

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

**Authors :** Steffen Raach, David Schlipf, and Po Wen Cheng

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highlighted text: see comment

## Section 1

1. due to interactions between individual wind turbines in a wind farm
2. of interest to whom?
3. velocity deficit and turbulence intensity are not "phenomena"
4. have
5. a lower
6. contains
7. and
8. ambiguous, makes it sound like it's the cost/availability of wind turbines -- reword
9. A model-based estimation approach is presented and used to obtain...
10. , and a closed loop controller is...

Combine last two paragraphs of introduction.

## Section 2

11. redirection
12. two main tasks must be considered
13. redirection
14. between the measurement and control tasks
15. The main issue in the context of wake tracking algorithms is that no clear definition exists for the wake center.

Refer the reader to references below for a review of wake center estimation methods.

Doubrawa, Paula, Rebecca J. Barthelmie, Hui Wang, and Matthew J. Churchfield. "A Stochastic Wind Turbine Wake Model Based on New Metrics for Wake Characterization." *Wind Energy* 20, no. 3 (March 1, 2017): 449–63. doi:10.1002/we.2015.

Howland, Michael F., Juliaan Bossuyt, Luis A. Martinez-Tossas, Johan Meyers, and Charles Meneveau. "Wake Structure of Wind Turbines in Yaw under Uniform Inflow Conditions." *arXiv:1603.06632 [physics]*, March 21, 2016. <http://arxiv.org/abs/1603.06632>.

Combine last two paragraphs of Section 2.1.

16. not sure what you mean by "manipulate" wake quantities?
17. as
18. its desired value
19. to
20. put this in parenthesis

21. while providing

### Section 3

- 22. through the use of simulation data, which can cover a larger area at a higher spatial and temporal resolution than measurements would be able to provide.
- 23. oriented
- 24. the downstream position where a hypothetical turbine of identical characteristics and yaw angle would produce the least power.
- 25.  $y=0$
- 26. window
- 27. obtained
- 28. turbulence intensity
- 29. it is not  $\text{microsecond}^{-1}$  but instead  $\text{meter second}^{-1}$  so put a space between m and s
- 30. The problem of wake center estimation is different from other problems in lidar-based wind field reconstruction.
- 31. When the wake center is defined as
- 32. neither is
- 33. "seems to be very convenient" is not scientific language

Combine last two paragraphs of Section 3.2.

### Section 4

- 34. directly measurable
- 35. wind lidar systems
- 36. they return
- 37. Most of your citations are of people that you've worked with or of your immediate network, it's best to diversify this a bit to show you've done your research and consider the body of work in the field while performing your analyses. Have you seen the reference below for model simulations of lidar measurements in the wake?

Lundquist, J. K., M. J. Churchfield, S. Lee, and A. Clifton. "Quantifying Error of Lidar and Sodar Doppler Beam Swinging Measurements of Wind Turbine Wakes Using Computational Fluid Dynamics." *Atmos. Meas. Tech.* 8, no. 2 (February 23, 2015): 907–20. doi:10.5194/amt-8-907-2015.

- 38. The "s" of Figure 3 is chopped off
- 39. example (never exemplary)

**exemplary** |ig'zemplərē|

adjective

**1** serving as a desirable model; representing the best of its kind: *an award*

*for exemplary community service.*

**2** (of a punishment) serving as a warning or deterrent: *exemplary sentencing may discourage the ultraviolent minority.*

- Law (of damages) exceeding the amount needed for simple compensation.

40. evolves

41. it's not really because they are PDOs that it is difficult to use Navier-Stokes for your purposes. It's because of the non-linear terms and the closure problem that arises from the non-linearity, right?

42. the rotor diameter D comes up several times before so please define it at its first occurrence and just use "D" after that. Also, perhaps avoid using 2D for two-dimensional, just spell it out to avoid confusion.

43. ...are shown for  $\gamma=0$  and  $\gamma=25$  deg.

44. consistency in your units...  $\text{m s}^{-1}$  instead of m/s

## Section 5

45. As summarized before, the estimation

46. tracks the wake

47. Shouldn't this be capitalized?

48. I am not sure what this means, "fits well for the application"

49. used

50. Two different cases are analyzed. In the first case, the turbine rotor is perpendicular to the wind direction ( $\gamma=0$  deg) and these results are shown in Figure 8. In the second case, the yaw misalignment is 30 deg so that the wake is deflected.

