On the application of LiDARs in wind farm control

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Summary

Within the project LAWINE, partially sponsored by the dutch government via the program TKI Wind op Zee, research is performed on the application of LiDAR sensing technologies for wind measurements in wind farms. One of the tasks in this project is on the use of LiDAR measurements for improving wind farm control algorithms, such as ECN's Active Wake Control concept. Active Wake Control is an approach of operating wind farms in such a way as to maximize the overall wind farm power production. It consists of two concepts patented by ECN: pitch-based Active Wake Control (called Heat & Flux), and yaw-based Active Wake Control (called Controlling Wind).

Both these Active Wake Control methods require wind speed and direction measurements to operate properly. However, measurements on the research turbines located at ECN Wind Turbine Test Site Wieringermeer (EWTW) indicate that the turbines operate with a significant yaw error of around 4°. While this yaw error is not significant with respect to the power production, it constitute a very significant error when when it comes to Active Wake Control, and especially Controlling Wind, application. It is shown that such a yaw error completely destroys the benefit from Controlling Wind. Heat & Flux proves to be a more robust strategy with this respect and while its benefit decreases under yaw errors, this is much less pronounced than for Controlling Wind.

Finally, a number of possible applications of LiDARs are discussed in the context of optimizing the performance of a wind farm with respect to its power production. Several options are considered, such as, (1), improving the accuracy of the wind direction measurements, (2), fine-tuning the underlying farm wake modeling, and (3) using LiDARs (nacelle-mounted backward looking or ground-based scanning) to do online model-free Active Wake Control optimization driven by wake measurements (rather than using wake simulation models). The last option might be very promising with respect to Active Wake Control applications in wind farm in complex terrain, for which no accurate wake models with reasonable computational complexity exist. Also studied are the requirements on the LiDAR measurement equipment necessary to enable application of the proposed model-free Active Wake Control strategy.

This work is performed within the project LAWINE, subsidized by the Dutch government within the framework of the TKI Wind op Zee program.

1

Introduction

Active Wake Control aims at improving the overall wind farm performance in terms of power production *at below rated wind conditions*. It consists of a pitch-based approach (also known as Heat & Flux), and a yaw-based approach (called Controlling Wind).

The idea behind the Heat & Flux concept, patented by ECN [3], is to operate the turbines at the windward side at a lower axial induction factor than the Lanchester-Betz optimum of 1/3. To achieve this, the pitch angle of the blades is increased. This reduces the power production of these upstream turbines, but the downstream turbines in their wakes get higher wind speed and make up for this power production loss, resulting in a net increase of the power output of the farm. Also the fatigue loads reduce and are more evenly distributed over the turbines.

The Controlling Wind concept, also patented by ECN [4], consists of yawing the upstream wind turbines away from the wind. Due to the resulting yaw misalignment, the wakes behind the yawed turbines are redirected aside from the downstream wind turbines, which therefore receive (a larger portion of) the undisturbed wind stream. Controlling Wind optimizes the yaw misalignment angles of each individual wind turbine in such a way, that the overall power production of the whole wind farm is maximized.

Both the Heat & Flux and Controlling Wind concept require accurate measurement of the wind direction to determine the setpoints for the pitch angle and/or yaw misalignment. Conventionally, these can either be obtained from the measurement mast, or from the nacelle-mounted wind anemometers/vanes. Metmast measurements represent, however, just one single point in space and are not representative for the whole farm. Moreover, when the metmast is positioned in the wake of the farm, the measurement is not useful for AWC. The wind vane measurements, on the other hand, are local but not very accurate and reliable. Measurements on the research turbines located at EWTW indicate that the turbines operate with a significant yaw error of 4°-7° [1, 8]. While the effect of this yaw error on the power production is not very high, the error constitutes a very significant error when used for Active Wake Control. Therefore, the first part of this report is dedicated to study more closely these yaw errors, look for their cause, and investigate their effect on the performance of Heat & Flux and Controlling Wind. This is the topic of Chapter 2.

Chapter 3 discusses a number of possible applications of LiDARs for optimizing the performance of a wind farm with respect to its power production. Possible options discussed are, (1), increasing the reliability of Active Wake Control by improving the accuracy of the wind direction measurements, (2), fine-tuning the Active Wake Control settings by improving the underlying farm wake modeling, and (3) using LiDARs (nacelle-mounted backward looking or ground-based scanning) to move from the current model-based Active Wake Control approach (using a wake model) to online model-free Active Wake Control that is directly driven by wake measurements. The last option might be very promising with respect to Active Wake Control applications in wind farm in complex terrain, for which no accurate wake models with reasonable computational complexity exist. The requirements on the LiDAR measurement equipment to enable application of the proposed model-free Active Wake Control strategy are also studied.

2

Active Wake Control in the presence of yaw errors

The Active Wake Control concepts Heat & Flux and Controlling Wind require accurate wind direction measurements for proper functioning, because the optimal settings (pitch angle for Heat & Flux and yaw misalignment for Controlling Wind) depend on the mean wind direction, and this relationship is rather sensitive for some wind directions. This can be observed in the plots in Figure 1, borrowed from [7], wherein the solid lines represent typical AWC settings as function of the wind direction. Clearly, especially in the case of Controlling Wind (left plot), even just a few degrees of error in the wind direction can result in a very large change of the Active Wake Control settings. The purpose of this chapter is to show whether the accuracy of the wind direction measurement is indeed as crucial for Active Wake Control as it seems from Figure 1.

