RC1 review

Title : Lidar-based wake tracking for closed-loop wind farm control

Dear reviewer,

We really appreciate your comments and have tried to adopt and consider all of them. Please find below a point-to-point reply. Further, in the supplementary material, a latexdiff is given.

Thank you very much for your effort!

Best
Steffen on behalf of the authors.

***Summary review** : The work seems to be innovative and of value to the scientific community, but the manuscript is extremely hard to follow because of the wording / order of statements. The writing needs to be overhauled so that it can be more accessible. Below some specific suggestions are made to improve clarity.*

We have considered all of your points, see below, and tried to give more structure. We highly appreciate your effort!

Page	Lines	Comment	Reply
1	8	issues in the wind farm as opposed to...? the individual turbine?	Rephrased to clarify
	15	Or > and	Changed
	19	In relation to wind turbine control, the same two goals are valid for wind farm control > The same two goals are valid for both wind turbine and wind farm control	Thanks for the suggestion. We adopted it.
	20	These goals were addressed in research with different approaches unclear whether you are talking about previous research or your own, please reword it	We shortened the sentence and rephrased.
2	1	In > at	Thanks
	4-5	the barrier is not necessarily a lack of devices, but their cost, logistics, etc?	In the past, there wasn't a measurement device available to measure flow at different locations remotely like a lidar can do. But you are right about the other barriers. We have added them.
	6-8	weird sentence, I suggest rewording similar to Lidar can be a useful tool to address the measurement problem in wind farm	Thanks!

		applications, while bearing in mind the instrument limitations and the assumptions required to extract the information and exploit the lidar measurement data.	
	9	It aims to enable closed-loop wake redirection	Thanks.
	12	Incomplete sentence?	Sorry about that. We have corrected it.
Introduction		Since you are going into so much detail and level of simplicity when you put things in context in the introduction (e.g. flow is modeled by Navier Stokes), you should also briefly explain difference between open vs closed loop control, and why focus on one vs the other. Also, introduction makes it sound like no one else has looked into this before (closed loop wake redirection), is this the case? If so that's fine otherwise you should refer to their work.	Thank you for the advice. Since my background is control engineering I have assumed a lot. I tried to add a paragraph which briefly explains the advantage of closed-loop wake redirection vs. open-loop. We do not know a publication about lidar-based closed-loop wake redirection at the moment.
Figure 1		Remove a	Thanks!
	20	Exist > exists There isn't a > there is no	Thank you. I have changed.
	21	which is a concept based on time averaged profiles of the wake behind a turbine.	Thanks.
	22	Give a time scale for these averages Having averaged the flow something like a > the language is too informal, reword something like "Averaging the flow yields a (double) Gaussian function for the velocity deficit profile in the horizontal and vertical directions..."	We tried to be more specific, thank you for your suggestion.
	23-24	taking a different method of defining the shape, the wake center position could be at a different position although the flow would be the same > also needs rewording, suggestion something like "when different methods are used to define the shape, wake center estimates may be vary under the same flow conditions"	Thank you.
	24-25	Thus, there isn't a unique wake center definition. This makes a comparison difficult and needs to be considered when comparing results. Suggestion...	Thank you clarifying. We took you suggestion.

		The absence of a unique wake center definition must be considered when comparing results as it precludes direct comparisons (across different studies?).	
	27-28	Considering the task of lidar-based wake tracking then this includes first a reference definition of the wake center and second an estimation method which is used to get the closest estimation of the wake center from the lidar measurement data.	We rephrased it. Thanks.
	30	Which want to > to	Thanks.
3	2-3	Estimate verb repetition…	We shortened the sentence to be more clear.
	5	you repeat over and over again "a redirecting" which sounds really off -- either remove "a" or change to a better noun, e.g. redirection	We changed to redirection.
	7	compensates > compensates for	Thanks.
	8	can be > is , which is due > due	Thanks.
	9	first, the measurement problem is addressed. the measurement problem is addressed first.	Thanks.
	11-12	Keep in same paragraph!	Sorry for that.
	14	The in the following described tasks ??	We removed parts to state more clearly.
4	3	As described before, first a reference is needed to be defined. As previously mentioned, it is first necessary to define a reference. (still sounds like an incomplete sentence, a reference what?)	We changed to be more precisely.
	3-4	Can you be a bit less concise here? Unclear what the Vollmer work is. Example: The minimum wind power method proposed by Vollmer et al. (2016) is adopted here to identify the wake shape/center…….	We rephrased and adopted your suggestion.
	4	Is all the work 2D? Not yet very clear until this point	It depends on the method. In our point of view the wake center definition is also not 2D, since all directions are present.
	9	which is every second > sampled at 1 Hz frequency?	Thanks.
	9-10	In addition to Vollmer et al. (2016)	We rephrased to be clearer.

		You mean in addition to using the method proposed by Vollmer?	
	10	with different time constants you mean over different running window lengths? over different time intervals? averging time T?	Same here.
	11-12	Therefore, a SOWFA simulation with low turbulence level and a mean wind speed of 8 m/s is used in which the flow field is sampled and every 1 s. Therefore? This is a conclusion from something? Needs rewording...ex: The results presented are for a low turbulence (TI=??) SOWFA simulation under a mean (free stream, hub height?) wind speed of 8 m/s...	Thanks for the comment. We reworded according to you suggestion.
Figure 2		Caption is not descriptive, stand-alone and clear enough. Something like... Time evolution of wake center (meters away from hub? what is negative vs positive?) when different periods T (s) are used to average the flow during the wake center calculation. Why are first 100 s so different? Is this some model spin up, while the wake is still slowly developing? If so, maybe this data should not be part of the analysis, or this should be acknolwedged somewhere?	Thanks for the suggestion. We adopted the caption. Yes, it comes from the wake development. I have changed the figure according to your suggestion.
	16	approached > approaches	Thanks.
	17	can first compare to existing quantities. > can first be compared.....	Thanks.
	16-17	like estimation of the rotor-effective wind speed, or estimating u and v wind vector components using lidar measurements like in Schlipf et al. (2012), this whole thing should be in parenthesis to make sentence more readable (e.g., estimation of the rotor-effective wind speed, or of u and v wind vector components as in Schlipf et al. (2012)	You are right. Thank you, we adopted it.
	18	be used predict > be used to predict after line-of-sight velocities can you put (v_los) so that when it shows up in the next figure the reader is already familiarized with your nomenclature / symbology	Thanks.

Figure 3		The general concept of model-based wind field reconstruction: Estimating the wind field characteristics by fitting simulated lidar measurement data (v los,s) to the measured ones (v los,m). The general concept of model-based wind field reconstruction, in which the wind field characteristics are estimated by fitting simulated lidar measurement data (v los,s) to measurements (v los,m).	Thanks. This makes it more clearer.
5	16	simulated lidar measurements I am not sure you should call it measurements if they are not measurements!	Thank you. We have changed it here.
	19	What's the " wind field parameter"?	We specified. We meant the model parameter (e.g. wake center, wake decay, wake deficit, etc.)
	20--	This whole paragraph, please rewrite, words and concepts are repeated a lot, very unclear.	We have rewritten.
6	9	horizontal rotation of the wind field you mean the wind direction? Also I'm pretty sure you mean underlying whenever you have underlaying	Yes, we mean aligned with the wind direction. Yes, sorry about that!
	13	...and the subscript i represents...?	We explained.
	14	component. Thus, this yields > components, yielding	Thanks.
Figure 5		If the coordinate system follows the wind turbine reference frame, then what do negative wind speed values mean? Also, does it matter at which downstream distance this is? And is there any yaw misalignment here? Unclear	We specified the conditions.
7	4	the deficit is cleared over distance > the momentum deficit recovers?	Yes, thanks.
	8	What is s?	s*Gamma gives the solution for the initial wake deficit. There is no meaning for s -> one could see it as local gain.
	15	what does " impulse dissipation" mean	We meant wake recovery.
8	1	You might want to use D instead of d, or maybe x for the downstream distance, because in equations the little d looks like a derivative, as in Eq 8 I	Thanks. The multiplication sign helped.

		first thought it was derivative of the dissipation. Or maybe just put a multiplication sign there, or the d outside of the fraction multiplying everything...	
	19	by constant you mean steady (constant in time) ?	Mean wind speed is meant
9	7	the model parameter still confused that THE parameter is?	Changed
	12-13	The way you worded this sentence makes the reader think you want to make a point here. If it's just an example (which at least in this section, it is because now the section is over) then say so--for example: An example of an estimation step of the wake tracking from a measurement campaign at the alpha ventus offshore wind farm is shown in Figure 7.	Thanks.
Figure 7		A plot of you don't need to say this is a plot! five distances > five downstream distances is this looking down or upstream?	Thanks ;) We clarified the setup.
	15	has already shown > shows (you haven't discussed Figure 7 at all)	Thanks.
	17	merged to a wind field what does this mean? also use a different symbol in your 7x7, maybe $\times$ wherever it appears in manuscript	We removed the unclear part and used the times symbol.
10	1	In >at	Thanks
	4	most far > furthest (wherever it appears in manuscript) the wake parameter , what is this again?	Thanks. We have added some lines before. So the parameter question should be clear.
	6	positions > position there isn’t a > there is no	Thank you.
		How did you come up with 0.1 for your dissipation?	It is the result of the model fit.
Figure 8		Time series of model parameters for wake tracking of simulation data? missing a period	We specified the conditions.
11	8	sorry what is "the filtering"? can you be more specific, I don't remember anymore at this point	Removed the sentence, since it isn’t necessary here. It is only confusing.
12	5	An > a	Thanks