51. are

52. to estimate

53. its

54. parameters

55. example

56. D

## Section 6

57. repetitive, please reword, e.g. the Smith Predictor approach, which is based on an internal model control, has been derived and used in many applications. Also combine paragraphs 1 and 2 here (lines 2-6)

58. It consists of a proportional-integral controller.

59. what is approximated with a delay? sentence has no subject?

60. main wind direction? or mean?

61. induced?

62. I think you already defined  $c_t$  up above so no need to spell out thrust coefficient?

63. define PI up above when you first talk about it

64. precludes

65. measurement

66. what is the complementary sensitivity?

## **Section 7**

67. You might want to mention that your work is unique because you look at the very near wake, which is quite challenging, while other work has mostly focused on  $d \geq 2D$ ?

68. redirection

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

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**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 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, wind farm control has gained more and more importance in the wind energy control community, [1]. ~~The wake interaction can result in less power compared to a free 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 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 [2]. Different models have been developed to address different [3], such as the velocity deficit and the increased turbulence intensity. There are empirical models, data driven models, 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.

The same two goals are valid for both wind turbine and wind farm control: 1) maximization of the total power and 2) reduction of the structural loads. Two main concepts [4] been introduced for wind farm control: 1) axial induction control and 2) wake redirection control. Axial induction control aims at manipulating the axial induction by the blade pitch or torque actuator and operating the wind turbine at a lower production level. This results in [5] 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. 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. (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 (at a seven diameter downwind distance) by yawing the turbine up to 40deg, see Fleming et al. (2014b). Different investigations have shown promising results 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 [REDACTED] drawbacks: 1) Applying optimized yaw angles in a feed-forward approach does not guarantee that the wake is going to the desired direction [REDACTED] 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 has been the lack of measurement devices to measure the flow interactions between wind turbines, [REDACTED]. 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, 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 closed-loop wake redirecting by presenting a method to obtain the wake position using lidar measurements. Further, the difficulty in wake position definition and measurability is discussed.

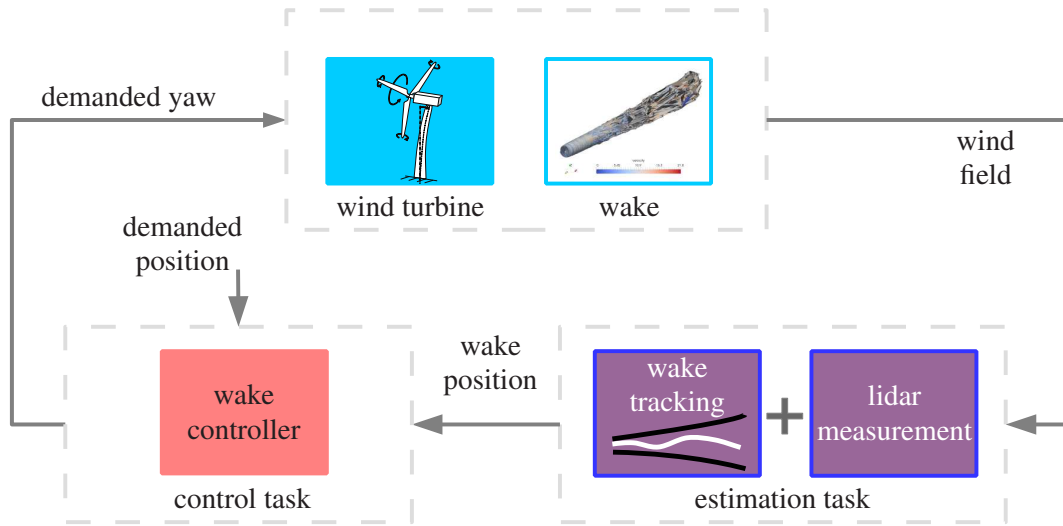
[REDACTED] to obtain important quantities for wake redirecting using a nacelle-based lidar system facing downwind. Furthermore, [REDACTED] closed loop controller is designed and analyzed. In summary, this work presents an entire concept for lidar-based closed-loop wake redirecting.

## 2 Methodology

In order to enable a lidar-based closed-loop wake [REDACTED] within a wind farm, [REDACTED]: 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 [REDACTED] and the link [REDACTED].

