented in Figure 2 (d) the mean velocity profile at hub height measured in a horizontal line at a downstream distance of $x/D=3$ is showing two distinct minima which indicates that the measurement location in the near wake. For the case of overspeeding to $\lambda_{T1}=7.0$, the velocity deficit near the blade tip is seen to increase, while more kinetic energy is left in the center of the wake. Thus, the total kinetic energy integrated over the rotor swept area stays rather constant compared to the to the design case at tip speed ratio $\lambda_{T1}=6.0$.

Setting up another turbine at the exact same location at $x/D=3$ makes it possible to measure the power coefficient $C_{P,T2}$ and thrust coefficient $C_{T,T2}$ of the downstream turbine as presented in Figure 2 (e) and (f).

$$C_{P,T2} = \frac{P_{T2}}{0.5\rho A_{\text{rot}} U_{\text{ref}}^3} \quad (5)$$

$$C_{T,T2} = \frac{F_{T,T2}}{0.5\rho A_{\text{rot}} U_{\text{ref}}^2} \quad (6)$$

Note that for better comparability the reference velocity $U_{\text{ref}}$ for both model turbines is the velocity measured at the inlet contraction of the test section $x/D=2.0$ upstream of the upstream turbine.

It can be observed that the power and thrust coefficient for the downstream turbine is not significantly affected by overspeeding the upstream turbine. The downstream turbine experiences very similar total thrust and power indicated by matching performance curves.

In case the upstream turbine is downrated, i.e. slowed down to lower tip speed ratios, both the power and thrust coefficients are reduced as indicated in Figures 2 (a) and (b). Although the total axial induction is also reduced, an increase of the induction factor is observed in the center of the rotor up to about $r/R=0.3$. The radial distribution of the induction factor is again modified, the opposite effect as for the case of overspeeding is observed. The induction increases in the center while it reduces towards the blade tips. The increase in axial induction consumes more energy in the center of the upstream rotor. As a consequence the mean velocity profile in the wake is observed to flatten out for $\lambda_{T1}=5.0$ (Figure 2 (d)). More kinetic energy is left in the tip region of the rotor, while the kinetic energy in the wake center is further reduced.

In case of downrating the upstream rotor to $\lambda_{T1}=5.0$, only a slight increase of about 2% in the downstream turbine efficiency can be measured. When slowing down the upstream rotor to close-to-stalled-conditions at $\lambda_{T1}=4.0$, about 20% more power can be gained at the downstream rotor compared to the upstream case as shown in Figure 2 (e). This can, however, not account for the power losses at the upstream rotor. As a consequence the total wind farm efficiency is decreased as further discussed in section 4.3.

Correspondingly, the downstream turbine’s thrust coefficient $C_{T,T2}$ is somewhat higher for when slowing down the upstream turbine to $\lambda_{T1}=4.0$, while it is almost not affected at all when slowing it down to $\lambda_{T1}=5.0$. The outer blade elements of the upstream rotor might be partly stalled $\lambda_{T1}=4.0$ already loving significantly more kinetic energy in the wake than at $\lambda_{T1}=5.0$. 
Figure 2 (a). Upstream turbine power coefficient $C_{P,T1}$. Markers indicate chosen operating points.

Figure 2 (b). Upstream turbine thrust coefficient $C_{T,T1}$. Markers indicate chosen operating points.

Figure 2 (c). Calculated axial induction factor over the upstream rotor blade span at different tip speed ratios.

Figure 2 (d). Mean velocity measurements in a horizontal line at hub height, $x/D=3$ behind the upstream rotor for three different tip speed ratios.

Figure 2 (e). Power coefficient $C_{P,T2}$ of the downstream rotor located $x/D=3$ behind the upstream rotor for different upstream turbine tip speed ratios.

Figure 2 (f). Thrust coefficient $C_{T,T2}$ of the downstream rotor located $x/D=3$ behind the upstream rotor for different upstream turbine tip speed ratios.
4.2. Pitch angle variation (β-control)

In a second parameter variation the effect of an upstream turbine pitch angle variation on the performance characteristics of the downstream turbine is investigated. Therefore, the downstream turbine’s performance is measured when the upstream turbine is slightly pitched towards feathered position. A pitch angle range from $\beta_{T1}=0^\circ$ to $\beta_{T1}=-7^\circ$ is investigated while the upstream rotor tip speed ratio is kept constant at $\lambda_{T1}=6.0$. In this study the pitch angle is defined to be negative when pitched towards feathered position. Thus, the angle of attack decreases with decreasing pitch angle, which is in agreement with the definition given by Hau [22].