2.1 Yaw errors in practice

Before we study the effect of yaw errors on the performance of the Active Wake Control algorithms, let's first analyze the yaw behavior of a commercial wind turbine, namely one of the 2.5MW research wind turbines (the second one from West, also known as

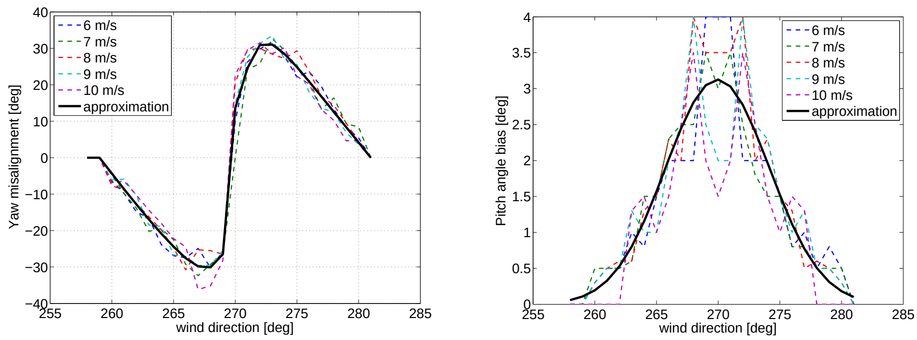


Figure 1: Typical Active Wake Control settings as function of the wind direction. Left plot represents the yaw misalignment in Controlling Wind, and the right plot – the pitch angle offset in Heat & Flux.

N6) located at EWTW. Earlier studies [1, 8] indicate that this turbine operates under yaw misalignment. In [1] this conclusion is made based on comparison of the rotor orientation with the wind direction measurement taken on a closely located (at a distance of around 200 m) metmast. The reported yaw misalignment is around -6 to -7°, and it is mentioned that even under free stream conditions the yaw misalignment seems to be slightly higher (up to -8°) for wind directions around close to the direction of the row of turbines (275°). This might be due to the air stream blockage effect of the wind turbines. The yaw misalignment conclusion has also been independently confirmed in [8] based on measurements with a 2-beam Wind Iris nacelle LiDAR taken 5 years later. The yaw misalignment there is estimated to be on the average -4° based on LiDAR measurements with a duration of 3 months.

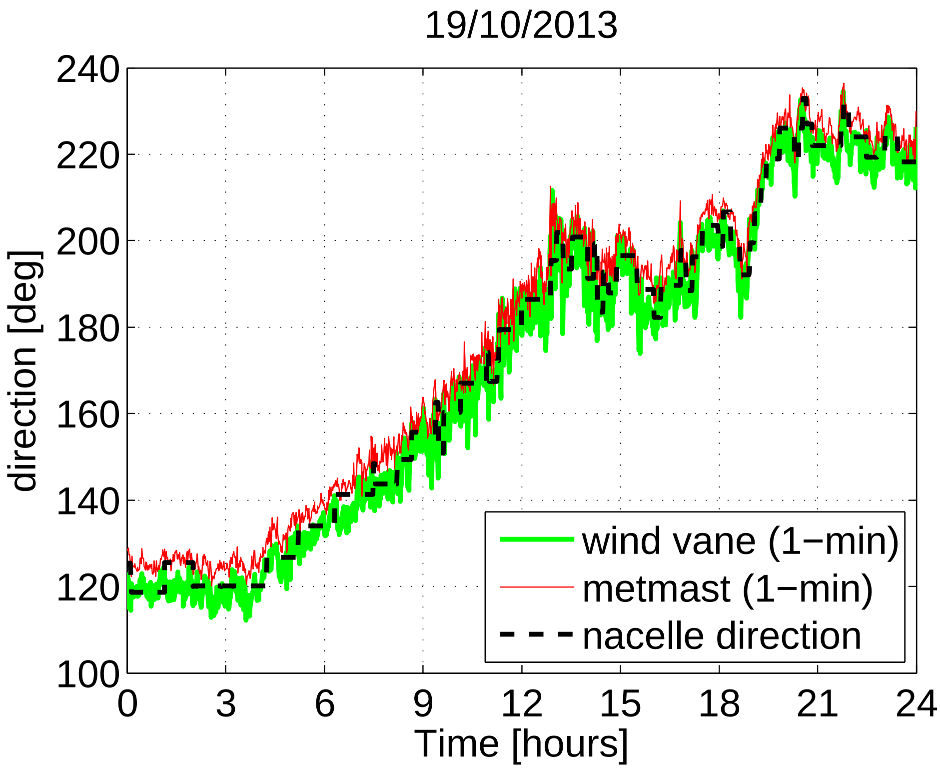
In order to investigate the reason for the yaw error operation, one month of measurement data has been studied further here, namely the measurements on the N6 from October 2013 (these data was also part of the data analyzed in [8]). The misalignment of the rotor is determined by comparing the rotor orientation to the wind direction measured by the wind vane, metmast, and LiDAR. The wind direction measurements of the vane and LiDAR are relative to the nacelle orientation, which is calibrated with respect to the magnetic North using a compass. Only wind directions between 120 and 260°are considered, for which N6 is operating in free stream. The yaw errors' results are summarized in Table 1. The result from the table is well in line with the earlier results: the misalignment with respect to both the metmast wind direction (-3.6°) and the LiDAR measurement (-3.7°) agree very well with the reported figures in [1] and [8]. Moreover, since these two figures are very close to each other, it can be concluded that the wind direction measurements from both the LiDAR and the metmast are very well calibrated. Interestingly, the yaw error with respect to the wind vane on the nacelle is much smaller (less than 2°) and in the opposite direction. Therefore, the wind direction measured by the wind vane differs from both the metmast and LiDAR measurements by as much as 5.5°. This is most probably due to calibration error in the wind vane.