### 2.1 Problem formulation for wake-tracking

[REDACTED] moreover, the idea of a wake center is a concept based on time averaged profiles of the wake behind a turbine (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, when different methods are used to define



**Figure 1.** The conceptual idea of 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.

the shape, wake center estimates may ~~be~~ vary under the same flow conditions, see Vollmer et al. (2016). The absence of a unique wake center definition 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.

The task of lidar-based wake tracking includes first, a reference definition 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 to   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   described in Section 5.

## 2.3 The control task

The second task towards a closed-loop wake redirection is the control task. Its main challenge is to convert the estimated wake position information and   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 is measured with a delay due to the wake propagation time, the controller has to be designed

overcome this limitation.

In the following 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

- 5 wake redirecting controller is presented which uses the obtained wake information, and steers the wake ~~center~~ using the yaw actuator ~~to a desired position~~. The overall goal of this paper is to ~~also~~ present the framework of lidar-based closed-loop wake redirection exemplary models and controller.

### 3 Reference definition and its impact on the estimation task

In this section the wake center definition is addressed

#### 3.1 Wake center definition

As previously mentioned, it is first necessary to define the wake center. The minimum wind power method proposed by Vollmer et al. (2016) is adopted and modified to identify the wake center. Thus, it is defined as

- 15 yields the minimization problem This

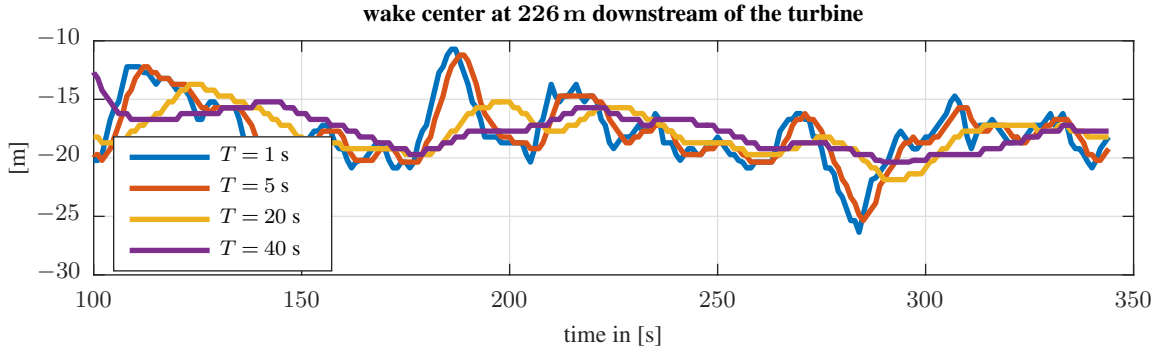
$$\min_y \int_0^{2\pi} \int_y^{R+y} u(r, \phi)^3 r \, dr d\phi, \quad (1)$$

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

- 20 The flow field is time averaged over different running window lengths and the impact of the lengths is analyzed. The calculated wake center (at a 1.8 diameter downwind distance) with a running averaged filter with different window lengths are presented in Figure 2. The presented results are for a low ( $TI = 6\%$ ) SOWFA simulation under a mean hub-height free-stream wind speed  $^{-1}$ . 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
- 25 be considered when choosing an averaging time.

#### 3.2 Problem discussion of lidar-based wake tracking

Other model based approaches in wind field reconstruction (e.g. estimation of the rotor-effective wind speed, or of  $u$  and  $v$  wind vector components using lidar measurements as in Schlipf et al. (2012)) can first be compared to existing quantities. Further,



**Figure 2.** Time evolution of wake center (at a 1.8 diameter downwind distance) when different window lengths  $T$  are used to average the flow during the wake center calculation.

the 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.

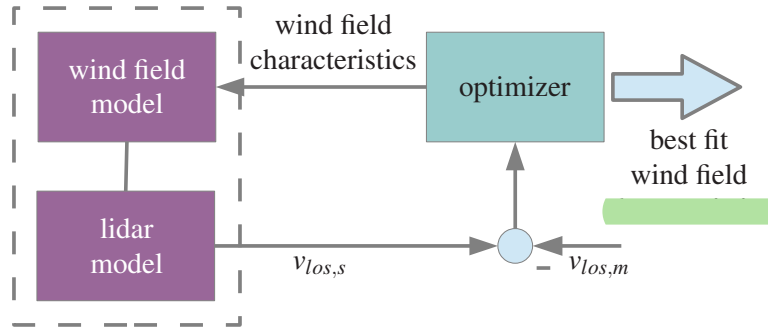
in Eq. (1) the prediction of the wind field from a given position is not possible and a direct comparison of line-of-sight data ~~is not possible~~. Nevertheless, the wake center position definition and is therefore used as reference.