Figures 3 (a) and (b) display the power and thrust coefficients of the upstream turbine for different blade pitch angles. Pitching the rotor towards the feathered position, both the power and thrust coefficient decrease. It is observed that the run-away tip speed ratio is reached earlier when pitching the turbine towards feathered position. The general trends in $C_P$ and $C_T$ for a pitched turbine compare well to simulations on the NREL 5 MW reference turbine by Annoni et al [9] as well as the data presented in Johnson and Fritsch [6] as well as Hau [22]. The pitch-dependent performance characteristics of the model turbine however differ for different rotor designs. A strong dependence on the specific blade design is observed. For the present design of the NTNU model turbines the optimum power point of the upstream turbine is shifted towards lower tip speed ratios at a rate of about $\lambda/\beta\approx0.25/1^\circ$ when the turbine is pitched out. This shift in optimum power point is indicated by the inclined brown line in Figures 3 (a) and (b).

A BEM calculation of the radial distribution of the axial induction factor for different pitch angles is presented in Figure 3 (c). It is observed that the induction factor is decreased uniformly over the entire blade radius when the turbine is pitched towards feathered position. This radially uniform reduction in induction is also visible in the mean wake profile measured at $x/D=3$ downstream of the turbine. As shown in Figure 3 (d), significantly higher mean velocities are measured for the negative blade pitch angles $\beta_{T1}=-2^\circ$ and $\beta_{T1}=-5^\circ$ in the entire area behind the rotor. Due to the quite uniform reduction in induction the wake shape remains similar to the one of the design case at $\beta_{T1}=0^\circ$. For both investigated pitch angles $\beta_{T1}=-2^\circ$ and $\beta_{T1}=-5^\circ$ the velocity profile features two distinct minima, while a local maximum is observed around $z/R=0.2$. The asymmetry in the wake profile can be ascribed to the influence of the turbine tower wake [18]. The velocity in the freestream ($z/R\approx\pm1.5$) $x/D=3$ behind the upstream turbine is measured to be slightly higher than the reference velocity $U_{ref}$. This local speed up in the freestream is due to the blockage effect by the wind tunnel walls. It is observed that the speed up due to blockage decreases when the upstream rotor is pitched and thus the induction is reduced. Furthermore, it can be observed that a small part of the added kinetic energy in the wake is diffused into the freestream flow at $z/R>1$ and $z/R<-1$ already at $x/D=3$ rotor diameters downstream.

The power and thrust coefficients of a second turbine located at $x/D=3$ downstream of the first rotor are presented in Figures 3 (e) and (f). In general, it is observed that more energy can be recovered by the downstream turbine when the upstream turbine is pitched towards the feathered position. In average, the power production of the downstream turbine increases at a rate of about $\Delta C_{P,T2}/\Delta \beta_{T1} \approx 13\%/^\circ$. When pitching the upstream rotor blades $\beta_{T1}=-2^\circ$ for instance, 26% more energy can be recovered at the downstream turbine compared to the reference case of $\beta_{T1}=0^\circ$. The energy recovered by the downstream turbine does, however, not account for the energy missing on the upstream turbine as further discussed in section 4.3.

The thrust coefficient of the downstream turbine $C_{T,T2}$ is trending accordingly. Up to a tip speed ratio of $\lambda_{T2}=3.0$, the upstream turbine pitch angle $\beta_{T1}$ does not have any significant influence on the downstream turbine performance as it operates in stalled conditions.
Figure 3 (a). Upstream turbine power coefficient $C_{P,T1}$ for different pitch angles.

Figure 3 (b). Upstream turbine thrust coefficient $C_{T,T1}$ for different pitch angles.

Figure 3 (c). Calculated axial induction factor over the upstream rotor blade span for different pitch angles.

Figure 3 (d). Mean velocity measurements in a horizontal line at hub height, $x/D=3$ behind the upstream rotor for three different pitch angles.

Figure 3 (e). Power coefficient $C_{P,T2}$ of the downstream rotor located $x/D=3$ behind the upstream rotor for different upstream turbine pitch angles.