Table 1: Yaw errors for N6 in the period 1-31 October 2013 for wind directions 120-260°

Yaw error with respect to	[deg]
wind vane	1.9
metmast	-3.6
LiDAR	-3.7

It is interesting to analyze the yaw error with respect to the wind vane measurement more closely, since this yaw error is directly being controlled by the yaw control algorithm. To this end, Figure 2 depicts the yaw control behavior during one day (19 October 2013) for the N6 wind turbine, wherein the red thin curve represents the metmast measurement of the wind direction, the green thick curve represents the wind direction measured by the wind vane, and the black dashed line gives the yaw orientation of the nacelle. It is clearly visible in the figure that there is a positive offset between the nacelle orientation and the metmast measurement, and a (smaller) negative offset between the nacelle orientation and the wind vane direction. This confirms the results in Table 1. It is, however, interesting to observe that during the scope 24 hours the wind direction gradually increases from about 120°to about 220°. Since the yaw control has a very slow dynamics, it is expected that the yaw orientation of the nacelle lags the

Figure 2: Typical result for the wind direction measured by the metmast (red/thin line) and wind vane (green/thick line), and the yaw orientation (black/dashed line) of the nacelle.



wind direction changes. For the data plotted in Figure 2, therefore, one would expect the black dashed line (nacelle orientation) to lie on the average below the green thick curve (the wind direction measured by the wind vane) since the former tries to track the latter which increases during most of the considered 24 hours. It is therefore very well possible that the small difference of about 2°between the nacelle orientation and the wind vane direction is an internal software setting (yaw bias) in the yaw controller of the turbine. Notice as well that this bias results in the nacelle orientation coming closer to the metmast and LiDAR measurements.

2.2 Effect of yaw errors on Active Wake Control

In the previous section it was shown that the research turbines at EWTW operate under yaw error of almost 4°. In this section, the effect of yaw error on the performance of the Active Wake Control algorithm will be analyzed. Both static and quasi-dynamic analysis will be presented. To this end, FarmFlow simulations are performed with a single row of seven generic 6MW wind turbines at distances of around 7D. As the purpose is to study the effects of yaw errors on the power production with AWC, it is not necessary to consider all possible wind directions. Instead, it suffices to focus on just one row of turbines and to consider only a sector of wind directions around the orientation of the row of turbines.

The row of turbines is simulated with FarmFlow for wind directions from 258° to 281° (the orientation of the row is 269.5°) and wind speeds of 6-10 m/s. The Active Wake Control settings depend on the wind direction only; these are represented by the thick curves in Figure 1. However, to model the effect of yaw errors on the Active Wake Con-

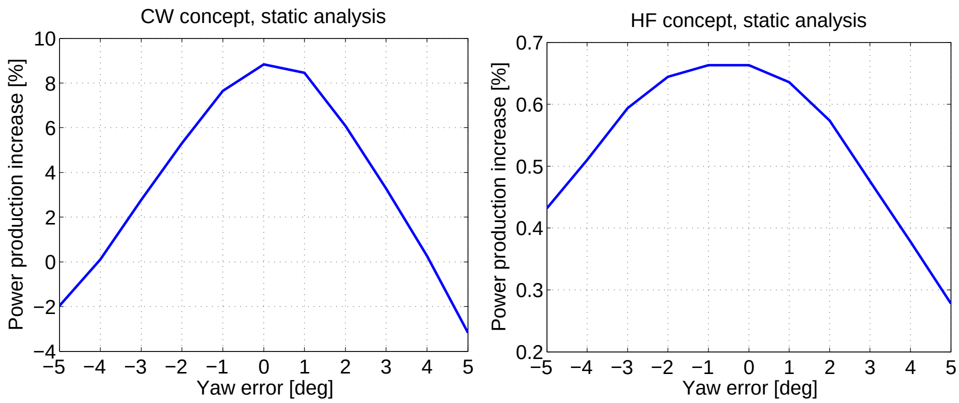


Figure 3: Static analysis of the effect of yaw errors on the power production gain by Controlling Wind (left) and Heat & Flux (right).

trol settings, these curves are shifted along the x-axis by as much as the modelled yaw error. In this way the Active Wake Control settings will be biased with respect to the optimal settings for zero yaw error. Yaw errors between -5° and 5° are considered in this analysis. The results of all these FarmFlow simulations are stored in a lookup table, that provides the power productions of the turbines in the row for a given wind speed, wind direction, and the Active Wake Control settings.