#### 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 and have to be estimated from the measurement data. One main limitation of is that 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 these limitations is to implement model-based wind field reconstruction. Wind field reconstruction methods have been developed and used for different applications of lidar systems in wind energy, f

Here, the concept of wind field reconstruction is used to obtain information about the wake.

The general approach of wind field reconstruction from lidar data is to estimate wind field characteristics from an internal model by fitting simulated lidar 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 model parameter (e.g. wake center position, wake decay, wake deficit, etc.).

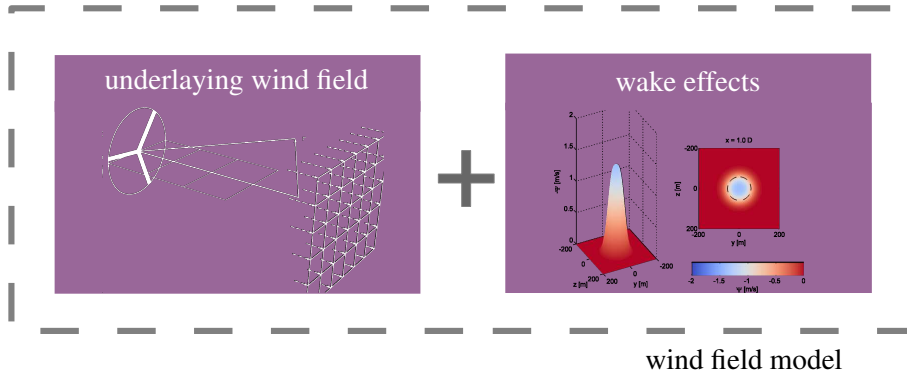


**Figure 3.** The general concept of model-based wind field reconstruction, in which the wind field characteristics are estimated by fitting simulated lidar measurement data ( $v_{los,s}$ ) to measurements ( $v_{los,m}$ ).

In this work, a lidar and a wind field model is used. The wind field model consists of a background wind field model, which defines the ambient wind speed and its profile, and a wake model. The wake model includes the main wake effects: wake deficit, wake evolution, and wake center displacement. The models are presented in the following section.

#### 4.1 Wind field model

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



**Figure 4.** The submodels of the wind field model (in the wind coordinate system  $W$ ): 1) the underlying 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

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

where  $\alpha$  is the horizontal rotation of the wind field. The underlying wind field includes the rotor effective wind speed  $v_0$  and vertical linear shear  $\delta_V$ . It is assumed that the wind field has only a  $u$  component. Thus, in the  $W$  coordinate system, the

5 underlying wind field vector at point  $i$  with the coordinates  $[x_i, y_i, z_i]^T$

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

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  $\Psi$  for the  $u$  and  $v$  components yielding

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

10 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 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

15 the initial deficit, the energy extraction is mapped by applying Prandtl's root and tip loss function  $\Gamma_{\text{Prandtl}}$ . Applying the energy conservation assumption yields

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

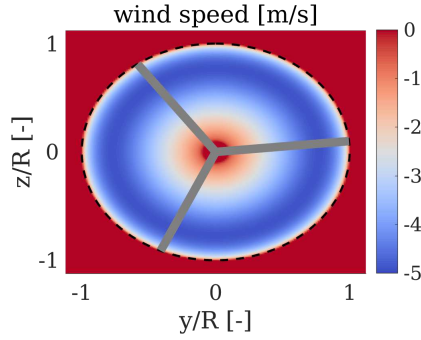
with the power coefficient  $c_P$ . Solving this equation for  $s$  gives the initial wake deficit

$$\Psi_{\text{init}} = s_{\text{solution}}\Gamma_{\text{Prandtl}}. \quad (6)$$

20 An initial wake deficit  $\Psi_{\text{init}}$  is shown in Figure 5.

The wake as it moves away from the wind turbine. ~~New~~ energy flows in from the freestream and mixes with the wake. ~~Physically these dynamics are described via the Navier Stokes equations.~~

