Active Wake Control: loads trends

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Abstract

Active Wake Control (AWC) is a strategy, developed and patented by ECN, for operating wind farms in an economically optimal manner. It makes use of the wake interactions between the wind turbines to maximize the power production of the whole wind farm and/or reduce the loading of the individual wind turbines. The wakes are controlled by either pitching the blades of upstream wind turbines (pitch-based AWC), thereby increasing the wind velocity in the wake, or by misaligning the rotors with the wind (yaw-based AWC), thereby moving the wakes aside from the downstream wind turbines.

The purpose of this report is to analyse the effect of AWC on the loads of the wind turbines. It provides insight into the factors that contribute to these loads (yaw misalignment, turbulence intensity, wake location, wake deficit profile, etc). The conclusions made in this report indicate that it seems possible to apply yaw-based AWC to increase the power capture while keeping the DEL within the design envelope.

This work is performed within the project "*Wind Farm Wake Modelling, Fatigue Loads and Control*", partially sponsored by the Far and Large Offshore Wind (FLOW) programme of the Dutch government (project number P201102-004-ECN).

List of Abbreviations

AWC	Active Wake Control
CAPEX	Capital expenses
TI	Turbulence intensity
DEL	Fatigue damage equivalent load

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Introduction

Active Wake Control (AWC) is a concept to operate wind farms in an economically optimal manner, offering the following user benefits:

- Maximize the wind farm power production
- Reduce O&M costs by minimizing the fatigue loading
- Allow for reduction of CAPEX by placing the turbines closer (reduce electrical infrastructure costs) when applied at the design phase of the wind farm.

Different studies indicate that a lifetime power increase of up to 1-1.5% can be achieved with AWC. A quantitative analysis of its effect on the O&M costs and CAPEX is currently ongoing.

The AWC concept is applicable at below rated wind speeds, and consists of two strategies, both patented by ECN (Corton, Lindenburg, & Schaak, Assembly of energy flow collectors, such as windpark, and method of operation, 2004) (Corton & Schaak, Method and installation for extracting energy from a flowing fluid, 2004), that can either be applied individually or in combination:

- **Pitch-based AWC**: The pitch angles of the upstream wind turbines are increased (or the active power set-point is decreased) to increase the wind speed and reduce the turbulence intensity (TI) in the wake.
- **Yaw-based AWC**: Upstream wind turbines are operated with rotor yaw misalignment to divert their wakes away from the downstream wind turbines.

Pitch-based AWC can increase the power production while at the same time reducing the loads. Experience shows, however, that it is much less beneficial in terms of power production than yaw-based AWC. On the other hand, yaw-based AWC can, when not designed properly, lead to an increase of the loads. It is therefore important to develop an efficient optimization algorithm for designing the yaw-based AWC settings aimed at maximizing the power production while keeping the loads within their design limits. The purpose of this report is to analyze the effect of AWC on the loads of the wind turbines. It provides insight into the factors that contribute to these loads (yaw misalignment, turbulence intensity, wake location, wake deficit profile, etc). It is also meant to provide a basis for building an efficient constrained optimization algorithm for the yaw-based AWC design.

1.1 Pitch-based AWC

The pitch-based AWC concept (called *Heat & Flux* in the past), has been studied extensively last years, both experimentally (in wind tunnel tests (Corten & Schaak, 2004) and in full-size field tests (Boorsma K. , 2012) (Barth, 2007) (Machielse, Barth, Bot, Hendriks, & Schepers, 2007)) and numerically (using detailed *FarmFlow* calculations (Kucuksahin, 2012) (Kanev & Savenije, 2013)).

Recently, within the EU FP7 Framework project *ClusterDesign*, a detailed study has been performed on the optimization of pitch-based AWC for the *Nordsee Ost* wind farm of *RWE Innogy* (Kanev & Savenije, 2013) (Brand, Bot, Kanev, Savenije, & Ozdemir, 2014). Therein, the possibilities for both maximization of the wind farm power production, and minimization of the average damage equivalent loading (DEL) on the tower throughout the farm have been carefully analysed. For this purpose, the *FarmFlow* software has been used in combination with a normalized DEL database generated by the wind turbine manufacturer *Senvion* (the wind farm consists of 48 REpower 6MW wind turbines). The layout of the Nordsee Ost wind farm is given in **Figure 1**
When it comes to maximizing the power yield, pitch-based AWC only needs to be applied to the first wind turbine in the row (see also [7]). The reason that pitch-based AWC application to the second (and later) wind turbines in the row does not lead to noticeable power yield improvement is that the TI after the first wind turbine increases too much (see FarmFlow simulation results in **Figure 2**), and therefore also the wake recovery. As a result of that, the wake effects decrease and so does the benefit of AWC.

Figure 1: The Nordsee Ost wind farm layout. The numbers on the axes represent distances in terms of rotor diameters