Static analysis The static analysis is performed as follows. For a given yaw error, the biased Active Wake Control settings are determined, and the corresponding power productions are extracted (interpolated) from the data base for the considered wind speeds and directions. The probabilities of these wind speeds and directions are then used to calculate the average production for all considered winds. To ensure that the results are comparable to those from the quasi-dynamic analysis below, the wind speed and distribution probabilities are calculated based on the time-series data used in the quasi-dynamic case (see below). The power production gain is calculated as the relative increase with respect to the power production with no Active Wake Control for different yaw errors. The results are depicted in Figure 3 for the two Active Wake Control concepts, i.e. Controlling Wind (left plot) and Heat & Flux (right plot). It can be seen from the plots that Heat & Flux is much more robust with respect to yaw errors than Controlling Wind, wherein the fall-off of the power gain is much steeper. Indeed, yaw errors of 4°of larger destroy all benefits from Controlling Wind, while Heat & Flux looses at most about 50% of its benefit for yaw errors of up to 5°. To avoid large losses of the benefit from Controlling Wind, it needs to be ensured that the yaw error remains within $\pm$2°.

Quasi-dynamic analysis The quasi-dynamic analysis is performed by means of feeding the lookup table, described above, with real-life wind data, obtained from metmast 3 at EWTW. The wind data used is collected at a height of 80 m, is sampled at 10 seconds and has duration of 5 years (2008 to 2012). Out of these data the longest time interval is taken that contains wind speed signals between 6 and 10 m/s and wind direction that remains within an interval of 20°. It has a length of $17\frac{2}{3}$ hours in the period of 14-15 August 2012. The wind direction signal is then centered at 269.5° to make it vary around the orientation of the row. These data is used to feed lookup table, described above. For determining the Active Wake Control settings, the wind direction is further low-pass filtered (cutoff frequency 1/120 Hz) and down-sampled

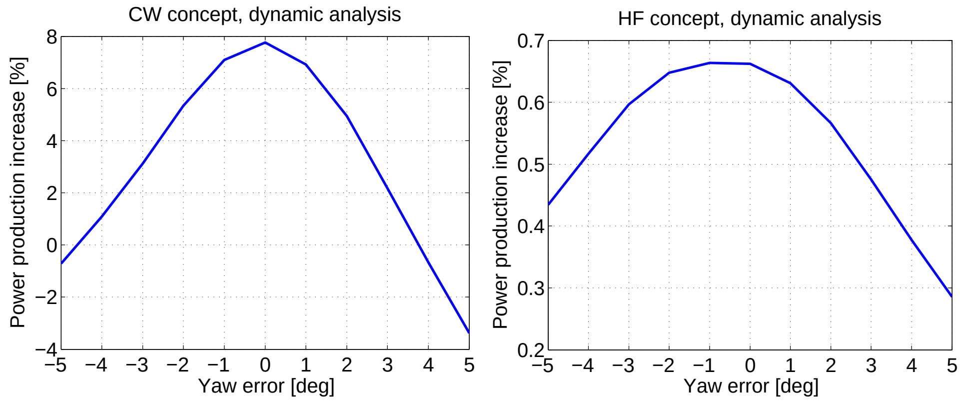


Figure 4: Quasi-dynamic analysis of the effect of yaw errors on the power production gain by Controlling Wind (left) and Heat & Flux (right).

to 60 seconds, and subsequently offset by the considered yaw error. The resulting biased Active Wake Control settings are used in combination with the 10 sec wind data to feed up the lookup table for calculating the power productions. For more information about this quasi-dynamic simulation setup, see [7]. Using this simulation setup, the relative decrease in the produced energy by the dynamic Active Wake Control adaptation strategy with respect to the theoretical maximum achieved with instantaneous adaptation is calculated for the considered range of yaw errors. The results are presented in Figure 4. These results are very similar to those from the static analysis, given in Figure 3, and the same conclusion holds therefore here.

3

LiDAR based Active Wake Control

LiDAR's can be used for different purposes when it comes to farm management and control. The focus in this section is on the use of LiDAR for optimizing the performance of the wind farm with respect to the power production, i.e. LiDAR assisted AWC.

3.1 Model-based Active Wake Control

As explained in the previous chapter, the settings of the Active Wake Control algorithm are optimized using a farm model such as FarmFlow. The implementation of these settings in the field requires accurate measurements of the wind directions within the wind farm, since even a relatively small wind direction measurement error (yaw error) of about 4°can destroy the benefit of Active Wake Control or, even worse, can lead to a power loss. To prevent this, LiDAR's can be used. Three-dimensional scanning LiDAR's, for instance, can nowadays scan at distances of up to 10-15 km and can therefore cover a very large area of the wind farm. Ground-based scanning LiDARs can be located at several possible locations of the wind farm or outside the wind farm with a clear open view on the turbines of interest. In offshore wind farms, positioning 2 or 3 such scanning LiDAR's on, e.g., the power station could already be sufficient to enable scanning of the wind throughout the complete wind farm. It does not suffer from the turbine motions (yaw, tilt and roll), therefore the measurements are kept accurate and well located. Moreover the LiDAR deployment does not required to stop any wind turbine and will continue the measurement even though a wind turbine is off. Several wind turbine wakes can be mapped together and wakes interactions would also be captured allowing for more advanced controls strategies. As an alternative, nacelle-based LiDAR's can be used to scan the wind field in front of each wind turbine and determine the wind direction accurately. Whatever LiDAR technology used, the measurements would increase the reliability of Active Wake Control by ensuring that the settings are properly implemented.