However, here an empirical model is used which



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

models the wake recovery. However, in contrast to other wake models, the wake evolution is modeled by a Gaussian shape 2D filter. The 2D filter  $\Xi$  depends on the distance  $d$  behind the wind turbine

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

with

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

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

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

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

#### 4.1.2 Wake deflection model.

The wake deflection caused by a yaw misalignment  $\gamma$  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

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

with the initial angle of the wake at the rotor

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

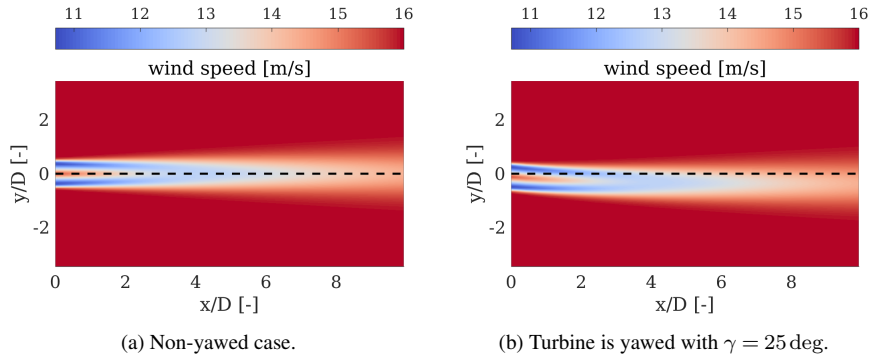
and model parameter  $\beta$ , which defines the sensitivity of the wake deflection to yaw and is here assumed to be known in advance. Further,  $c_T$  is the thrust coefficient Further, the yaw induced deflection at the downwind position  $d$  is according to Gebraad et al. (2014)

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

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

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

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



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

## 5 The estimation task - model-based wake tracking

task 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

- 15 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

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

## 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

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

where in  $p$  all free model parameters are included. The free model parameters are listed in Table 1. An example of an estimation step of the wake tracking from a measurement campaign at the offshore wind farm is shown in Figure 7.

## 5.3 Evaluation and discussion

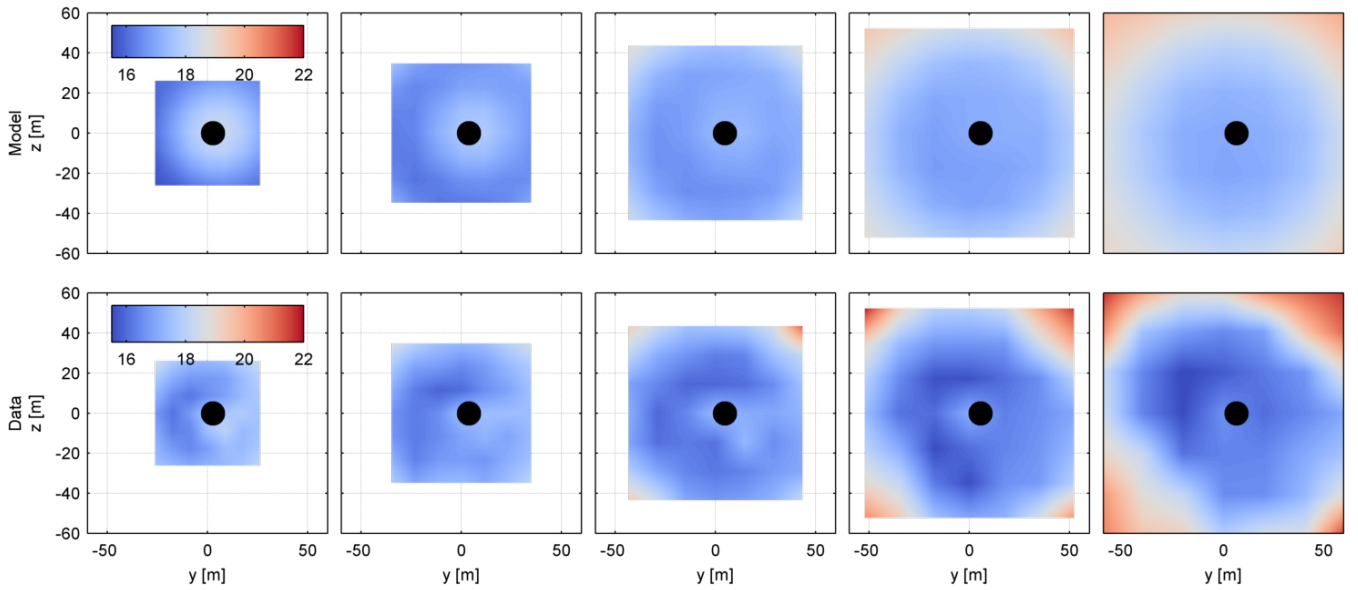
Figure 7 shows that and can be applied with real measurement data. In the following, SOWFA (Churchfield and Lee (2012)) is as simulation tool. Flow snapshots of a simulation of a single wind turbine are stored. The flow field is then scanned with a lidar simulator. The lidar scans with a  $7 \times 7$  grid at five distances from 0.6 to 1.4 times the rotor diameter ( $D = 126$  m).