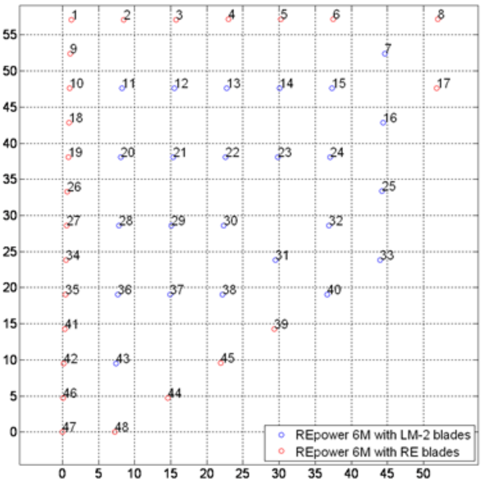
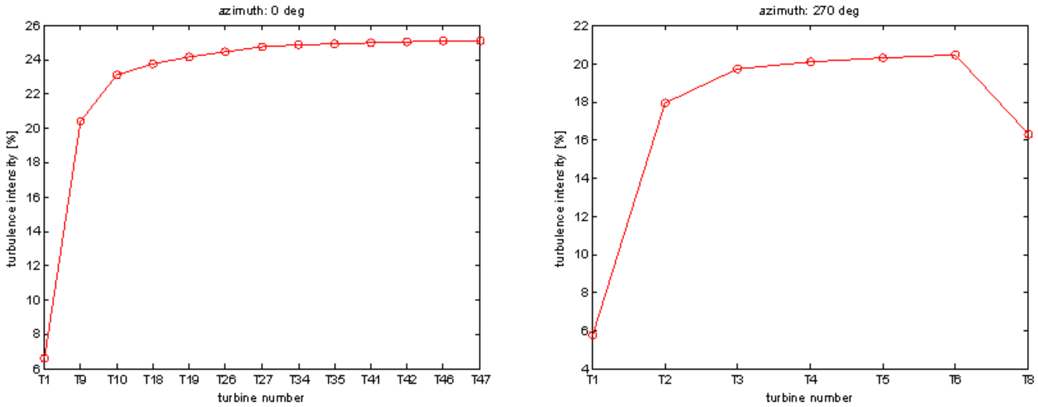


Figure 2: Variation of the turbulence intensity for two rows of wind turbines, when the wind blows from the North (left plot) and West (right plot)



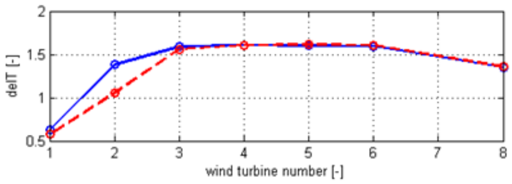
Within *ClusterDesign*, pitch-based AWC has been optimized with respect to both power production and DEL, and the results have been reported in (Kanev & Savenije, 2013). For a single wind speed of 8 m/s and Western wind direction, the power production increase on the most Northern row of wind turbines (T1-T8 in **Figure 1**) is as high as 3.3%. Under the same inflow conditions, loads-optimized pitch-based AWC resulted in a reduction of the DEL of T2 by about 40% (Brand, Bot, Kanev, Savenije, & Ozdemir, 2014).

Applying pitch-based AWC (again to the first wind turbines in the rows only) with the goal of minimizing the DELs in the farm leads to drastic load reductions at the second wind turbines (for Western wind: T2, T11, T20, etc.), but practically no change of the DEL of the remaining wind turbines. This effect is clearly observed in **Figure 3** where the DELs are given for the wind turbines in the most Northern row of *Nordsee Ost*. This effect indicates that

- Loads-optimized pitch-based AWC could be beneficial with respect to the O&M costs of mainly the second wind turbine in the row, because O&M costs are known to be related to fatigue loading (vibrations).
- When applied only to the first wind turbine, loads-optimized pitch-based AWC has no effect on the maximum tower fatigue loading in the farm (the DEL of the third wind turbine is already very close to the maximum one according to **Figure 3**).

However, with respect to loads reduction, it might be beneficial to implement pitch-based AWC to the second wind turbine (and possibly also deeper in the farm) with the intention to reduce the maximum loading (see **Figure 3**), and therefore enable material cost reduction by also optimizing the support structure design.

Figure 3: Normalized DEL on tower bottom (delT) for a row of wind turbines under normal (blue) and load-optimized pitch-based AWC operation on the leading wind turbine only (red)



Altogether, it can be stated that pitch-based AWC increases the power production of the wind farm, while at the same time reducing the loads.

1.2 Yaw-based AWC

Yaw-based AWC (also known as Controlling Wind, or Wake Steering) has attracted some attention by the research community lately (Wagenaar, Machielse, & Schepers) (Gebraad, et al., 2014) (Fleming, et al., High-fidelity simulation comparion of wake mitigation control strategies for a two-turbine case, 2013) (Fleming, et al., Evaluating techniques for redirecting turbine wake using SOWFA, 2013) (Teeuwisse, 2013). Yaw-based AWC has a higher potential for increasing the power yield because the wake is actually being diverted so that the downstream turbines can get (a large portion of) the undisturbed wind field instead of the wake of the upstream wind turbine. That makes yaw-based AWC beneficial already for just two wind turbines in a row (Fleming, et al., Evaluating techniques for redirecting turbine wake using SOWFA, 2013) (Fleming, et al., High-fidelity simulation comparion of wake mitigation control strategies for a two-turbine case, 2013), while pitch-based AWC becomes interesting for three or more turbines in a row.

ECN has performed internally many studies on yaw-based AWC and how to optimize it to maximize the power capture. For the *Nordsee Ost* wind farm, for instance, the top row of turbines increases its production by as much as 17.4% with yaw-based AWC when the wind comes from the West at 8 m/s (compare to the 3.3% production increase achieved by pitch-based AWC in this case).

However, even more important is to consider the loads: yawing a wind turbine can significantly increase its fatigue loading. Moreover, with respect to the wind turbine in its wake, it can change the situation from full to partial wake. The resulting asymmetric loading increases the loads on blades, tower and other components of the wind turbine. Therefore, when applying yaw-based AWC it is important to ensure that the loads remain within the design envelope.

To this end, an extensive loads database is being developed by ECN in the project "*Wind Farm Wake Modelling, Fatigue Loads and Control*", partially financed by the Dutch government under the FLOW program. The data base includes loads on different components under tens of thousands of different conditions, such as different wind speeds, TI's, wake deficit profiles, wake locations, yaw misalignments, wake meandering, etc. The data base is formed using aerodynamic simulations with ART 5MW - a slightly modified version of the UpWind reference wind turbine.