Figure 9		I assume this is a mistake? I don't understand why it's same caption as above but results are different!	Yes! As mentioned before, we have specified the conditions.
13		Figure 11 is talked about in text before Figure 10 so these should be swapped? Actually seems like Figure 10 never comes up?!	It was mentioned in the text. Before Sect. 6.
	6	the assumptions of a constant thrust coefficient, c T , is made. the assumption of a constant thrust coefficient is made	Thanks.
14	5	is this so obvious to the community that it doesn't need a reference?	A reference is given.
15	2	what is subscript dem?	A description is added.
	8	using a Smith Predictor. A Smith Predictor uses > using a Smith Predictor, which uses	Thanks.
	21	the sensitivity and the complementary sensitivity As someone not in controls field I don't understand this. It's weird that in some spots you get into such seemingly unecessary descriptions of things (again, saying the flow is modeled with Navier Stokes for example) but then at other points you assume all your readers will know these concepts? If it's not too difficult, add a line explaining what these concepts mean or refer the reader to some reference. There is a lot of very controls-specific stuff throughout your paper which is fine and great since that's your main topic, but your paper will reach a much broader audience if you make it clearer and more readable to people that do wind research but focus on other aspects, and who may be interested in applying what you've done.	We have added a reference. Sorry about that. It is very difficult to address and assume the right audience. Our assumption was to address someone who has basic knowledge in control theory.
15	12	enable > enables	Thanks
16	5-6	Keep in same paragraph	Changed.
	6	An > a	Thanks!

RC3 review

Title : Lidar-based wake tracking for closed-loop wind farm control

Dear reviewer,

We really appreciate your comments and have tried to adopt and consider all of them. Please find below a point-to-point reply. Further, in the supplementary material, a latexdiff is given. (Having already considered the review of reviewer 1)

Thank you very much for your effort!

Best
Steffen on behalf of the authors.

***Summary review** : The article provides a novel approach to tracking the wake center behind a wind turbine using lidar measurements, which will be of value to the wind energy community when trying to develop a closed-loop wind farm controller. The concepts discussed in the paper are well organized and overall has good flow. I was hoping to see more discussion of the controller performance at the end, but this paper is more about the wake tracking than the controller. Perhaps controller performance was discussed in Raach et al. (2014), and could be played up more in this paper to address a reader's desire to see controller performance. It would be nice to see in figures 8 and 9 a comparison to the lidar's tracking of the wake center to the actual wake center. However, defining the wake center is not easy and that is acknowledged by the authors. In practice in the field, defining the wake center is nearly impossible to do anyway as full flow field knowledge is virtually impossible.*

Thank you for your review. You are completely right, this paper covers more the estimation task and the 2016 ACC and also my current work focus on the control part. I will mention it in the beginning of the control part and in the conclusion. Figure 10 gives exactly what you asked for. You are completely right, however, when talking about the wake center definition and comparability challenge.

Page	Lines	Comment	Reply
1	3	The tracking is demonstrated… > The wake tracking is demonstrated…	Thanks
1	4	Spell out the acronym "SOWFA"	Changed.
	9-10	"The wind speed in the wake of a wind turbine…" This sentence looks to describe a wake, but seems out of place. Perhaps the wake concept can be introduced in the previous sentence "…installations are limited, the interactions between…" > "…installations are limited, the wake interactions between…" Then this sentence makes more sense.	Thanks for the suggestion. I considered it.

	11	If a wind turbine is hit… > If a wind turbine is impacted…	Thanks.
	21	…is proposed and… > …was…	Has been rephrased.
	22	…torque actuator and steering the wind turbine to… > …torque actuator and operating the wind turbine at…	Thank you. We adopted it.
	23	This results in a weaker… > This results in less of a…	Thanks.
	26	…Fleming et al. (2014b, a); > …Fleming et al. (2014a, b);	Thanks. This was a strange behavior of the bibtex package
2	1	…(in seven diameter… > …(at a seven diameter…	Thanks.
	1	…by yawing the turbine up to 40 deg. Is there a reference to back this sentence up?	Added.
	12	…a closed loop controller is In summary,… It seems there is something missing between "is" and "In	Our fault. We have corrected it.
	20	…a main problem exist. > …there exists a main problem.	Thanks.
	22	Having averaged the flow… > After having averaged the flow…	Rephrased.
	23-24	However, taking a different method of defining the shape, the wake center position could be at a different position although the flow would be the same, see Vollmer et al. (2016).	Rephrased.
	27	Considering the task of a lidar-based wake tracking then this includes first a reference definition of the wake center and second… > The task of lidar-based wake tracking includes first, a reference definition of the wake center and second,…	Thanks. We adopted it.
	30	…a closed-loop controller which want to manipulate… > …a closed-loop controller which look to manipulate…	We rephrased and tried to make it clearer.
3	1	…device, a lidar, and processing… > …device, such as a lidar, and processing…	Thank you.
	10	In the following,… > In the following sections,…	Thanks.

	10-16	This should all be one paragraph	Ok
	14	The in the following described tasks present… It seems something is missing between "The" and "in"	We rephrased it.
4	3	…first a reference is needed to be defined. In this work an adaptation… > …first a reference of the wake center is needed to be defined. In this work, an adaptation…	We removed parts and rephrased the beginning.
	7	For equation 1, can you specify the variable y in the following paragraph? I assume it is the spanwise offset.	Thank you. We missed that. But we prefer to use "lateral offset".
	9	The wake center is calculated every time step… Can you specify how far downstream the wake center is being calculated here and in figure 2?	Thanks, good point!
	12-13	The wake center clearly converges to a steady value with increasing averaging time T. This sentence implies that an increasing averaging time is better. So, just always choose an increasing averaging time is the thought process in my head when I read this. Perhaps it should be stated that there are adverse effects for choosing an increasing averaging time. I could see that an increased averaging time would be slower to adjust to a changing wind direction, and so this should be considered when choosing an averaging time to use	Very good point, we have added a sentence like you suggested.
	14	For section 3.2, the discussion here about comparing between lidar measurements and real data is a little confusing. I think this is being compared in simulation results. I think that this section should start by stating that these comparisons are being	We have added something at the beginning of section 3.

		made in simulation to help a reader to understand these comparisons.	
	18	…the used models can be used… > …the models can be used…	Thanks.
5	10	A solution to this limitations… > A solution to these limitations…	Thanks.
	11	…applications of lidar system usage in wind energy… > …applications of lidar systems in wind energy…	Thanks.
	12	...reconstruction methods, see Raach et al… > ...reconstruction methods, Raach et al… To be consistent with the other reference notation in this sentence.	Thanks.
6	1	In the discussion of the main wake effects, I was thinking that wake meandering should be included in this list, but perhaps that falls into the category of wake evolution. Maybe wake meandering should be its own item in the list, but I do not have a strong opinion one way or another.	Since it is not modeled in the reduced order model, we haven't mentioned it. Since the model is used for identification the meandering DOF is not necessary at the moment, but could be considered if necessary.
	8	In the discussion with equation 2, I am wondering why do you need to rotate the coordinate system? I am sure there is a reason, and perhaps you can state why.	It is just a convention to introduce different coordinate systems for wind, lidar, turbine. It gives the freedom to yaw the turbine, or consider a misaligned wind field in the reconstruction.
7	12-13	New energy is flowing from the side and above and the flow is mixed. > New energy flows in from the freestream and mixes with the wake.	Thank you, good point!
	15	In contrast to other wake models, however, … > However, in contrast to other wake models, …	Thanks.
8	7	…optimization of the yaw angles for a wind farm… > …optimization of the yaw angles for a simulated wind farm…	Ok.
8	18	…non yawed… > …non-yawed…	Thanks.

9		For the caption for figure 6, change “Non yawed” to “Non-yawed”	Done.
9	7	As depicted in Figure 3 … > As depicted in Figure 3, …	Thanks.
10		In figure 7, it would be nice if above each figure in the top row there was a title that specified the downstream distance of each measurement: 0.6 D, ? D, ? D, ? D, 1.4 D. All I know is 0.6 and 1.4, but the inner distances are not specified.	We have added the distances in the caption.
	2	Second, the turbine is misaligned… Could you specify how much the turbine is misaligned	It is done.
11/12		In figure 8/9, the title of the subplot “wake misalignment” is confusing. Do you mean the turbine’s yaw error over time?	Yes. I will correct.
12	5	…approximated with an delay. > …approximated with a delay.	Thanks.

Lidar-based wake tracking for closed-loop wind farm control

Steffen Raach[1], David Schlipf[1], and Po Wen Cheng[1]

[1]Stuttgart Wind Energy (SWE), University of Stuttgart, Allmandring 5B, 70569 Stuttgart, Germany

Correspondence to: Steffen Raach (raach@ifb.uni-stuttgart.de)

Abstract. This work presents two advancements towards closed-loop wake redirecting of a wind turbine. First, a model-based wake tracking approach is presented which uses a nacelle-based lidar system facing downwind to obtain information about the wake. The method uses a reduced order wake model to track the wake. The wake tracking is demonstrated with lidar measurement data from an offshore campaign and with simulated lidar data from a ~~SOWFA simulation~~ simulation with the Simulator fOr Wind Farm Applications (SOWFA). Second, a controller for closed-loop wake steering is presented. It uses the wake tracking information to set the yaw actuator of the wind turbine to redirect the wake to a desired position. Altogether, the two approaches enable a closed-loop wake redirection.