Another possible application of LiDAR measurement technology is to boost up the performance of Active Wake Control by improving the underlying farm wake modeling.

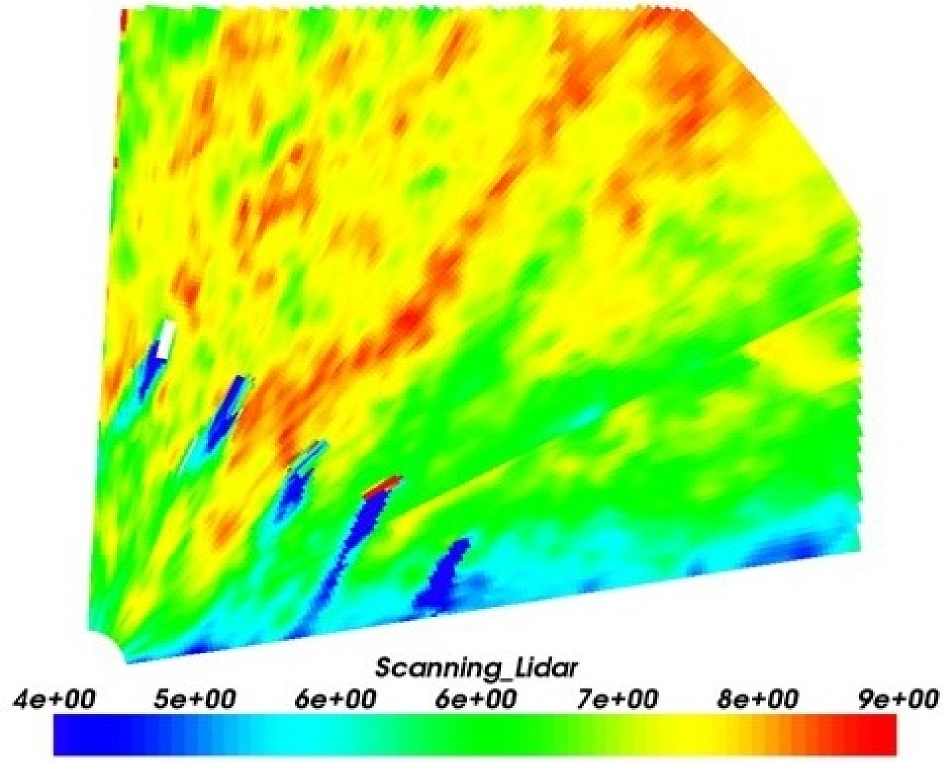


Figure 5: Wind speed measurements with a ground-based scanning LiDAR around and inside wind turbines wakes [5]. The wake locations and wind speed deficits are clearly visible behind the five turbines.

More specifically, LiDAR measurements can be used to improve the accuracy of the models that relate blade pitch angle offsets and/or yaw misalignment on the wake to the wake properties (wake location, and width and depth of the wake deficit profile). This would allow, after farm installation, to fine-tune the Active Wake Control settings to minimize the effect of model uncertainties (modelling errors) on the Active Wake Control performance. To this end, a short measurement campaign could be planned using LiDAR after wind farm installation, possibly by instrumenting just a single wind turbine inside the farm with a backwards looking LiDAR to avoid unnecessary power losses, or by using a ground-based scanning LiDAR to scan the wakes of several wind turbines (see Figure 5). Experiments could then be performed with a pre-defined set of yaw misalignment and pitch angle offsets under different incoming wind field conditions (i.e. in free stream, or in the wake of other turbines). Using the LiDAR measurements, the wake characteristics could be reconstructed and correlated to the implemented settings and inflow conditions. This would allow to improve the accuracy of the wake model and fine-tune the Active Wake Control settings.

3.2 Model-free Active Wake Control

Instead of trying to improve the farm wake models, LiDAR's could potentially also be used to perform *model-free* Active Wake Control. One idea could be to use backwards oriented LiDAR's to measure the wake location and profile (width and depth of the wake deficit "bulge"), and feed this information to an online optimizer for the Active Wake Control settings. Alternatively, ground-based scanning LiDAR could be employed to determine the wakes of several turbines and communicate this information to the individual turbines. Forward-looking LiDAR represents yet another alternative, but requires information exchange between the turbines.