For designing yaw-based AWC, its effects on the loading of the wind turbines need to be clearly understood. The following conditions, influenced by yaw-based AWC, affect the loads and will be addressed in the remaining part of this document.
- Yaw misalignment
- Turbulence intensity (TI)
- Wake location

2

Effect of yaw misalignment on DEL

2.1 Previous work

In the past few years, a few publications have appeared wherein the effect of yaw misalignment on the fatigue loading is analysed, based on both aero-elastic simulations (Kragh & Hansen, 2013) (Fleming, et al., Evaluating techniques for redirecting turbine wake using SOWFA, 2013) (Fleming, et al., High-fidelity simulation comparion of wake mitigation control strategies for a two-turbine case, 2013) and wind tunnel measurements (Boorsma K. , 2012). The general conclusion that can be drawn from these publications is that when the TI is low, the blade flap DEL is lowest at some nonzero yaw misalignment angle due to the effect of wind shear. Below and above this optimum yaw misalignment angle the blade flap DEL increases. The results in (Boorsma K. , 2012) show that this optimum yaw misalignment angle decreases with the wind speed, ranging from about 15 degrees at very high winds to about 2 degrees at winds just below rated; this result however highly depends on the wind shear.
These results for the blade DEL are well in line with the observations made in (Kragh & Hansen, 2013) based on simulations with the NREL 5MW reference turbine at 15 m/s wind speed. There the optimum yaw misalignment angle at low TI (4.5%) is calculated to be 20 degrees. With increasing TI, the effect of yaw misalignment on the blade DEL decreases substantially. However, the results for the tower bottom DEL, reported in (Kragh & Hansen, 2013) are inconsistent with those in (Boorsma K. , 2012)!

The results reported by NREL (Fleming, et al., Evaluating techniques for redirecting turbine wake using SOWFA, 2013) (Fleming, et al., High-fidelity simulation comparion of wake mitigation control strategies for a two-turbine case, 2013), obtained with SOWFA simulations under low turbulence conditions at 8 m/s, indicate that, depending on the direction of the yaw misalignment, the blade bending DEL either increases or decreases. In the evaluated range of yaw misalignment angles between -40 and 40 degrees, the blade loading is clearly decreasing, which is not completely in line with the results in (Boorsma K. , 2012) and (Kragh & Hansen, 2013). The results from the simulations,

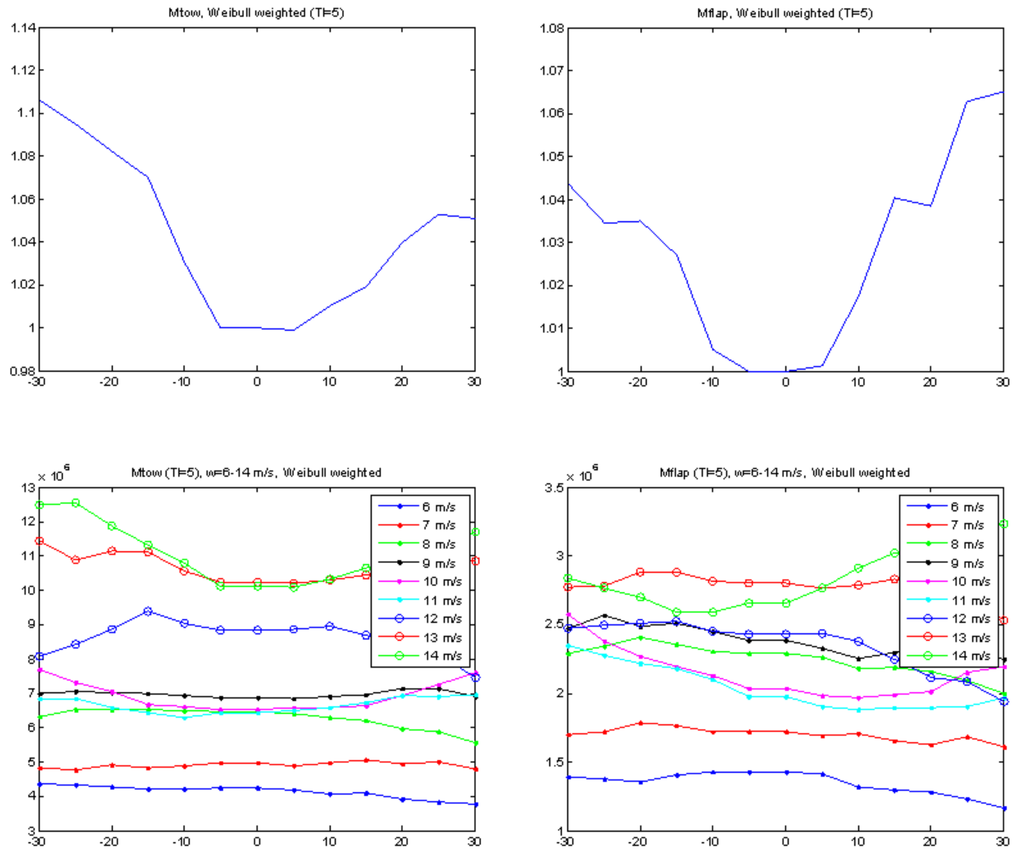
reported in the present work, indicate that the relation between the blade DEL and the yaw misalignment is not consistent for different wind speeds, and can be quite different depending on the wind speed. This could be the reason for the small disagreement of NREL's results with those in (Boorsma K. , 2012) and (Kragh & Hansen, 2013).
Above discussion indicates the need to analyse the DEL on the tower and blades more thoroughly, using simulations at different wind speeds, TIs, and yaw misalignment angles. To this end, numerous **Phatas** simulations have been performed with the ART 5MW wind turbine model. These are shortly presented next, accompanied by a discussion.