The results of the wake tracking shown in Figure 9. In both figures the wake center is estimated at the furthest scanning distance of  $1.4D = 176.4$  m. In both cases the method shows the ability the wake parameter and tracking center.

As mentioned before the wake center position needs to be calculated using a specific definition and there 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.

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

underlying wind field		wake model	
$v_0$	rotor effective wind speed	$c_T$	thrust coefficient
$\delta_V$	vertical linear shear	$c_P$	power coefficient
		$\gamma$	turbine yaw angle
		$\epsilon$	wake dissipation coefficient



**Figure 7.** An 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 (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.

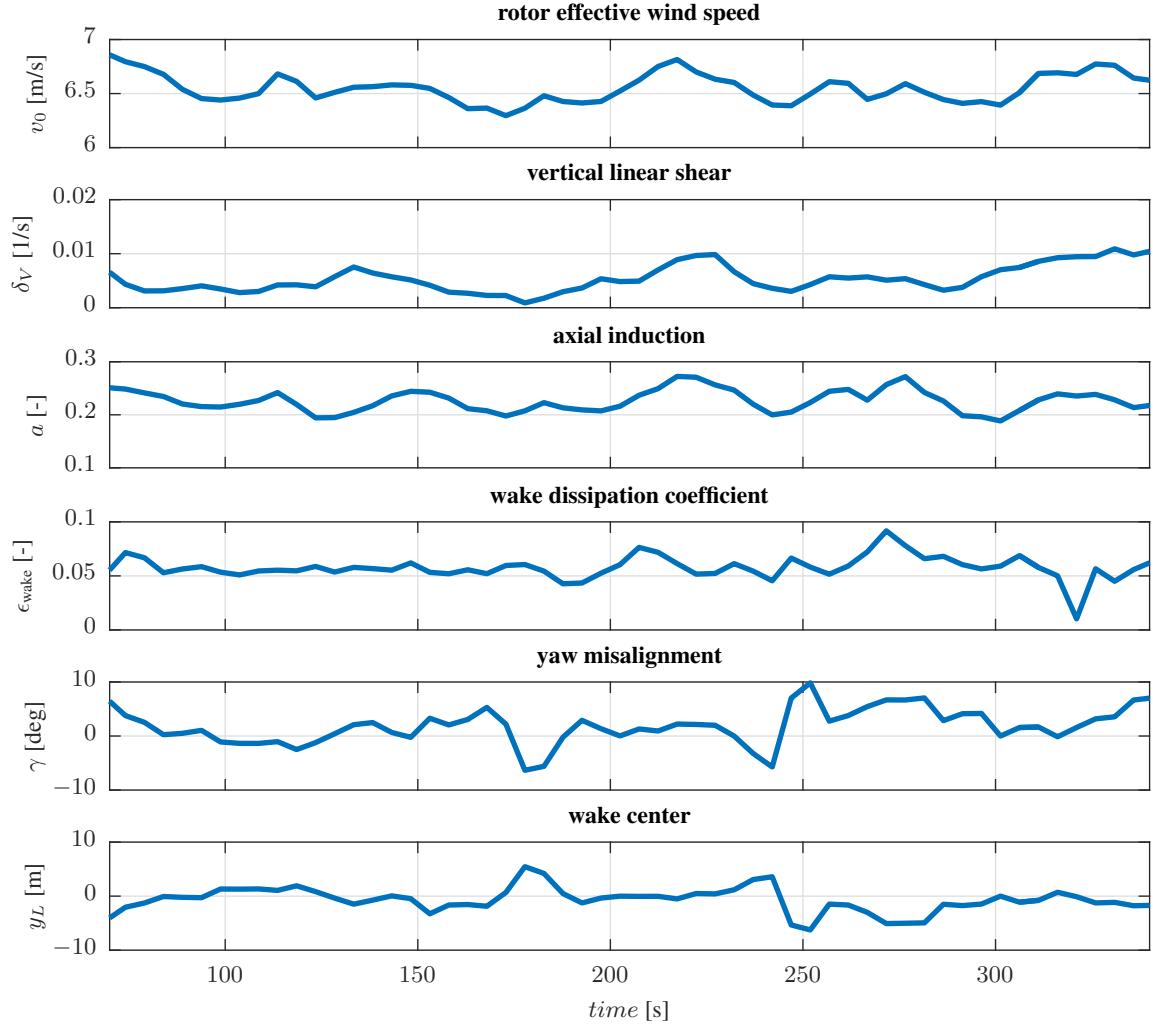
## 6 The control task

The following closed-loop controller was first presented in Raach et al. (2016) and is recapped here. Consider also Raach et al. (2017) where a  $\mathcal{H}_\infty$  controller design for closed-loop wake redirection with defined performance margins.

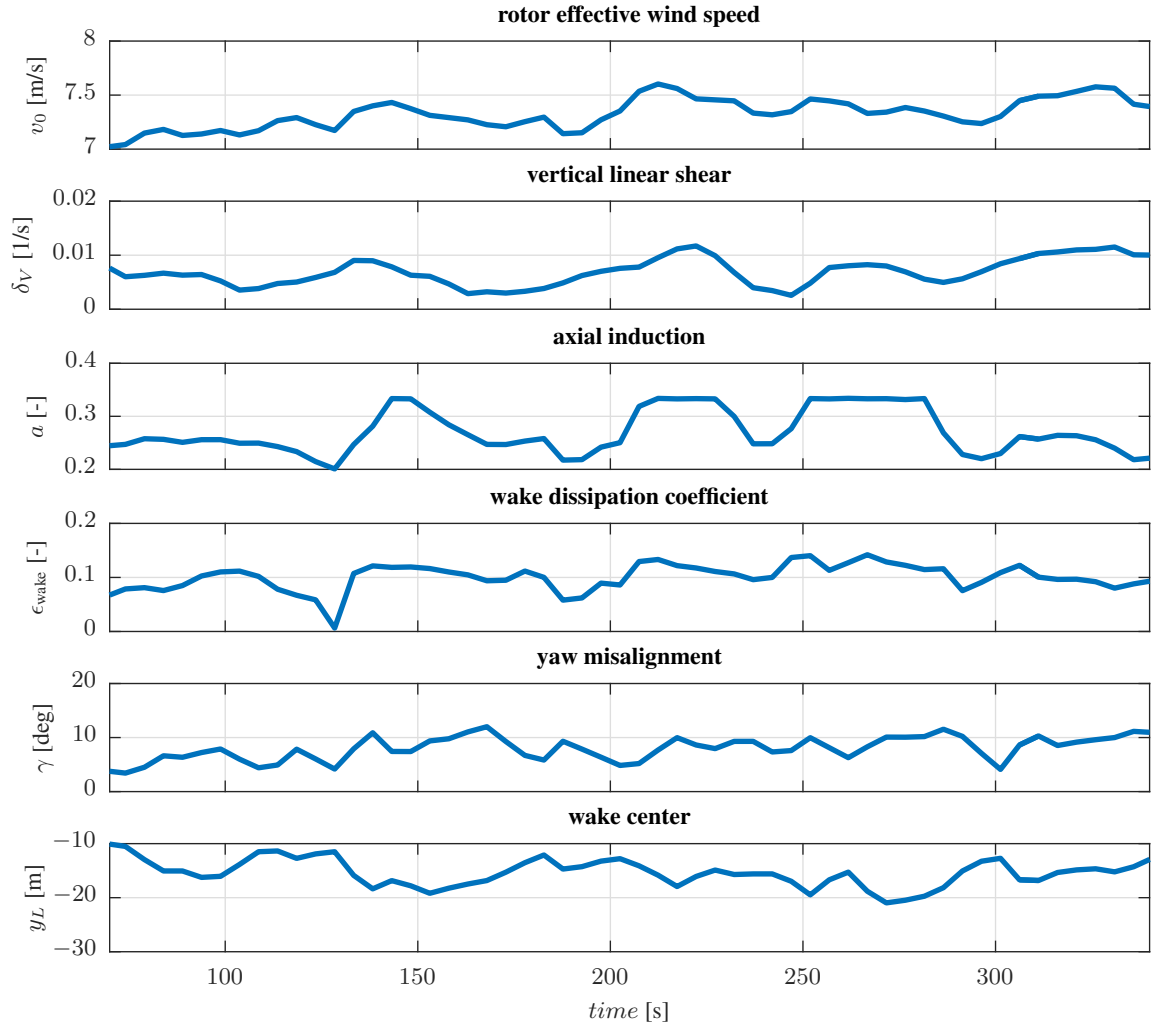
As mentioned above, the reaction of the wake to a yaw action can only be measured with a time delay. To control a delayed system,