1 Introduction

In recent years, ~~the focus of control applications in wind energy has shifted~~ wind farm control has gained more and more ~~to issues~~ importance in the wind ~~farm. Since wind turbines are growing in size and the available areas for installations are limited, the interactions between~~ energy control community, since wind turbines in a wind farm ~~array are becoming more important.~~ can interact by their flow. The wake interaction can result in less power compared to a fee-stream operation and can result in higher structural load of the downstream turbine due to higher turbulence in the flow and possible partial wake impingements. The wind speed in the wake of a wind turbine is reduced with respect to the free stream wind speed. Additionally, the turbulence in the wake is increased. If a wind turbine is ~~hit~~ impacted by a wake from a wind turbine located upwind, the wind turbine produces less power and is faced with higher structural loads because of the increased turbulence, see Borisade et al. (2015). Describing the wake effects and quantifying the decay has been of interest for years. Different models have been developed to address different phenomena, such as the velocity deficit and the increased turbulence intensity. There are empirical models, data driven models, ~~or~~ and models which describe the physical behavior in the wake, all varying in complexity and computational effort. Mainly, models with low complexity are steady state models which means they describe the interaction in a static manner and no wake propagation is modeled. Further research is needed to develop control oriented dynamic wake models.

~~In relation to wind turbine control, the~~ The same two goals are valid for ~~wind~~ both wind turbine and wind farm control: 1) maximization of the total power and 2) reduction of the structural loads. ~~These goals were addressed in research with different approaches~~Two main concepts has been introduced for wind farm control: 1) axial induction ~~based wind farm control is proposed and investigated and~~ control and 2) ~~an approach was introduced to redirect the wake~~ wake redirection control. Axial induction control aims at manipulating the axial induction by the blade pitch or torque actuator and ~~steering~~ operating the wind turbine ~~to~~ at a lower production level. This results in ~~a weaker~~ less of wake deficit and aims at minimizing structural load effects on the downwind wind turbines and preserving energy in the flow for downstream turbines. The effects on the overall energy capture of the wind farm is not clear yet~~, see Annoni et al. (2015).~~ . Consider Boersma et al. (2017) for a general overview on wind farm control.

The idea of redirecting the wake by the yaw actuator instead of trying to mitigate its intensity has been discussed in different publications, see ~~Fleming et al. (2014b, a); Gebraad et al. (2014)~~Fleming et al. (2014a, b); Gebraad et al. (2014). In simulation studies it was shown that the wake is redirected up to 0.54 times the rotor diameter (~~in~~ at a seven diameter downwind distance) by yawing the turbine up to $40\,\mathrm{deg}$, see Fleming et al. (2014b). Different investigations have shown promising results ~~using this method in~~ in improving the power output of a wind farm by applying yaw offsets in open-loop approaches, see Gebraad et al. (2014) and Fleming et al. (2014a). Nevertheless, the form in which it has been applied so far does contain drawbacks: 1) Applying optimized yaw angles in a feed-forward approach does not guarantee that the wake is going to the desired direction - thus, the quality of the model, which is used to compute the yaw angles, highly influences the control performance. 2) There is no observation of whether the wake is being redirected correctly. The concept of closed-loop wake redirection, which was introduced in Raach et al. (2016), can help to overcome the drawbacks.

A major barrier for wind farm control applications ~~is~~ has been the lack of measurement devices to measure the flow interactions between wind turbines, but also their cost and availability. Further, modeling the three dimensional flow field is not a straight forward approach since the flow is usually described by the Navier-Stokes equations. Lidar can be a useful tool to address the measurement problem in wind farm applications~~although the limitations of a lidar system always remain and assumptions are necessary~~ , while bearing in mind the instrument limitations and the assumptions required to extract the information and exploit the lidar measurement data.

This paper addresses the wind farm control concept of wake redirecting. It aims to enable ~~a~~ closed-loop wake redirecting ~~using lidar measurements~~ by presenting a method to obtain the wake position ~~. The~~ using lidar measurements. Further, the difficulty in wake position definition and measurability is discussed.

First, it presents a model-based estimation approach to obtain important quantities for wake redirecting using a nacelle-based lidar system facing downwind. Furthermore, a closed loop controller is designed and analyzed. In summary, this work presents an entire concept for lidar-based closed-loop wake redirecting.

2 Methodology

In order to enable a lidar-based closed-loop wake redirecting within a wind farm, the problem can be divided into two main tasks: 1) the measurement task and 2) the control task. This work focuses mainly on the measurement task but gives also a summary of a solution to the control task, which was presented in Raach et al. (2016). Figure 1 presents the general concept of the closed-loop wake redirecting and the link between measurement task and control task.

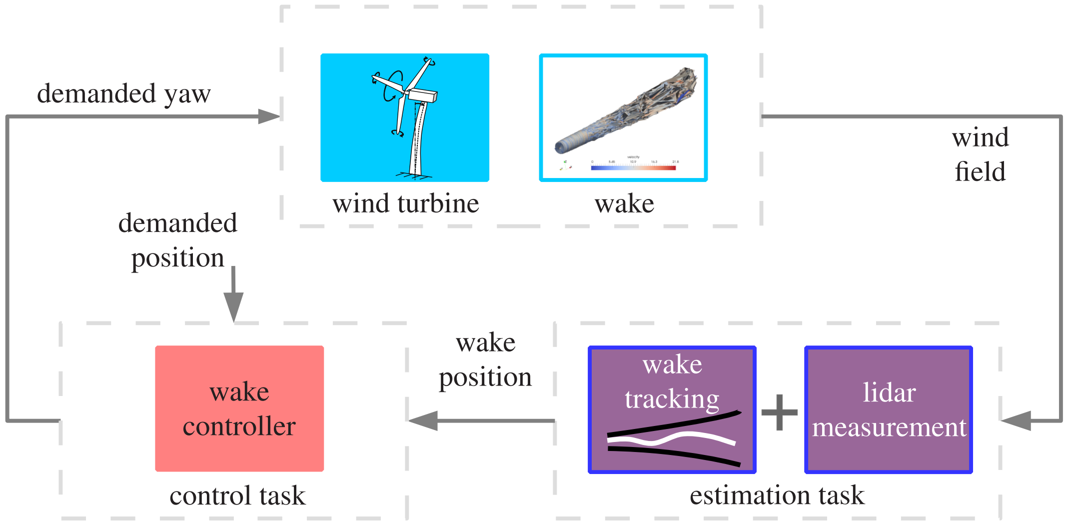


Figure 1. The conceptual idea of ~~a~~ closed-loop wake redirecting and its two main tasks: 1) the estimation task addressed in Section 5 and 2) the control task addressed in Section 6.

2.1 Problem formulation for wake-tracking

When talking about wake tracking or a wake center position there exists a main problem~~exist. There isn't a~~. There is no clear definition of the wake center, moreover, the idea of a wake center ~~comes from time averaging~~ is a concept based on time averaged profiles of the wake behind a turbine ~~and then characterizing the averaged profile. Having averaged the flow something like a double-Gaussian shape or a Gaussian shape can be observed~~(1 to 10 minutes averages). Averaging the flow yields a (double) Gaussian function for the velocity deficit profile in the horizontal and vertical directions. From this a wake center can then be defined easily. However, ~~taking a different method of defining~~ when different methods are used to define the shape, ~~the wake center position could be at a different position although the flow would be the same~~ wake center estimates may be vary under the same flow conditions, see Vollmer et al. (2016). ~~Thus, there isn't~~ The absence of a unique wake center definition ~~. This makes a comparison difficult and needs to~~ must be considered when comparing results. Furthermore, this means even with full flow field information the wake center is not a measurable quantity and depends on definition.

~~Considering the~~ The task of lidar-based wake tracking ~~then this includes first~~includes first, a reference definition of the wake center~~and second an estimation method which is used to get the closest estimation of the wake center~~. Then, the result of the estimation method from the lidar measurement data can be compared to the reference definition.

2.2 The estimation task

Measuring flow quantities is crucial for enabling a closed-loop controller ~~which want~~ to manipulate the wake quantities. The task of the measurement problem is to provide the necessary quantities for the controller. This means using a measurement device, such as a lidar, and processing the measurement data in such a way that they are useful for the controller. Since the lidar measurement principle has several limitations in providing wind field information an adequate estimation technique is used ~~. This estimation approach is crucial in estimating parameters of the wake and is~~ that is described in Section 5.

2.3 The control task

The second task towards a closed-loop wake ~~redirecting~~ redirection is the control task. Its main challenge is to convert the estimated wake position information and the demanded position to a demanded yaw signal. A feedback controller has to be designed which steers the wake center to the desired position and compensates for uncertainties in the models. Since the reaction of a change in the yaw ~~can be~~ is measured with a delay ~~, which is~~ due to the wake propagation time, the controller has to be designed in such a way that it can overcome this limitation.

In the following ~~, first,~~ section, the measurement problem is addressed first. A method is presented to estimate wake information from lidar measurement data using a nacelle-based lidar system.

Second, the controller problem is addressed in Section 6. A wake redirecting controller is presented which uses the obtained wake information, namely the wake center position, and steers the wake center using the yaw actuator to a desired position.

~~The~~ The overall goal of this paper is to ~~present a concept for~~ also present the framework of lidar-based closed-loop ~~wake redirecting. The in the following described tasks present a solution to the problem. Therefore, the models can be replaced, modified, or improved but the general concept remains for closed-loop~~ wake ~~redirecting~~redirection with exemplary models and controller.

3 Reference definition and its impact on the estimation task

In this section the wake center definition is addressed. The comparisons are being performed in simulation since in reality a full flow knowledge is impossible.