2.2 Phatas results with 5% turbulence intensity

Simulations are performed at a low TI of 5%, in order to draw conclusions about the loading of an upstream wind turbine that operates with yaw misalignment to achieve yaw-based AWC. The results are given in **Figure 4** for the DEL on the tower bottom (plots in the left) and blade flap moment (right plots). The plots on the top represent the Weibull-averaged DEL over all considered wind speeds (6-14 m/s), while the plots below give the DEL per wind speed (two 10-minute simulations per wind speed are used for each yaw misalignment).
The following observations can be made from **Fout! Verwijzingsbron niet gevonden.**:

- From the bottom plots one can see that the shape of the relation between DEL and yaw misalignment can be quite different for different wind speeds. This clarifies the inconsistencies in previous results, mentioned in Section 2.1.
- From the top plots it becomes clear that, for the considered low TI, the tower bottom DEL can increase to at most 10% for yaw misalignment angles of up to 30 degrees, and to about 5% in the opposite direction. The blade DEL increases even less. Notice that this numbers are only calculated using the wind speeds in the region 6-14 m/s. Given the fact that for a given wind turbine yaw-based AWC is only applied at below rated wind speed, and only in a very restricted sector of wind directions, the lifetime DEL increase is expected to be much lower (less than 1%). For wind turbines in the wake of an upwind turbine, this small fatigue load increase gets easily outweighed by the load reduction due to lower TI levels (outside the wake) under yaw-based AWC.

Figure 4: Effect of yaw misalignment on DEL at 5% turbulence intensity: above the DEL averaged over the wind speed as function of the yaw misalignment angle, and below the DEL per wind speed. The plots on the left represent the tower bottom XY moment, and on the right – the blade out-of-plane moment

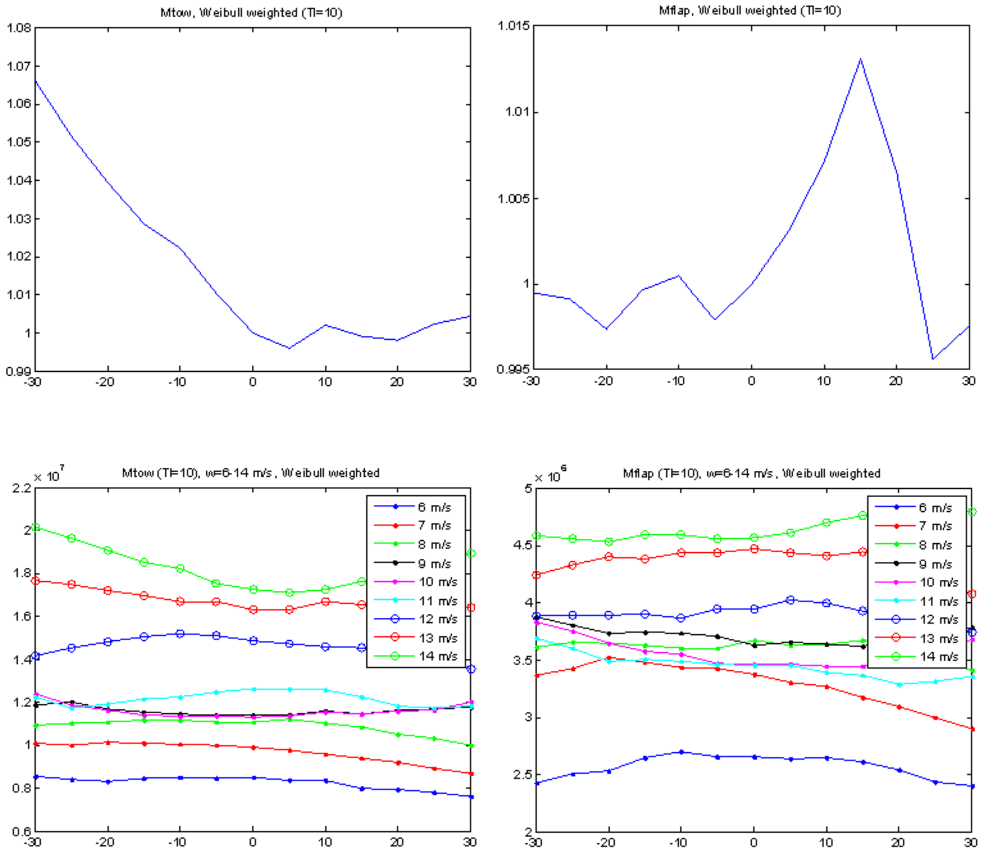


Conclusion: when the TI is 5%, by applying yaw misalignment (as part of yaw-based AWC) on an (upstream) wind turbine, the fatigue loading increases somewhat, but remains much lower than the loading experienced by downstream wind turbines before applying yaw-based AWC.

2.3 Phatas results with 10% and higher turbulence intensity

Next, Phatas simulations have been performed at TIs of 10%, 13% and 20%. The results for 10% only are depicted in **Figure 5** for the DEL on the tower bottom (plots in the left) and blade flap moment (right plots). The plots on the top represent the Weibull-averaged DEL over all considered wind speeds (6-14 m/s), while the plots below give the DEL per wind speed (six 10-minute simulations per wind speed are used for each yaw misalignment).

Figure 5: Effect of yaw misalignment on DEL at 10% turbulence intensity: above the DEL averaged over the wind speed as function of the yaw misalignment angle, and below the DEL per wind speed. The plots on the left represent the tower bottom XY moment, and on the right – the blade out-of-plane moment



First of all, it can be seen from **Figure 5** that the relative DEL increase due to yaw misalignment at 10% TI is much lower than at 5% TI (compare to **Figure 4**). Especially the blade DEL (top-right plot) remains practically unaffected by the yaw misalignment when averaged over the considered wind speeds. The reason for this is that the TI has a much more pronounced effect on the DEL, so that the relative effect of the yaw misalignment on loads reduces. At single wind speeds there are variations present, but as they are not consistent for all wind speeds, they get smeared out when Weibull-averaged and the overall effect becomes insignificant. For the tower bottom loading (the plots on the left) one can see some increase of the DEL at negative yaw misalignments (up to 6-7%); positive yaw misalignments, however, do not increase the DEL on the tower.