Roughly speaking, the optimizer can increase or decrease the yaw misalignment angle in a Controlling Wind setting until the measured wake location is moved to a desired position. With respect to Heat & Flux, it will be the pitch angle offset that the optimizer will adapt until the depth (and width) of the wake deficit bulge are optimized. Of course, since the final objective is to maximize the power yield rather than the wake properties, some simple model will have to be used to estimate the *relative* effect on the *aerodynamic* power. In other words, we should be able to say how much power is relatively being lost by applying given Active Wake Control settings upstream, and how much aerodynamic power is being added (relatively) downstream by these settings. Even though at first sight it may seem that such an approach is rather indirect, as one could argue that a existing measurements of the *electrical* power production are equally well useful and do not require expensive LiDAR measurement equipment, this is not the case. The reason for that is that the measured electrical power fluctuates largely with time due to many factors, such as the incoming wind conditions (wind speed, wake profile, turbulence intensity, wind direction) but also turbine parameters such as the pitch angle offset and the yaw misalignment. Therefore, it might be simpler to consider the available aerodynamic power in the wind instead of using the power measurements.

Table 2: Summary of LiDAR applications in Active Wake Control (AWC)

LiDAR type	measurement	purpose
ground-based scanning	wakes in whole farm	model tuning, dynamic/model-free AWC
nacelle-based forward-looking	yaw misalignment	dynamic AWC
nacelle-based backward-looking	wake position & deficit	model-free AWC

A simplified model for the *relative* power loss and power gain due to Active Wake Control is constructed as follows. Suppose turbine T_i is operated at yaw misalignment of ϕ_i. According to the FarmFlow model [2], at below rated winds the relative power loss due to misalignment is

$$\Delta P_{loss}^{(CW)}(\phi_i) = \frac{P(\phi_i)}{P(0)} = \cos(\phi_i)^{2.3}. \quad (3.1)$$

Similarly, if turbine T_j is operated with a blade pitch angle offset of θ_i, the relative power loss can be modelled as

$$\Delta P_{loss}^{(HF)}(\theta_j) = \frac{C_p(\theta_{opt} + \theta_j, \lambda_j)}{C_p(\theta_{opt}, \lambda_{opt})}, \quad (3.2)$$

wherein C_p is the rotor power coefficient, θ_{opt} and λ_{opt} are the optimum blade pitch angle and tip speed ratio, and λ_i represents the tip speed ratio that corresponds to the applied pitch angle $(\theta_{opt} + \theta_j)$ under Heat & Flux.

Therefore, equations (3.1)-(3.2) provide means to evaluate the relative aerodynamic power loss due to application of the Controlling Wind or Heat & Flux settings. Notice that these relative expressions do not depend on the wind conditions.

To evaluate the power gain due to the application of Active Wake Control, let's assume that a LiDAR scans the wind velocity in the wake of each turbine at, for instance, hub height, allowing to reconstruct the profile of the wake deficit. The form of the wake profile has been studied in detail within the FLOW project "Wind Farm Wake Modelling,

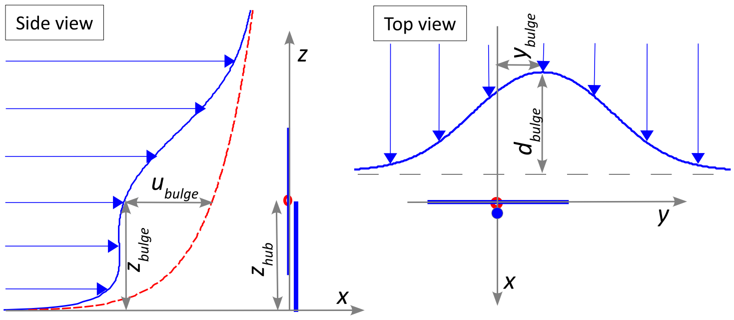


Figure 6: Visualization of the wake profile (bulge) parameters

Fatigue Loads and Control" [6], and although not explicitly provided in the mentioned citation, the following relation is implemented in ECN's software FarmFlow and Make-Wake for approximating the wake deficit profile

$$\begin{aligned} u(y,z) &= u_{free}\left(1+\alpha_{sh}\ln\left(\frac{z}{z_{hub}}\right)\right) \\ &\quad -\frac{1}{2}u_{bulge}\left\{1+\cos\left[\pi d(y,z)\left(d_{bulge}^4+d^4(y,z)\right)^{-\frac{1}{4}}\right]\right\} \end{aligned} \tag{3.3}$$

wherein u_{free} is the wind speed of the free stream at hub height, y horizontal displacement with respect to the rotor center of the turbine that receives this wind profile, z is the height, α_{sh} is the vertical shear parameter, z_{hub} is the hub height, u_{bulge} is the wake bulge depth (i.e. the largest wind speed deficit in the wake), d_{bulge} is the wake bulge width,

$$d(y,z) = \left[(y-y_{bulge})^2+(z-z_{bulge})^2\right]^{\frac{1}{2}}$$

is the distance of a point (y,z) to the center of the bulge (y_{bulge}, z_{bulge}), y_{bulge} being the horizontal distance of the center of the bulge to the rotor center, and z_{bulge} – the the height of the bulge center (which could be assumed for simplicity to be equal to the hub height z_{hub}. These parameters are visualized in Figure 6, wherein an example is shown of the vertical form of the wake profile (the side view in the left plot) and the horizontal form (the top view in the right plot). The vertical wake profile is superimposed over the vertical wind shear profile, given by the red dashed curve in the left plot. The location of the rotor and tower is also depicted in the figure.