3.1 Wake center definition

As ~~described before, first a reference is needed to be defined. In this work an adaption of the~~ previously mentioned, it is first necessary to define the wake center. The minimum wind power ~~presented in Vollmer et al. (2016) is used. The wake center~~method proposed by Vollmer et al. (2016) is adopted and modified to identify the wake center. Thus, it is defined as the position where ~~the same wind turbine~~a second wind turbine, which orientated identically and has the same rotor diameter than

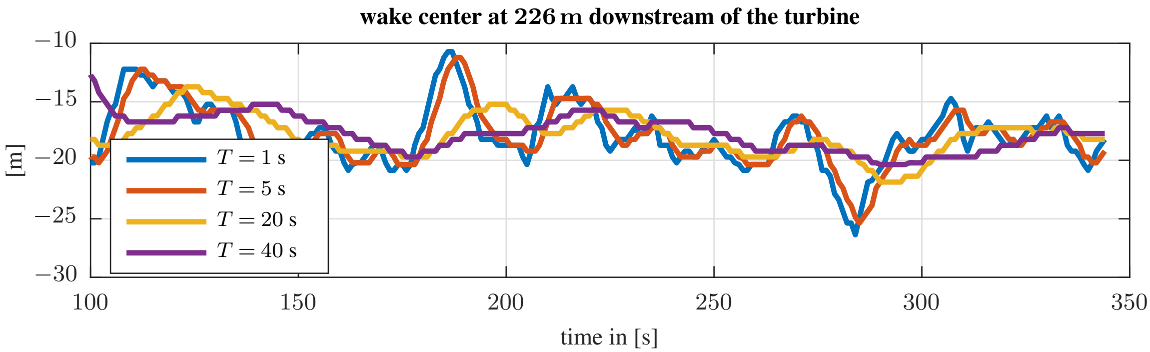


Figure 2. ~~Analysis~~ Time evolution of ~~the impact of~~ wake center (at a 1.8 diameter downwind distance) when different ~~running average filters applied~~ window lengths T are used to average the flow ~~on~~ during the wake center calculation.

the first, would produce the least power~~resulting in~~. This yields the minimization problem

$$\min_{y} \int_{0}^{2\pi} \int_{y}^{R+y} u(r,\phi)^3 r \, \mathrm{d}r\mathrm{d}\phi, \tag{1}$$

where the position of the turbine is described in the polar coordinate system (r,ϕ) with the origin at y (lateral offset) and $z = 0$ (hub-height). The definition then assumes that the wake center is at (y,z).

The ~~wake center is calculated every time step of the available flow field data which is every second. In addition to Vollmer et al. (2016) the flow field is time averaged with different time constants. The impact of time averaging is analyzedwith different running average filters for the flow and shown~~ flow field is time averaged over different running window lengths and the impact of the wind lengths is analyzed. The calculated wake center (at a 1.8 diameter downwind distance) filtered with a running averaged filter with different window lengths are presented in Figure 2. ~~Therefore, a SOWFA simulation with low turbulence level and a mean wind speed of 8 m/s is used in which the flow field is sampled and every 1 s~~ The presented results are for a low turbulence ($TI = 6\%$) SOWFA simulation under a mean hub-height free-stream wind speed $8\,\mathrm{ms}^{-1}$. The available flow field data has a sampling frequency of 1 Hz and the wake center is calculated from each sample. The wake center clearly converges to a steady value with increasing averaging time T. An increased averaging time, however, slows the adjustment, e.g. to a changing wind direction, or a set point change, and should be considered when choosing an averaging time.

3.2 Problem discussion of lidar-based wake tracking

Compared to other problems in lidar-based wind field reconstruction the problem of wake center estimation is different. Other model based ~~approached~~ approaches in wind field reconstruction ~~like~~ (e.g. estimation of the rotor-effective wind speed, or ~~estimating~~ of u and v wind vector components using lidar measurements ~~like in Schlipf et al. (2012), can first compare~~ as in Schlipf et al. (2012)) can first be compared to existing quantities. Further, the ~~used~~ models can be used to predict line-of-sight velocities (v_{los}) of lidar measurements and be directly compared to the real data. Therefore, the model can be used in two directions, estimating and predicting the wind field.

Here, having the wake center defined like in Eq. (1) the prediction of the wind field from a given position is not possible and further a direct comparison of line-of-sight data is not possible. Nevertheless, the wake center position definition seems to be very convenient and is therefore used as reference.

4 A simplified wake model for wake tracking

The estimation task addresses the processing and estimation of useful information and provides them to the controller. Since a lidar system has several limitations, the desired quantities, like the wake position, or the wake deficit, are not measurable and have to be estimated from the measurement data. One main limitation of a lidar system is that it only returns the projection of the wind speeds along the direction of the laser beam. This means that a lidar system only provides scalar information of the actual wind vectors. Further, the wind speed is not measured at a certain point but in a volume around the desired measurement location. A solution to ~~this~~ these limitations is to implement model-based wind field reconstruction. Wind field reconstruction methods have been developed and used for different applications of lidar ~~system usage~~ systems in wind energy, for example static two- and three-dimensional, Schlipf et al. (2012), dynamic three dimensional wind field reconstruction methods, ~~see~~ Raach et al. (2014), and approaches for floating lidar systems, Schlipf et al. (2012). Here, the concept of wind field reconstruction is used to obtain information about the wake.

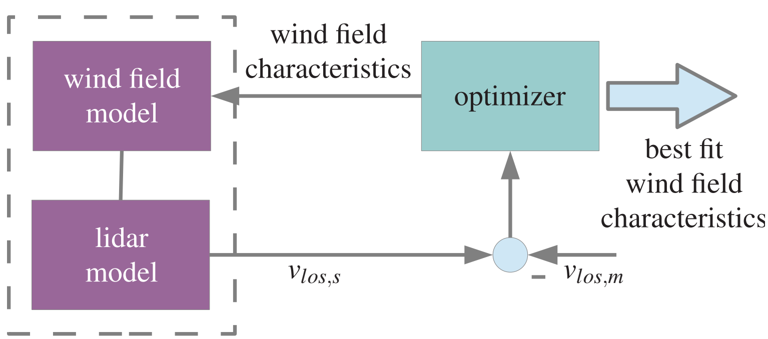


Figure 3. The general concept of model-based wind field reconstruction~~: Estimating~~ , in which the wind field characteristics are estimated by fitting simulated lidar measurement data ($v_{los,s}$) to ~~the measured ones~~ measurements ($v_{los,m}$).

The general approach of wind field reconstruction from lidar data is to estimate wind field characteristics from an internal model by fitting simulated lidar ~~measurements~~ data to the measured ones. In Figure 3 the basic idea of model-based wind field reconstruction is shown. An optimizer is used to find the best fit for a model of the assumed wind field with the defined lidar configuration. The optimizer minimizes the square error of the modeled (simulated) $v_{los,s}$ and the measured $v_{los,m}$ lidar line-of-sight velocities and returns the estimated ~~wind field parameter .~~ model parameter (e.g. wake center position, wake decay, wake deficit, etc.).

For the model-based wind field reconstruction an adequate wind field model is crucial. For estimating wake information and tracking the wake, the In this work, a lidar and a wind field model is used. The wind field model has to include a model for the wake in the wind field. Thus, consists of a background wind field model, which defines the ambient wind speed and its profile, and a wake modelis necessary which . The wake model includes the main wake effects: wake deficit, wake evolution, and wake center displacement. Further, an underlaying wind field model is used. The models are presented in the following section.

4.1 Wind field model

Figure 4 shows the subparts of the wind field model: 1) the underlaying wind field, and 2) the wake model.

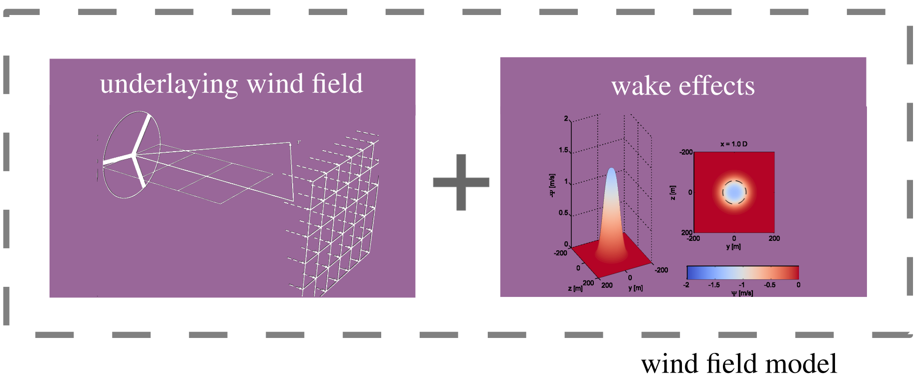


Figure 4. The submodels of the wind field model (in the wind coordinate system W): 1) the underlaying wind field, and 2) the wake model.