Similar, although less pronounced, is the situation at increasing TIs (13% and 20% have been simulated, though the plots are left out here). There, an increase in DEL is again only observed at the tower and not on the blades, and only for negative yaw misalignment. However, the relative increase of DEL tower load reduces with increasing TI: while the maximum relative increase is about 6.5% for 10% TI, it drops down to 4% for TI of 13%, and to less than 3% at TI of 20%. Again , this is for 6-14 m/s wind speeds; over the whole lifetime these figures are even smaller.

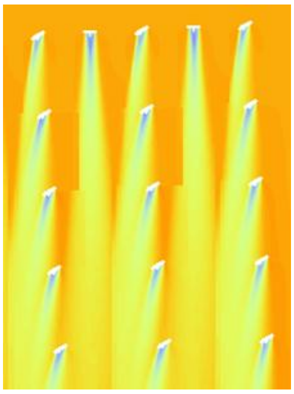
Conclusions: If a (downstream) turbine operates at TI of 10% or higher, negative yaw misalignment increases the tower loads somewhat when the whole lifetime is considered, but not the blade loads. The expected lifetime DEL increase is small (in the order of 1% or even less), but still needs to be considered when optimizing the yaw-based AWC settings.

2.4 Effect of yaw misalignment on downstream turbines

The discussion and results, described in Sections 2.1-2.3 above were related to the effects of yaw misalignment on the loading of a yawed wind turbine. In this section, the discussion is on the effects of yaw misalignment on the loading of the wind turbines in the wake of the yawed turbine.

Applying yaw-based AWC to a wind turbine diverts its wake, resulting in
- increase of the wind speed downstream (increases DEL generally)
- reduction of the TI downstream (decreases DEL)
- creation of half-wake operation downwind (increases DEL)

Figure 6: FarmFlow visualization of the wake redirection effect by yaw-based AWC



The influence of the first two yaw-based AWC effects on the DEL of a downstream wind turbine are discussed later on (see Section 3); when the downstream wind turbine does not operate in half wake conditions, a simple model as in Section 3 can be used to get a reasonable estimate of the DEL. However, a half-wake situation can be created due to yaw-based AWC, as can be evidenced in **Figure 6**.

It is clearly seen from Figure 6 how the wakes are moved aside from the downstream wind turbines, resulting in increase of the wind speeds downstream and a drastic reduction of the TIs (see **Figure 6**).

If it was not for the half-wake situations (which can have large impact on the DEL), the huge reduction of TI combined with just a slight increase of wind speed (**Figure 6**) would have led to a very significant reduction of the maximum DEL in the farm.

The effect of the wake position on the DEL is investigated in more detail in Section 4.3. However, it can generally be stated already that even though yaw-based AWC could move the wake from full to half wake situation for some wind directions, it will also lead to a movement of the wake from partial wake to no-wake situation in other wind directions. Although this needs to be investigated in the future, the yearly effect of yaw-based AWC “wake position” induced DEL is expected to remain small.

2.5 Conclusion on yaw-misalignment effects

Altogether, based on the conclusions in Sections 2.2 and 2.3, the general conclusion can be drawn that it seems possible to design yaw-based AWC in such a way that the maximum fatigue loading within the farm does not increase with respect to the reference case, while the power yield increases.

Further investigations are needed to see if yaw-based AWC can actually be used to reduce the maximum fatigue loading, as that may allow for reduction of foundation costs (as a rule of thumb, one percent DEL reduction in the support structure yields one percent support structure cost saving).

3

Effect of TI on DEL

This section describes the relation between the TI and the DEL. It is important to model this relation since AWC can have a large impact on the TI, as can be seen from **Figure 7**: TI can reduce be a factor of two under yaw-based AWC.

Figure 7: Typical effect of yaw-based AWC on the TI and wind speed at downstream wind turbines: the solid blue curve represents the TI at each wind turbine in a row without AWC, and the red dashed curve – with yaw-based AWC

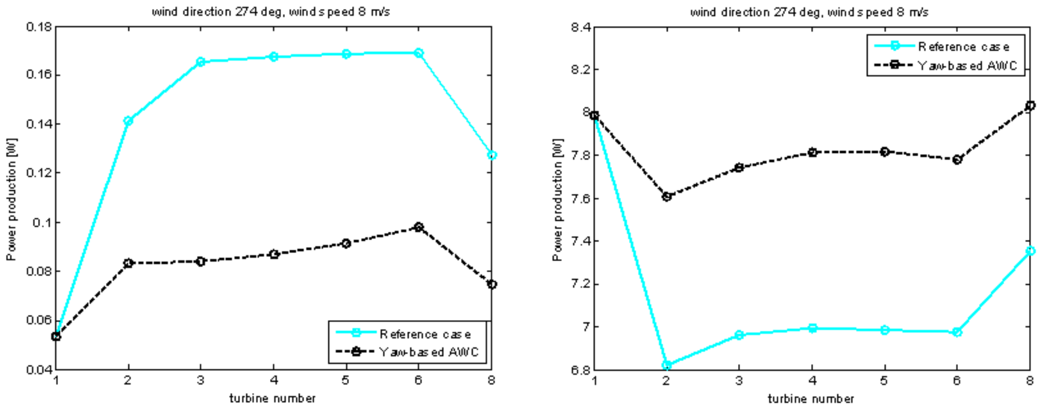
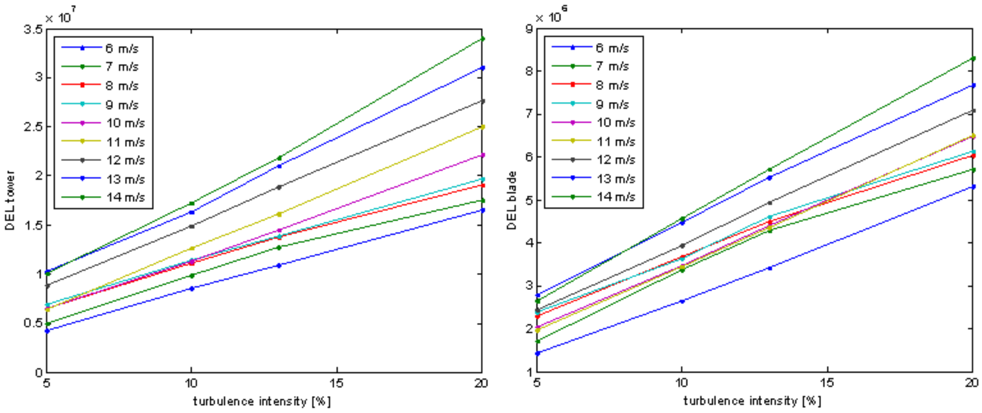