The wake profile in equation (3.3) proves to give a good approximation for the wake deficit as calculated by the FarmFlow software for different locations in a typical wind farm. For example, considering the row of wind turbines discussed in Section 2.2, the wake profile approximations (3.3) at the wind turbines are illustrated in Figure 7 as calculated by FarmFlow for wind direction 273°. Therein, the location and size of the rotors are indicated by the straight lines, and the wake profiles – by the curved lines. The blue lines represent the wake profiles in the reference case with no Active Wake Control, while the red curves – the wakes in the case of Controlling Wind. The wake redirection property of the Controlling Wind strategy can be clearly seen: the wake centers are moved more to the left and the wake deficits in front of the wind turbines are reduced.

For a given wind direction, the idea behind the suggested optimizer using LiDARs is:

- first, in the reference case (no Active Wake Control applied), measure the wind velocities in a number of points lying inside and outside of the wake. To remove the

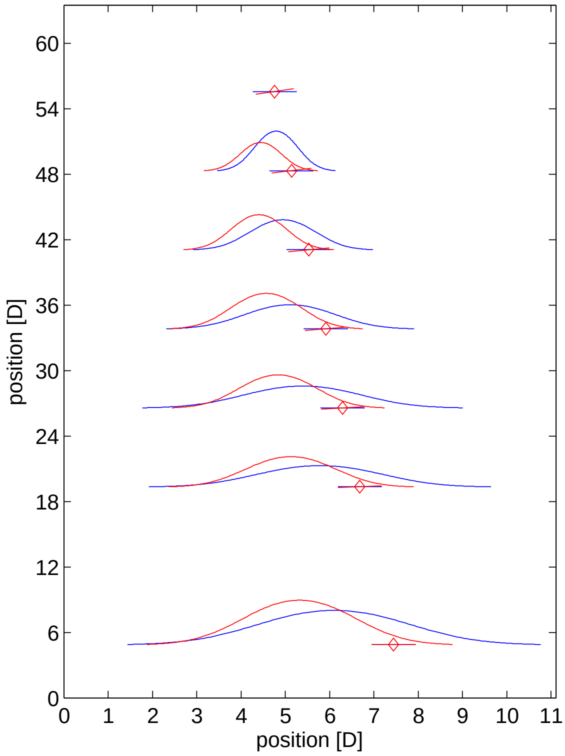


Figure 7: The effect of Controlling Wind on the wake deficits in a row of turbines

effect of the undisturbed wind speed, normalize the wake profile with respect to measurements of the wind velocities outside of the wake.

- calculate an approximation of the wake profile using the relation in equation (3.3), i.e. determine the wake parameters $\delta u^{ref}_{bulge} = u^{ref}_{bulge}/u_{outside}$, d^{ref}_{bulge} and y^{ref}_{bulge} (superscript "ref" to denote the values in the reference case. Here $u_{outside}$ is the measured wind velocity outside the wake.

- apply candidate Active Wake Control settings, measure the resulting wake profile, normalize as above, and determine wake parameters δu^{AWC}_{bulge}, d^{AWC}_{bulge} and y^{AWC}_{bulge}

- determine the power gain by

$$\Delta P_{gain} = \left(\frac{\iint_{y,z} u^{AWC}(y,z)dzdy}{\iint_{y,z} u^{ref}(y,z)dzdy} \right)^3$$

$$= \left(\frac{\delta u^{AWC}_{bulge}}{\delta u^{ref}_{bulge}} \frac{1+\iint_{y,z} \cos\left[\pi d^{AWC}(y,z)\left((d^{AWC}_{bulge})^4+(d^{AWC}(y,z))^4\right)^{-\frac{1}{4}}\right] dzdy}{1+\iint_{y,z} \cos\left[\pi d^{ref}(y,z)\left((d^{ref}_{bulge})^4+(d^{ref}(y,z))^4\right)^{-\frac{1}{4}}\right] dzdy} \right)^3 \quad (3.4)$$

Notice that in the expression above the double integration should be performed over the rotor plane and that the effect of wind shear is neglected (both simplifications made for the sake of notational simplicity).

- determine the effect on the power production of the whole farm by adding up the relative gains at different turbines, and subtracting the corresponding losses (3.1)-(3.2) due to deviations from the optimal turbine settings. This can be used as an op-