The wind field model is described in a wind coordinate system which is denoted by the subscript W. It is rotated horizontally with respect to the global inertial coordinate system I and aligned with the wind direction. The wind speed vector in the W-system is transformed in the I-system by

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix}_I = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}_W , \tag{2}$$

where α is the horizontal rotation of the wind field. The underlaying underlying wind field includes the rotor effective wind speed v_0 and vertical linear shear δ_V. It is assumed that the wind field has only a u component. Thus, in the W coordinate system, the underlaying wind field is underlying wind field vector at point i with the coordinates $[x_i, y_i, z_i]^T$

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix}_{i,W} = \begin{bmatrix} v_0 + z_i \delta_V \\ 0 \\ 0 \end{bmatrix} , \tag{3}$$

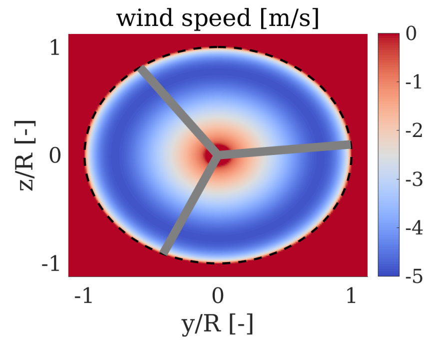


Figure 5. The initial wake deficit ~~over~~ directly evaluated at the ~~normalized~~ rotor ~~disk~~(at 0 m downstream). The mean hub-height wind speed (8 ms^{-1}) was removed for simplicity. No yaw misalignment is applied.

where z_i is the height above the ground. This is illustrated in Figure 4 on the left. Further, the wind field is linearly overlaid with the wake model Ψ for the u and v ~~component. Thus, this yields~~ components yielding

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix}_{i,W} = \begin{bmatrix} v_0 + z_i\delta_V + \Psi_{u,i} \\ \Psi_{v,i} \\ 0 \end{bmatrix}. \tag{4}$$

In the following section, the considered wake effects are described and the wake model is presented.

4.1.1 Wake deficit and wake evolution model.

The rotor extracts energy from the wind and converts it into electrical energy. Therefore, the wind speed is reduced behind a wind turbine. Through mixing and energy flow from the surrounding the ~~deficit is cleared over distance~~momentum deficit recovers. The wake deficit is modeled with an initial wake deficit at the rotor disk with tip and root losses depending on the energy extraction. In order to get the initial deficit, the energy extraction is mapped by applying Prandtl's root and tip loss function Γ_{Prandtl}. Applying the energy conservation assumption yields

$$(v_0 + s\Gamma_{\text{Prandtl}})^2 - (1 - c_P)v_0 = 0, \tag{5}$$

with the power coefficient c_p. Solving this equation for s gives the initial wake deficit

$$\Psi_{\text{init}} = s_{\text{solution}}\Gamma_{\text{Prandtl}}. \tag{6}$$

An exemplary initial wake deficit Ψ_{init} is shown in Figure 5.

The wake is evolving as it moves away from the wind turbine. New energy ~~is flowing from the side and above and the flow is mixed~~flows in from the freestream and mixes with the wake. Physically these dynamics are described via the Navier-Stokes equations. These are partial differential equations and it would be a very complex task to estimate the wake using these equations. However, here an empirical model is used which models the ~~impulse dissipation. In~~ wake recovery. However, in contrast to other wake models, however, the wake evolution is modeled by a Gaussian shape 2D filter. The 2D filter Ξ depends on the distance d behind the wind turbine

$$\Xi(d, y_i, z_i) = \exp\left(\frac{y_i^2 + z_i^2}{2\sigma_f^2(d)}\right) \tag{7}$$

with

$$\sigma_f(d) = \frac{d\epsilon}{2\sqrt{2\log(2)}} \frac{d \cdot \epsilon}{2\sqrt{2\log(2)}} \tag{8}$$

and y_i and z_i the grid points in distance d. With the parameter ϵ the dissipation rate can be set.

Thus, for every distance behind the rotor, the wake can be evaluated using the initial wake deficit Ψ_{init} and the filter (7). The wake deficit results from the convolution of the initial wake deficit Ψ_{init} with the filter $\Xi(d, y_i, z_i)$ to

$$\Psi(d, y_i, z_i) = \Xi(d, y_i, z_i) * \Psi_{\text{init}} \tag{9}$$

4.1.2 Wake deflection model.

The wake deflection caused by a yaw misalignment γ is additionally modeled. The relationship is derived in the study of Jiménez et al. (2010) and was successfully used in an optimization of the yaw angles for a simulated wind farm in Gebraad et al. (2014). The angle of the wake with respect to the main wind direction is

$$\xi(d, c_T, \gamma) = \frac{\xi_{\text{init}}(c_T, \gamma)}{\left(1 + \beta \frac{d}{D}\right)^2}, \tag{10}$$

with the initial angle of the wake at the rotor

$$\xi_{\text{init}}(c_T, \gamma) = \frac{1}{2}\cos^2(\gamma)\sin(\gamma)c_T \tag{11}$$

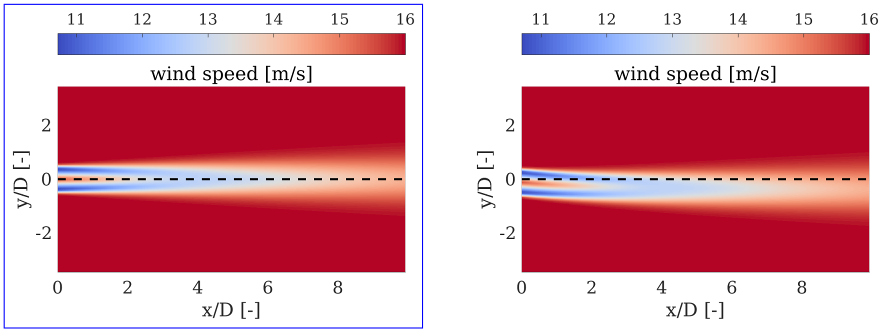
and the model parameter β, which defines the sensitivity of the wake deflection to yaw and is here assumed to be known in advance. Further, c_T is the thrust coefficient and D the rotor diameter. ThusFurther, the yaw induced deflection at the downwind position d is according to Gebraad et al. (2014)

$$\delta_{\text{yaw}}(d, c_T, \gamma) = -\xi_{\text{init}}(c_T, \gamma)\frac{D}{30\beta}\left[15\left(1 - \frac{1}{1 + \frac{2\beta d}{D}}\right) + \xi_{\text{init}}(c_T, \gamma)^2\left(1 - \frac{1}{\left(1 + \frac{2\beta d}{D}\right)^5}\right)\right]. \tag{12}$$

The rotation is applied to the wake deficit and yields a u and v component of the wake model,

$$\begin{bmatrix}\Psi_{u,i} \\ \Psi_{v,i} \\ 0\end{bmatrix}_W = \begin{bmatrix}\cos\xi(d, c_T, \gamma) & -\sin\xi(d, c_T, \gamma) & 0 \\ \sin\xi(d, c_T, \gamma) & \cos\xi(d, c_T, \gamma) & 0 \\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\Psi_i \\ 0 \\ 0\end{bmatrix}_W. \tag{13}$$

In Figure 6 two different wake situations are shown, the first is a non yawed non-yawed case and in the second case the turbine is yawed with $\gamma = 25\,\text{deg}$. In both cases the underlaying underlying wind field has a constant mean hub-height free stream wind speed of $v_0 = 16\,\text{m/s}$ and no vertical shear.



(a) Non-yawed case.

(b) Turbine is yawed with $\gamma = 25\,\text{deg}$.

Figure 6. Visualization of two wake situations within a constant wind field of $v_0 = 16\,\text{m/s}$, axial induction $a = 0.15$ and dissipation rate $\epsilon = 0.1$.

5 The estimation task - model-based wake tracking

As summarized before the estimation task performs the wake tracking using the presented wake model. To perform a lidar-based waked tracking a lidar model is needed. First, the lidar model is presented and then the wake tracking approach is described. Finally, estimation results of two different cases are presented and discussed.

5.1 Lidar model

The lidar measurements can be modeled by a point measurement in the wind field. In the inertial coordinate system this is done by a projection of the wind vector $\begin{bmatrix} u_i & v_i & w_i \end{bmatrix}_I^T$ onto the normalized laser vector in the i-th point $\begin{bmatrix} x_i & y_i & z_i \end{bmatrix}_I^T$ with focus distance $f_i = \sqrt{x_{i,I}^2 + y_{i,I}^2 + z_{i,I}^2}$ by

$$v_{los,i} = \frac{x_{i,I}}{f_i} u_{i,I} + \frac{y_{i,I}}{f_i} v_{i,I} + \frac{z_{i,I}}{f_i} w_{i,I}. \tag{14}$$

5.2 Model-based wake tracking

As depicted in Figure 3, the model based wind field reconstruction method estimates the model parameter by minimizing the error between measured line-of-sight wind speed $v_{los,m}$ and simulated line-of-sight wind speed $v_{los,s}$. A nonlinear optimization problem is formed for n measurement points. This yields

$$\min_p f(x) = \min_p \begin{bmatrix} (v_{los,m,1} - v_{los,s,1})^2 \\ \vdots \\ (v_{los,m,n} - v_{los,s,n})^2 \end{bmatrix}, \tag{15}$$

where in p all free model parameters are included. The free model parameters are listed in Table 1.

~~Figure 7 shows one~~ An example of an estimation step of the wake tracking from a measurement campaign at the alpha ventus offshore wind farm is shown in Figure 7.