Figure 8: reveals that there is an almost perfect linear relation between DEL and TI, calculated for the ART 5MW wind turbine. The figure depicts the DEL on blade (left) and tower (right) vs. the TI for wind speeds from 6 to 14 m/s.



Conclusion: The turbulence intensity has a huge effect on the loads on tower and blades. Interesting is the (almost) linear relationship between DEL and TI. AWC is able to reduce the TI on the wind turbines in the farm.

4

Wake effects on DEL

The purpose of this Section is to investigate the wake effects on the DEL on tower and blades. To this end, **PhatasWake** simulations with the ART 5MW model have been performed. The **PhatasWake** software allows to simulate a wind turbine in a wind farm environment. It allows to define the incoming wind inflow as a combination of the undisturbed wind stream and a wake. The form and position of the wake is specified by the following parameters:

- **bulge_depth**: this parameters specifies the depth of a bell-shaped function that describes the wind speed deficit in the wake of a wind turbine. The parameter **bulge_depth** describes the axial induction wind speed as portion of the undisturbed wind speed, i.e. the wind speed in the centre of the wake is (1-**bulge_depth**)***wind**. At the corners of the bell-shape describing the wind deficit in the wake, the wind speed equals the undisturbed wind speed. This parameter depends on the distance between the wind turbines.
- **bulge_width**: specifies the width of the bell-shaped curve describing the wind speed deficit. The width is defined in terms of number of rotor diameters. This parameter depends on the distance between the wind turbines.
- **bulge_y_pos**: this parameter defines the position of the wake with respect to the rotor, e.g. full wake or partial wake. The position is expressed in terms of number of rotor diameters, i.e. a value of 0.5 means that the centre of the wake is positioned at the edge of the rotor area, i.e. at a distance of one rotor radius from the centre of the rotor. This parameter also depends on the distance between the wind turbines.

Below, the effects of these parameters on the DEL of the tower bottom and blade root in out-of-plane direction are described.

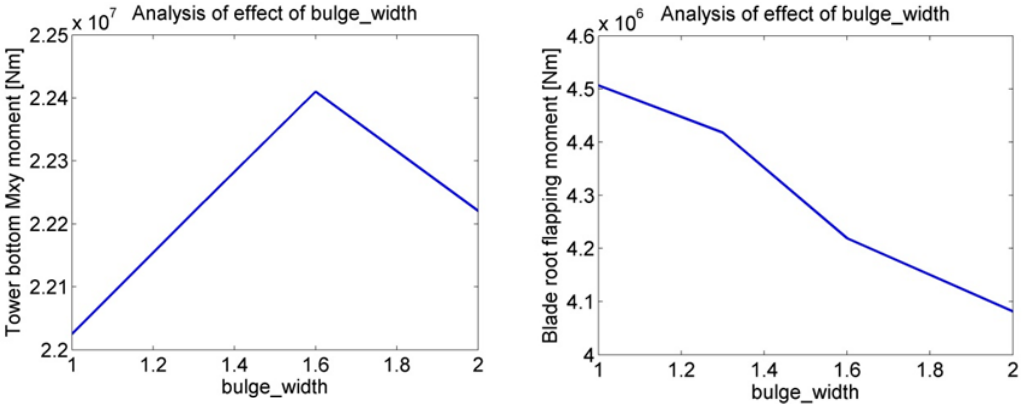
4.1 Effects of wake width on DEL

First, a PhatasWake simulation is performed to analyse the effects of the wake width (bulge_width) on the DEL on tower bottom and blade root. The following values are used:

Table 1: PhatasWake parameters used to evaluate the effect of the wake width on the loads

bulge_width	1.0, 1.3, 1.6, 2.0
bulge_depth	0.3
bulge_y_pos	0.5
wind_wave_series	10.00 1.1867 4.69 (i.e. wind speed: 10 m/s)
turbul_series	0.10
shear_series	0.12
yaw_error	8

Figure 9: Effect of the wake width (bulge_width parameter) on the DEL on tower bottom (left) and blade root (right) based on ART 5MW calculations with PhatasWake



The results from these simulations are given in **Figure 9** above. The blade fatigue loading decreases with increase of **bulge_width**, as expected. As **bulge_width** increases from 1 to 2 rotor diameters, the blade loads drop by about 10%. This is as expected, as the partial-wake effect (inducing asymmetric rotor loading) is weakened by increasing the width of the wake.
The effect on the tower loads, however, remains small (about 1%).