Figure 3 (f). Thrust coefficient $C_{T,T2}$ of the downstream rotor located $x/D=3$ behind the upstream rotor for different upstream turbine pitch angles.
4.3. Wind farm efficiency

By altering the tip speed ratio of both turbines, a matrix of the array efficiency

\[
E = \frac{P_{T1} + P_{T2}}{(P_{T1,\text{max}} + P_{T2,\text{max}})}
\]

(6)
of the two turbines is mapped for a separation distance of x/D=3. The array efficiency is found to be rather constant over a tip speed ratio range from \(\lambda_{T1}=4.5\) to \(\lambda_{T1}=6.5\), varying in the range of \(\pm 1.0\%\), as shown in Figure 4 (a). Considering the measurement uncertainty no significant increase in wind farm efficiency can be found. That means that approximately the same amount of energy which is lost on the upstream rotor can be recovered for a low turbine separation distance of x/D=3.

In Figure 4 (b) a map of the combined wind farm efficiency is shown for a variation of the upstream turbine’s pitch angle. It is observed that the kinetic energy surplus in the wake behind a pitched upstream turbine is most efficiently recovered by the downstream turbine for very small upstream turbine pitch angles up to \(\beta_{T1}=-1^\circ\). However, no increase in total wind farm efficiency is achieved for any of the investigated pitch angles.

These experimental findings contradict the calculated total efficiency improvements through axial induction based wind farm control as found by Horvat et al. [4], Lee et al. [5], Johnson and Fritsch [6], Marden et al. [7] or González et al. [8]. Most of these algorithms are, however, based on engineering wake models, which include a number of simplified assumptions. Annoni et al. [9] disclose some of the discrepancies of an engineering wake model by directly comparing it to a higher-order wake simulation based on LES computations. These higher-order simulations result in very similar trends as presented in this experimental study, although the turbine geometry and the boundary conditions are somewhat different.

A possible explanation for the non-recovery of the added energy in the wake can be found by taking a closer look at the wake flow. Analysing the wake flow (Figures 2(d) and 3(d)), it is observed that small parts of the added kinetic energy in the wake diffuse into areas outside the downstream rotor swept area due to turbulent mixing. The added energy in the wake thus cannot be recovered by the downstream turbine anymore.

For higher downstream distances the wake is supposed to re-energize, also meaning that even more added energy from the wake is diffused into the surrounding freestream flow. Consequently, controlling the upstream turbine is expected not to affect the wake flow and downstream turbine power to the same extent anymore for higher distances.

![Figure 4 (a). Map of the combined farm efficiency](image1)

![Figure 4 (b). Map of the combined farm efficiency](image2)
From another point of view it can be stated that the combined power is not very susceptible to deviations from the optimum rotational speed and pitch angle. This finding implies that that axial induction based wind farm control could be beneficial for achieving a more even load distribution between two consecutive turbine rows. As the combined power is almost constant in region down to $\lambda_{T1}=4.5$ respectively $\beta_{T1}=-1^\circ$, induction based turbine control could be used to pass on loads on the next turbine row to the cost of only very small power losses.

5. Conclusions

It is shown that the radial distribution of kinetic energy in the wake area can be controlled by modifying the upstream turbine’s tip speed ratio. Controlling the tip speed ratio of the upstream turbine away from its design point is observed to modify the radial distribution of kinetic energy in the wake. The added kinetic energy in the wake is decreased in the centre region of the wake and increased in a circular region behind the outer blade elements when the upstream rotor is downrated. When downrating the upstream turbine in the range of $\lambda_{T1}=4.5$-6.0, the major part of the kinetic energy can be recovered by the downstream turbine for low turbine separation distances up to x/D=3. However, a significant overall increase in power output of the two turbine array is not achieved.

By pitching out the upstream turbine’s blades the available kinetic energy in the wake is increased at an equal rate over the entire blade span. The total array efficiency of the two turbine setup is observed to decrease when the upstream turbine is pitched towards the feathered position. Also for this wind farm control mechanism, no significant increase in the two-turbine array efficiency is measured. For both control mechanisms it is observed that some of the added kinetic energy in the wake is diffusing into the freestream and cannot be recovered by the downstream turbine anymore.

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