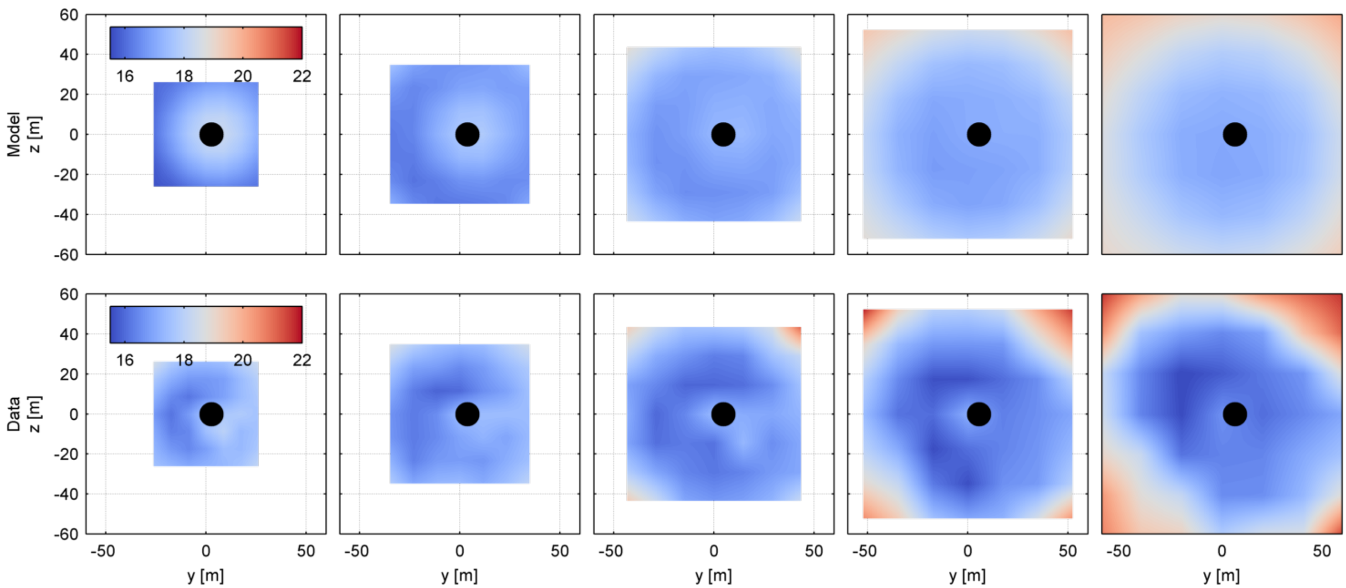


Figure 7. ~~A plot of one~~ An exemplary estimation step of the wake tracking. The simulated lidar measurements in the first row are compared to the measured lidar data in the second row for five downstream distances from 0.6 to 1.4 times the rotor diameter (from left to right, [0.6, 0.8, 1.0, 1.2, 1.4] , looking downstream). The estimated wake center is marked with the black dot.

5.3 Evaluation and discussion

Figure 7 ~~has already shown~~ shows that the model fits well for the application and can be applied with real measurement data. In the following, SOWFA (Churchfield and Lee (2012)) is considered as simulation tool. Flow snapshots of a simulation of a single wind turbine are stored~~and merged to a wind field which~~. The flow field is then scanned with a lidar simulator. The lidar scans with a ~~$7x7$ grid in~~ 7×7 grid at five distances from 0.6 to 1.4 times the rotor diameter ($D = 126\,\mathrm{m}$). Two different cases are analyzed: First, a case where the turbine is aligned with the wind direction. The estimation results are shown in Figure 8. Second, the turbine is misaligned with $30\,\mathrm{deg}$ to deflect the wake. The results of the wake tracking is shown in Figure 9. In both figures the wake center is estimated at the ~~most far~~ furthest scanning distance of $1.4D = 176.4\,\mathrm{m}$. In both cases the method shows the ability of estimating the wake parameter and tracking the wake center.

Table 1. The free model parameter for the wind field model which are estimated in the optimizer.

underlaying wind field		wake model	
v_0	rotor effective wind speed	c_T	thrust coefficient
δ_V	vertical linear shear	c_P	power coefficient
		γ	turbine yaw angle
		ϵ	wake dissipation coefficient

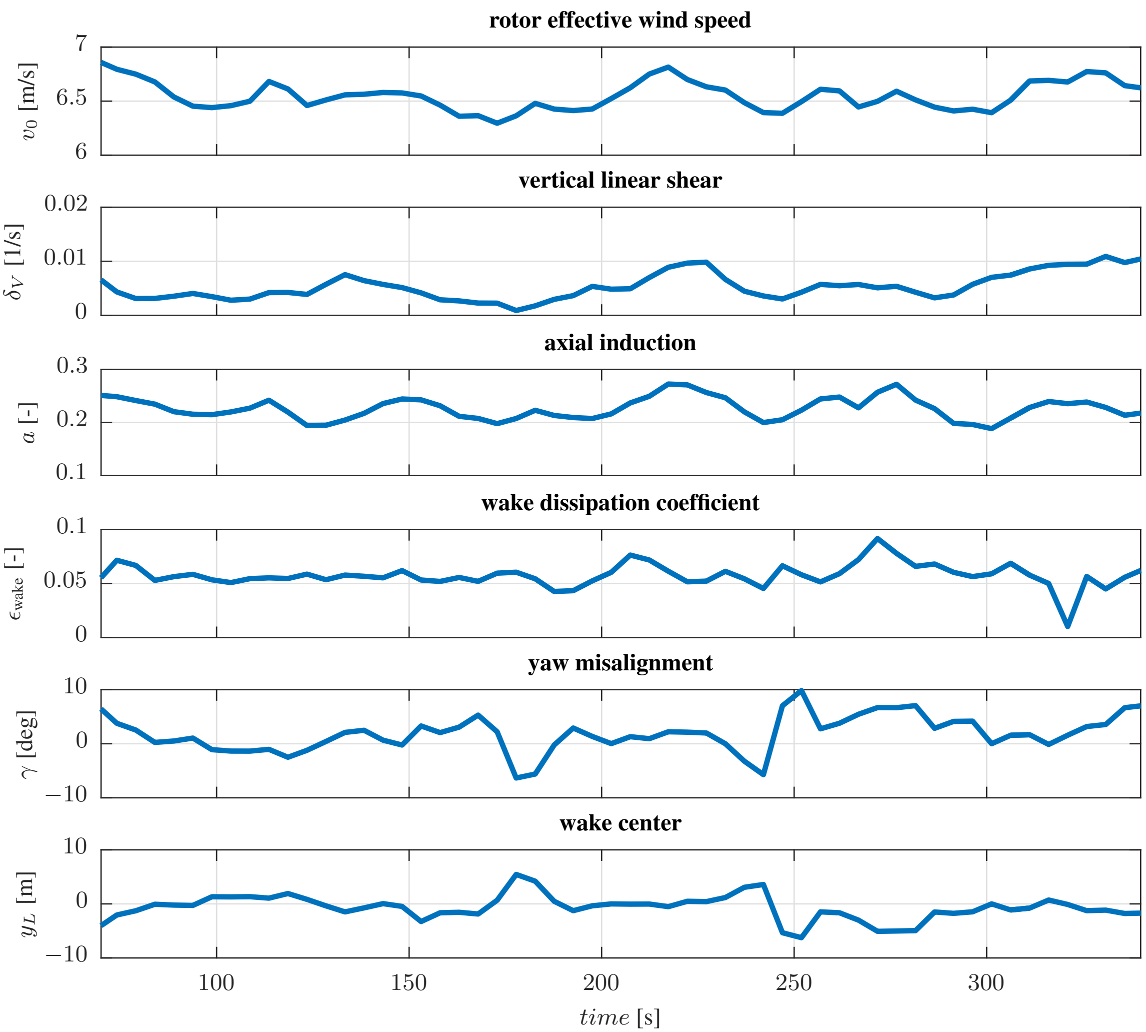


Figure 8. Time results of the wake tracking of a SOWFA simulation. The wind turbine is aligned with the main wind direction. The lidar scanned in a ~~$7x7$~~ 7×7 grid ~~in~~ at five distances from $0.6D$ to $1.4D$. The wake center is estimated at the ~~most far~~ furthest scanning distance $1.4D = 176.4\,\mathrm{m}$