4.2 Effects of wind deficit in the wake on the DEL

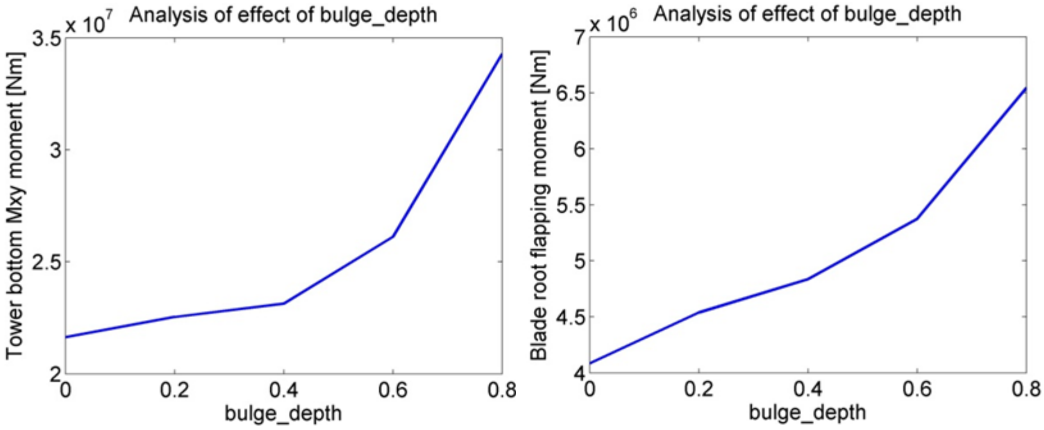
Next, the effect of the wind speed deficit in the wake, specified by parameter bulge_depth, is analysed using simulations for the following cases:

Table 2: PhatasWake parameters used to evaluate the effect of the wind deficit in the wake on the loads

bulge_width	1.3
bulge_depth	0.2, 0.3, 0.4, 0.6, 0.8
bulge_y_pos	0.5
wind_wave_series	10.00 1.1867 4.69 (i.e. wind speed: 10 m/s)
turbul_series	0.10
shear_series	0.12
yaw_error	8

The results from these simulations are visualized in **Figure 10**. From this figure, a large effect on the loads are observed: for **bulge_depth**=0.8, the fatigue load is 50-60% higher than for **bulge_depth**=0. This is expected as the wake center is located 0.5D aside from the rotor center (**bulge_y_pos**=0.5), so that increasing **bulge_depth** leads to an increase of the asymmetric loading on the rotor.

Figure 10: Effect of the wind speed deficit in the wake (bulge_depth parameter) on the DEL on tower bottom (left) and blade root (right) based on ART 5MW calculations with PhatasWake



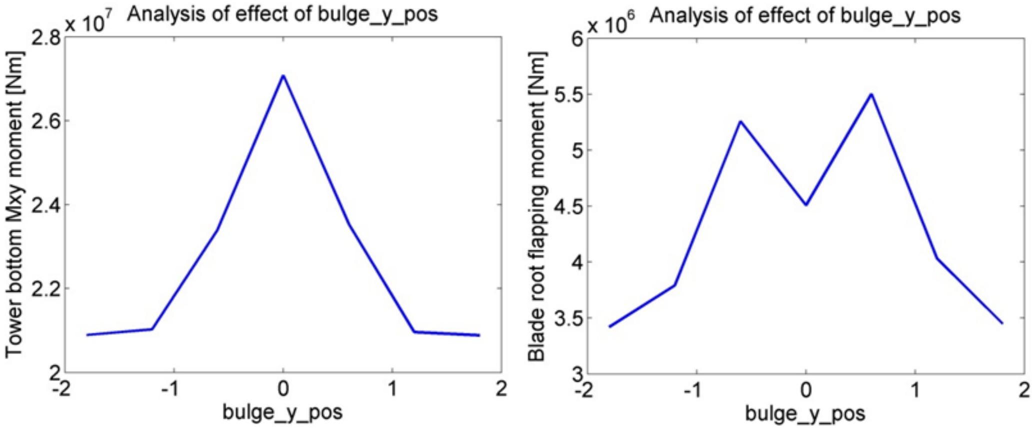
4.3 Effect of wake position on DEL

Finally, the effect of the position of the wake, specified by parameter **bulge_y_pos**, is analysed using simulations for the following cases:

Table 3: PhatasWake parameters used to evaluate the effect of the wake position on the loads

bulge_width	1.2
bulge_depth	0.5
bulge_y_pos	-1.8, -1.2,-0.6, 0, 0.6, 1.2, 1.8
wind_wave_series	10.00 1.1867 4.69 (i.e. wind speed: 10 m/s)
turbul_series	0.11
shear_series	0.09
yaw_error	8

Figure 11: Effect of the wake position (bulge_y_pos parameter) on the DEL on tower bottom (left) and blade root (right) based on ART 5MW calculations with PhatasWake



The results from these simulations are visualized in **Figure 11**. From this figure it can be observed that the wake position has a large effect on the loads. In a partial wake situation (non-zero **bulge_y_pos**), the tower loads are lower than under full wake (**bulge_y_pos=0**). However, the blade loads may increase substantially in a partial load situation. For instance, when the center of the wake is located at the edge of the rotor area (**bulge_y_pos=±0.5**), the blade out-of-plane DEL is 15-20% higher than in a full wake situation. The reason for this is the asymmetric loading of the blade over the rotor area. The DEL on the main shaft (not shown here) has similar dependence on the **bulge_y_pos** as the blade flapping DEL (**Figure 11** right); however, the load increase there in a 0.5D partial wake condition is as much as 30% higher than in full wake! Notice that these loads largely depend on the depth of the bulge (**bulge_depth**), see also **Fout! Verwijzingsbron niet gevonden.**.