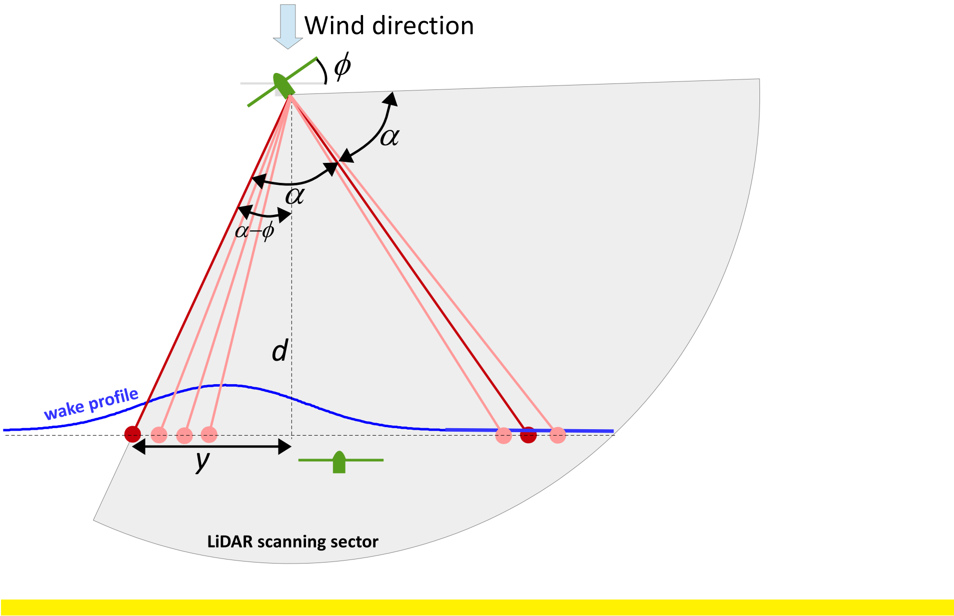


Figure 8: Scanning sector of backward looking LiDAR

timization criterion to be maximized, and a simple (N-dimensional) bisection type of algorithm could be used to optimize over the Active Wake Control settings.

In order to be able to implement the procedure described above, enough measurements of the wind speeds inside and outside of the wake are required so as to reconstruct the wake profile accurately enough. In order to understand the requirements on the LiDAR measurement system better, consider Figure 8 that provides an illustration of a two turbine setup in which the upstream wind turbine is yawed at ϕ° with respect to the free wind direction. Suppose we want to measure the wake profile at a distance of d downstream (for instance at a distance of one rotor diameter in front of the downwind turbine), and we need to be able to measure at lateral distances of $\pm y$ with respect to the rotor center of the upstream turbine. Assuming that the LiDAR scans a sector of $\pm\alpha$°, α needs to satisfy the conditions

$$\left| \begin{array}{rcl} \alpha & > & |\phi| \\ \tan(\alpha-\phi) & > & \frac{y}{d} \end{array} \right. \Rightarrow \alpha > |\phi| + \arctan\left(\frac{y}{d}\right).$$

In practice, it is expected that $y/d < 0.25$ (e.g. measuring up to 1D laterally at a distance of 4D), and $|\phi| < 35°$ so that $\alpha = 50°$ seems to suffice. That would mean that the LiDAR should be able to cover a sector of 100°, which seems realistic. Of course, these requirement becomes less demanding if the LiDAR can rotate (e.g. by placing it on a servo table).

In addition to above requirement on the width of the LiDAR measurement sector, we need to ensure there will be sufficient resolution in the measurements to reconstruct the wake profile accurately. For offshore applications, distances of 15D and more are not unusual, which imposes high demands on the LiDAR angular resolution. Indeed, if we need at least 5 measurement points per lateral interval of length D, the resolution of the LiDAR should be as high as 0.75°, resulting in as much as 134 measurement points in a sector of 100°.

Finally, the scanning distance should also vary from beam to beam, and should best be configurable depending on the free wind direction and applied yaw misalignment.

In the above analysis on the resolution requirements, a backward looking LiDAR was considered. For a scanning LiDAR the resolution requirements will be higher as it will cover a larger distance (several turbines).

4 Conclusion

Active Wake Control is a strategy, developed and patented by ECN, for operating wind farms in a way that improves their power performance and reduces fatigue loading. For proper operation, Active Wake Control requires accurate measurements of the direction of the incoming wind field. However, the presented results from the analysis of the wind direction measurements at ECN's test site EWTW indicate that the turbines operate with a significant average yaw error of around 4°. Furthermore, the effect of such yaw errors on the benefit from Active Wake Control is studied using a quasi-dynamic simulation environment based on post-processing FarmFlow calculations at different inflow conditions and Active Wake Control settings. This analysis indicates that the Controlling Wind benefit is very sensitive to yaw errors, and gets completely removed already at yaw error of 4°. Heat & Flux is also shown to suffer from yaw errors, but to a lesser extend. These results underline the need of accurate wind direction measurements, which could be improved using LiDARs.

In light of this, a number of possible applications of LiDARs for optimizing the performance of a wind farm with respect to its power production are also considered. Possible options discussed are, (1), increasing the reliability of Active Wake Control by improving the accuracy of the wind direction measurements, (2), fine-tuning the Active Wake Control settings by improving the underlying farm wake modeling, and (3) using nacelle-mounted backward looking LiDARs (or, possibly, ground-based scanning LiDARs) to move from the current model-based Active Wake Control approach (using the FarmFlow model) to online model-free Active Wake Control that is directly driven by wake measurements. The last option might be very promising with respect to Active Wake Control applications in wind farm in complex terrain, for which no accurate wake models with reasonable computational complexity exist. The requirements on the LiDAR measurement equipment to enable application of the proposed model-free Active Wake Control strategy are also briefly discussed. It is shown that a backward looking LiDAR that measures the wind speeds at hub height in a azimuthal sector of 100 degrees suffices. These requirement becomes, of course, less demanding if the LiDAR can rotate (e.g. by placing it on a servo table). The required resolution, however, is rather high (0.75°separation between the laser beams) to enable application in farms with larger distances between the turbines. These results, however, are just preliminary, and more detailed studies are required to analyze the potential of such approach in practice.

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