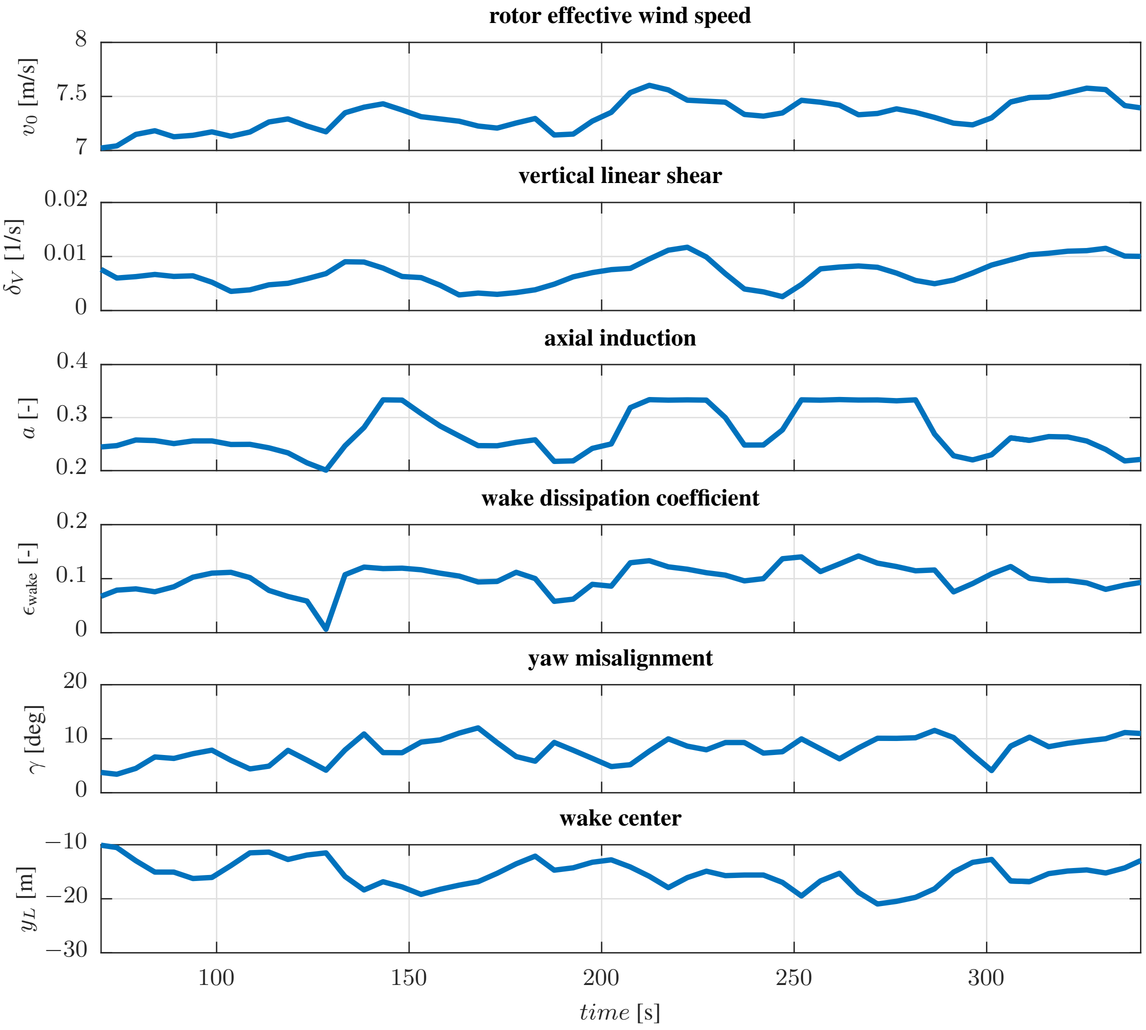


Figure 9. Time results A second time evolution of the different estimated wind field and wake tracking of a SOWFA simulationquantities. In this case, the wind turbine is misaligned with 30 deg and the wake is deflected. The lidar scanned in a $7x7$ 7×7 grid in at five distances from $0.6D$ to $1.4D$. The wake center is estimated at the most far furthest scanning distance $1.4D = 176.4\,\text{m}$

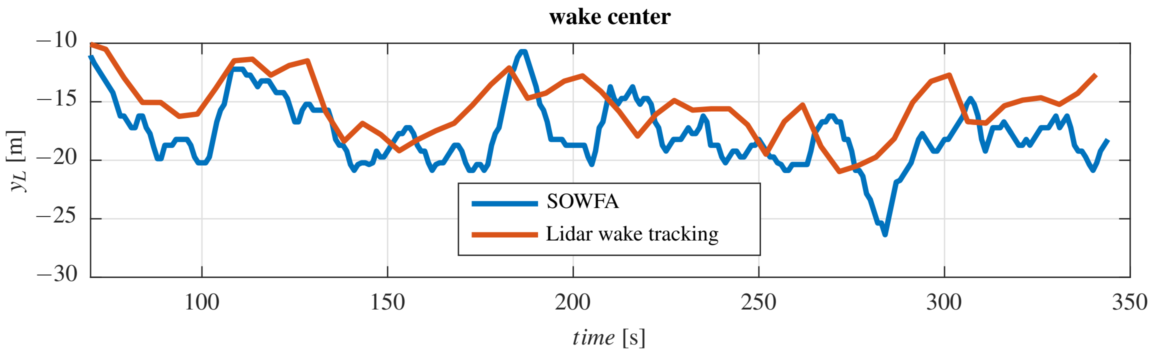


Figure 10. Comparison between the wake center estimation (see Eq. (1)) and the lidar-based wake tracking method.

As mentioned before the wake center ~~positions~~ position needs to be calculated using a specific definition and there ~~isn't a~~ is no direct measurable representation of it. In Figure 10 the lidar-based wake tracking is compared to the wake center estimation using the definition of Eq. (1) without any filtering.

6 The control task

The following closed-loop controller was first presented in Raach et al. (2016) and is recapped here. ~~Then, in a second step having analyzed the wake center displacement from the wake tracking, the filtering is discussed~~Consider also Raach et al. (2017) where a $\mathcal{H}_\infty$ controller design for closed-loop wake redirection with defined performance margins.

As mentioned above, the reaction of the wake to a yaw action can only be measured with a time delay. To control a delayed system, the Smith Predictor approach has been derived and used in many applications. Internal model control is the basic idea of a Smith Predictor.

The presented controller follows the idea of internal model control in which the difference between the actual system output and a predicted output is used within the controller to regulate the system. Therefore, a model is necessary for describing the wake effects in a simplified but sufficient way. It consists of the controller which is a classical proportional-integral controller. Further, an internal model is used which approximates the real system behavior. The wake propagation which exists because the wake flow has to evolve until it reaches the measurement location of the lidar system is approximated with ~~an~~ a delay. The time delay τ varies with respect to the mean wind speed. Finally, a filter is needed to cancel out controller actions which can not be observed because of the time difference between control action and measurement location. Figure 11 shows the general concept of the controller.

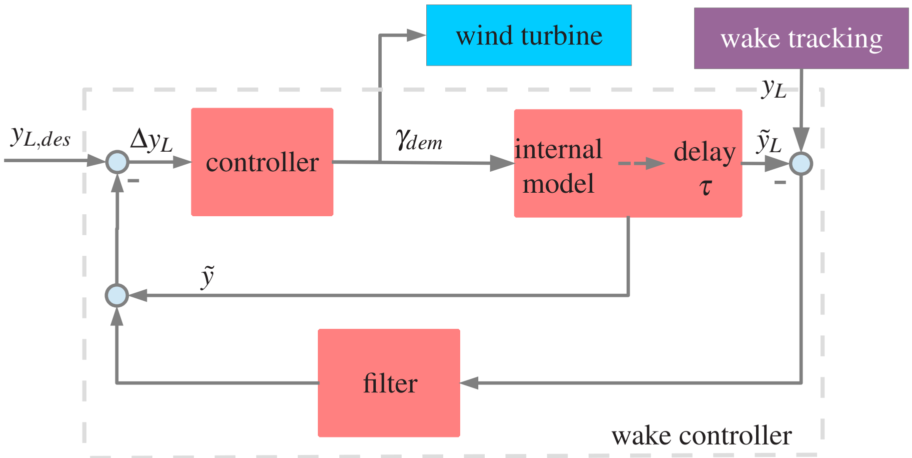


Figure 11. The general structure of the wake steering controller: The controller, a simplified wake model and the wake propagation modeled with a delay, and the filter. The controller uses the difference, δy_L , between the predicted output $\tilde{y}$, the measured output y_L and the desired output $y_{L,des}$ to set the demanded yaw angle γ_{dem} .

6.1 Internal wake model of the controller

As depicted in Fig. 11, the wake controller needs an internal model to predict the reaction of the wake to the demanded yaw angle. The internal wake model includes the yaw actuator and the yaw induces wake deflection. For the wake model the assumptions of a constant thrust coefficient , c_T , is made.

Altogether, this yields an internal controller model $\widetilde{\Psi}$ of the reality Ψ:

$$\widetilde{\Psi} : \begin{cases} \ddot{\gamma} + 2d\omega\dot{\gamma} + \omega^2\gamma = \omega^2\gamma_{dem} & \text{yaw actuator dynamic} \\ \tilde{y} = \delta_{\text{yaw}}(d_{\text{Lidar}}, c_{T,\text{const}}, \gamma) & \text{wake deflection model} \end{cases} \tag{16}$$

with γ_{dem} the demanded yaw angle and d_{Lidar} the distance to the measurement location.

There is a time delay because the wake first needs to evolve to the measurement location:

$$\tilde{y}_L(t) = \tilde{y}(t - \tau). \tag{17}$$

For the controller design, the time delay is approximated using the Pade Padé approximation of time delays, see Skogestad and Postlethwaite

6.2 Controller design

The primal goal of the wake controller is to steer the wake center to a desired point in a defined distance by yawing the wind turbine. As mentioned, this is done using a Smith Predictor. A Smith Predictor , which uses an internal model to predict the output reaction. Then the predicted wake center position and the filtered error between predicted and measured wake center position is fed back to the controller.

6.2.1 Controller

A standard proportional-integral (PI) controller is used. It is designed such that the closed-loop performance with the internal model (16) meets a phase margin of $60\,\mathrm{deg}$ and a closed-loop bandwidth of $\omega_{\mathrm{CL}} = \frac{1}{2\tau}$. This yields a controller of the form

$$u = K_p\Big(\Delta y_L + \frac{1}{T_i}\int \Delta y_L \mathrm{d}t\Big), \tag{18}$$

with the proportional gain K_p and the time constant T_i.

6.2.2 Filter

The wake propagation and the caused delay disables a direct measure of a yaw change and because of that one has to filter the measured feedback to prevent non-observable yaw actions. Since the delay τ is time varying and depends on the mean wind speed the filter has to be adaptable. Therefore, the cutoff frequency of the butterworth low-pass filter is set to $\omega_{\text{filter}} = \frac{\pi}{8\tau}$.

6.3 Evaluation and discussion

In the following the wake controller is analyzed. Further, the sensitivity and the complementary sensitivity of the closed-loop system is assessed. Consider Skogestad and Postlethwaite (2005) for a detailed description on controller design and analysis.

6.3.1 Controller analysis

In the following the transfer function of the wake controller is assessed. As shown in Figure 11 the wake controller consists of the internal controller C, an internal model $\widetilde{\Psi}$, the time delay approximation W and the filter F. Having merged all parts the wake controller K is

$$K = \frac{F}{(1 + C\,\Psi(1 - FW))}. \tag{19}$$

Figure 12 shows the bode analysis of the wake controller K. The controller shows integration behavior, starting with $-90\,\mathrm{deg}$ phase.