4.4 Conclusions

The wake situation (wake position with respect to rotor, and its bulge width and depth) affect the DEL on tower and blades. In a partial wake, the wind speed deficit in the wake leads to asymmetric loading on the rotor, thereby increasing the DEL by as much as 50-

60%. This represents a worst case scenario with respect to both the bulge depth (**bulge_depth=0.8**) and the wake position (**bulge_y_pos=0.5**).

The wake width increase, on the other hand, smears out the asymmetric loads distribution over the rotor, leading to a lower DEL.

Furthermore, even though for some wind directions yaw-based AWC moves the wake such that an originally full-wake situation transforms into a partial-wake situation with higher loads. For other wind directions, however, the opposite effect will be present: turbines will be relieved from a partial-wake situation in the reference case due to AWC moving the wake aside from it. That would reduce the loads.

5

Conclusions

AWC is a strategy to operate wind farms in an economically more efficient manner. It uses the wake interactions between the wind turbines to optimize the performance of the overall wind farm. The wakes are influenced by either increasing the pitch angle of upstream wind turbines (pitch-based AWC), or introducing yaw misalignment (yaw-based AWC). Pitch-based AWC is less radical to implement, and has a clear load reducing effect. Experience has shown, however, that yaw-based AWC is more beneficial with respect to the power production than pitch-based AWC; however, it can lead to load increase – it therefore needs to be optimized in such a way that the loads remain within the design envelope.

This report describes the effect of AWC on the loads of the wind turbines. It provides insight into the factors that contribute to these loads (yaw misalignment, TI, wake location, wake deficit profile, etc) and to what extent. It is also meant to provide a basis for building an efficient constrained optimization algorithm for the yaw-based AWC design.

It has been discussed that yaw-based AWC has influence on the following conditions, that affect the DEL:

- Turbulence intensity: it reduces under yaw-based AWC, as do the DELs induced by it
- Yaw misalignment: in the worst case, an increase of 10% of the DEL on the tower was observed. This worst case is, however, only valid for negative yaw misalignment. This loads increase can be removed by only applying only positive yaw misalignment. That will reduce the benefits from AWC in terms of production increase by about 50%. However, the results indicate that this won't be necessary because the DEL reduction due to reduced turbulence is outweighing the increase in DEL due to misalignment
- Wake location: for some wind directions, yaw-based AWC can transform an originally full-wake situation into a partial-wake one, therefore increasing the loads. For other directions, however, the opposite will happen: an originally partial-wake situation will be completely removed by AWC. Considering the lifetime, the effect of wake location on the DEL might turn out to be rather small.

These conclusions indicate that it seems possible to apply yaw-based AWC to increase the power capture while keeping the DEL within the design envelope.

Ongoing research focuses on yaw-based AWC optimization under the constraint that the loads do not exceed the design loads. For this purpose, an extensive loads data base is currently under development in the project “Wind Farm Wake Modelling, Fatigue Loads and Control”, partially financed by the Dutch government under the FLOW program. The data base includes loads on different components under tens of thousands of different conditions, such as different wind speeds, TI’s, wake deficit profiles, wake locations, yaw misalignments, wake meandering, etc. The data base is formed using aerodynamic simulations with ART 5MW - a modified version of the UpWind reference wind turbine.

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Bibliography

Barth, S. (2007). *Heat & Flux - Validation and Proof of Concept.* ECN report ECN-X–07-119.

Boorsma, K. (2012). *Heat and Flux. Analysis of field measurements.* ECN report ECN-E--12-048.

Boorsma, K. (2012). *Power and loads for wind turbines in yawed conditions.* ECN report ECN-E--12-047.

Brand, A., Bot, E., Kanev, S., Savenije, F., & Ozdemir, H. (2014). *Wind farm design and active wake control.* EWEA 2014.

Corten, G., & Schaak, P. (2004). More wind power and less loads in wind farms: "Heat and Flux". *European Wind Energy Conference.* London: also as ECN report ECN-RX--04-122.

Corton, G., & Schaak, P. (2004). *Patent No. WO 2004/111446 A1.*

Corton, G., Lindenburg, K., & Schaak, P. (2004). *Patent No. WO 2004/011799 A1.*

Fleming, P., Gebraad, P., van Wingerden, S. L., Johnson, K., Churchfield, M., Michalakes, J., et al. (2013). Evaluating techniques for redirecting turbine wake using SOWFA. *ICOWES2013 Conference.* Lyngby.

Fleming, P., Gebraad, P., van Wingerden, S. L., Johnson, K., Churchfield, M., Michalakes, J., et al. (2013). High-fidelity simulation comparion of wake mitigation control strategies for a two-turbine case. *ICOWES2013 Conference.* Lyngby.

Gebraad, P., Teeuwisse, F., van Wingerden, J., Fleming, P., Ruben, S., Marden, J., et al. (2014). A Data-Driven Model for Wind Plant Power Optimization by Yaw Control. *Proceedings of the American Control Conference.*

Kanev, S., & Savenije, F. (2013). *Heat & Flux Optimization for the Nordsee Ost Wind Farm.* ECN report ECN-X--12-114r2.

Kragh, K., & Hansen, M. (2013). Load alleviation of wind turbines by yaw misalignment. *Wind Energy, 17*(7), 971–982.

Kucuksahin, D. (2012). *Heat and Flux Configurations on Offshore Wind Farms.* ECN report ECN-X--12-079.

Machielse, L., Barth, S., Bot, E., Hendriks, H., & Schepers, G. (2007). *Evaluation of "Heat and Flux" Farm Control.* ECN report ECN-E–07-105.

Teeuwisse, F. (2013). Cooperative wind farm control. MSc Thesis, TU-Delft.

Wagenaar, J., Machielse, L., & Schepers, J. (n.d.). Controlling Wind in ECN's Scaled Wind Farm. *EWEA 2012.* Copenhagen, Denmark.

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