6.3.2 Closed-loop analysis

To perform closed-loop analysis the internal controller model $\widetilde{\Psi}$ is transformed to Laplacian space yielding the plant G. Then, the sensitivity S and the complementary sensitivity T that are

$$S = \frac{1}{1 + GK} \tag{20}$$

$$T = \frac{GK}{1 + GK}, \tag{21}$$

with the controller K are assessed and shown in Figure 13.

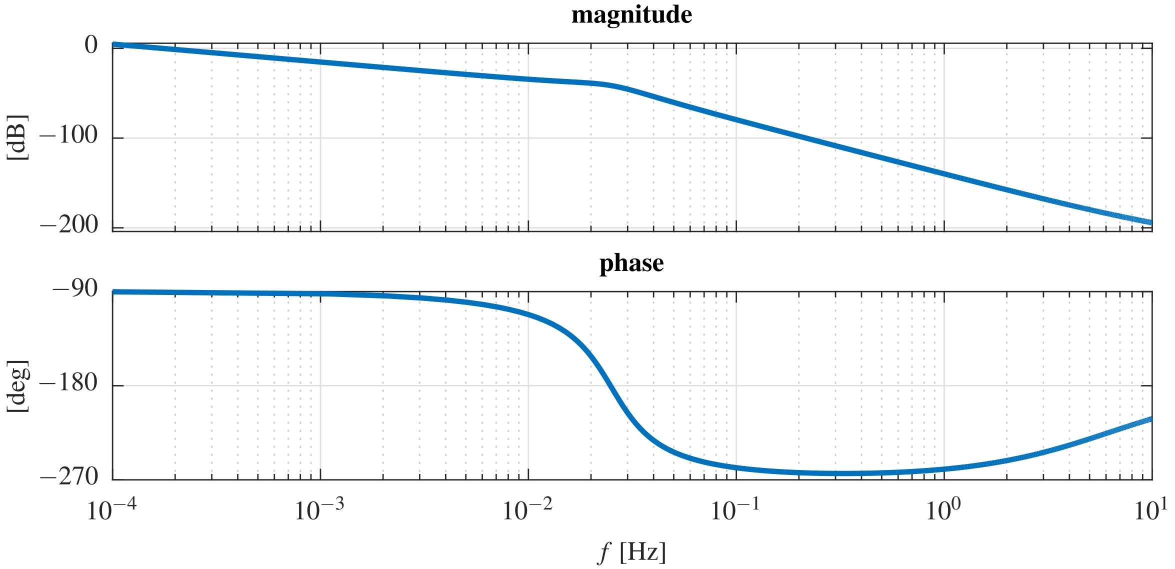


Figure 12. Bode analysis of the designed controller K.

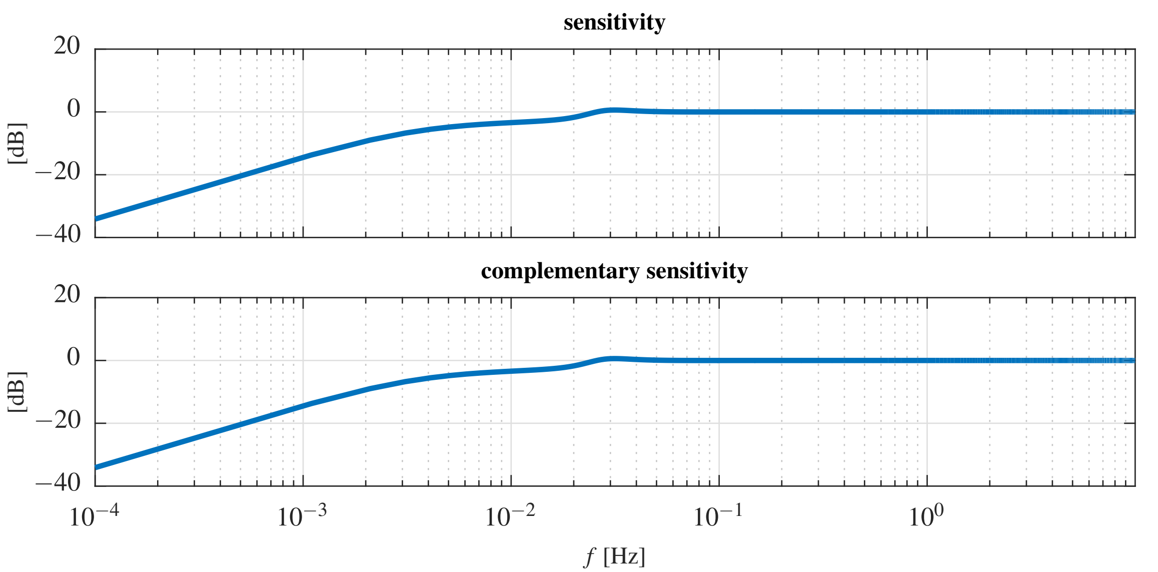


Figure 13. Sensitivity S and complementary sensitivity T analysis of the closed-loop system.

7 Conclusions

This paper introduces first a method which uses lidar measurements to estimate wind field parameters and ~~enable~~ enables a tracking of the wake center position. Second, a controller is presented which uses this information to redirect the wake to a desired position.

In two different cases using simulated lidar measurements of SOWFA simulations, the wake tracking shows promising results in estimating the wake center. The difficulty in wake center position definition is elaborated. A definition is used and the wake tracking results are compared to it.

The challenges of a lidar-based wake redirecting control problem are discussed and an appropriate controller is designed to meet the desired requirements.

This enables the next step towards a closed-loop wake redirecting in ~~an~~ a high fidelity simulation tool which is aimed as a next step.

As an outlook, the presented framework of lidar-based closed-loop wake steering offers new possibilities for wind farm control. In a next step, it will be implemented and tested in a high fidelity simulation tool and tested in real time. For the control problem ~~, different controller approaches~~ robust controllers will be investigated~~such as $\mathcal{H}_\infty$ controllers or robust controllers~~. Dynamic estimation techniques as well as other wake estimation models will be used for comparing the ability of tracking the wake and finding the most suitable approach for this task.

References

Annoni, J., Gebraad, P. M., Scholbrock, A. K., Fleming, P. A., and van Wingerden, J.-W.: Analysis of axial-induction-based wind plant control using an engineering and a high-order wind plant model, Wind Energy, 19, 1135–1150, 2015.

Boersma, S., Doekemeijer, B., Gebraad, P., Fleming, P.and Annoni, J., Scholbrock, A., Frederik, J., and van Wingerden, J.-W.: A Tutorial on Control-Oriented Modeling and Control of Wind Farms, in: Proceedings of the American Control Conference (ACC), 2017.

Borisade, F., Luhmann, B., Raach, S., and Cheng, P. W.: Shadow Effects in an Offshore Wind Farm - Potential of Vortex Methods for Wake Modelling, in: Proceedings of the German Wind Energy Conference DEWEK, Bremen, Germany, 2015.

Churchfield, M. and Lee, S.: NWTC design codes-SOWFA, URL: http://wind. nrel. gov/designcodes/simulator s/SOWFA, 2012.

Fleming, P., Gebraad, P. M., Lee, S., Wingerden, J.-W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P., and Moriarty, P.: Simulation comparison of wake mitigation control strategies for a two-turbine case, Wind Energy, 18, 2135–2143, 2014a.

Fleming, P. A., Gebraad, P. M., Lee, S., van Wingerden, J.-W., Johnson, K., Churchfield, M., Michalakes, J., Spalart, P., and Moriarty, P.: Evaluating techniques for redirecting turbine wakes using SOWFA, Renewable Energy, 70, 211–218, 2014b.

Gebraad, P. M. O., Teeuwisse, F. W., van Wingerden, J., Fleming, P., Ruben, S. D., Marden, J. R., and Pao, L. Y.: Wind plant power optimization through yaw control using a parametric model for wake effects—a CFD simulation study, Wind Energy, 19, 95–114, doi:10.1822/we, 2014.

Jiménez, Á., Crespo, A., and Migoya, E.: Application of a LES technique to characterize the wake deflection of a wind turbine in yaw, Wind Energy, 13, 559–572, 2010.

Raach, S., Schlipf, D., Haizmann, F., and Cheng, P. W.: Three Dimensional Dynamic Model Based Wind Field Reconstruction from LiDAR Data, in: Journal of Physics: Conference Series: The Science of Making Torque From Wind, vol. 524, Copenhagen, Denmark, 2014.

Raach, S., Schlipf, D., Borisade, F., and Cheng, P. W.: Wake redirecting using feedback control to improve the power output of wind farms, in: Proceedings of the American Control Conference (ACC), Boston, USA, 2016.

Raach, S., van Wingerden, J.-W., Boersma, S., Schlipf, D., and Cheng, P. W.: Hinf controller design for closed-loop wake redirection, in: Proceedings of the American Control Conference (ACC), 2017.

Schlipf, D., Rettenmeier, A., Haizmann, F., Hofsäß, M., Courtney, M., and Cheng, P. W.: Model Based Wind Vector Field Reconstruction from Lidar Data, in: Proceedings of the German Wind Energy Conference DEWEK, Bremen, Germany, 2012.

Skogestad, S. and Postlethwaite, I.: Multivariable Feedback Control: Analysis and Design, John Wiley & Sons, 2005.

Vollmer, L., Steinfeld, G., Heinemann, D., and Kühn, M.: Estimating the wake deflection downstream of a wind turbine in different atmospheric stabilities: an LES study, Wind Energy Science, 1, 129–141, doi:10.5194/wes-1-129-2016, 2016.