The 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.

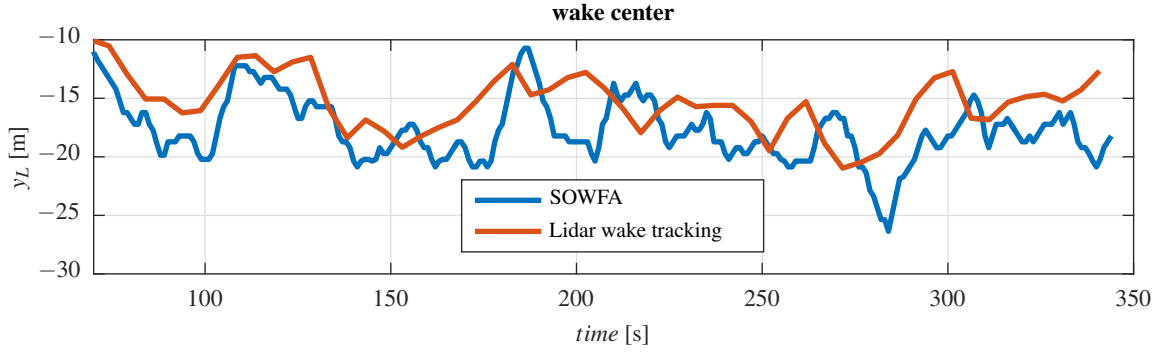
- 10 Further, an internal model is used which approximates the real system behavior. The wake propagation which exists because the wake flow has to evolve until it reaches the measurement location of the lidar system. The time delay  $\tau$  varies with respect to the mean wind speed. Finally, a filter 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.



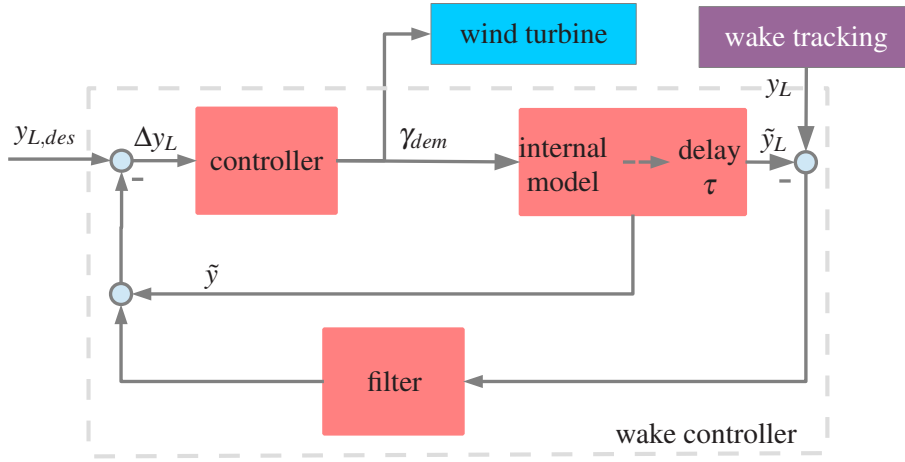
**Figure 8.** Time results of the wake tracking of a SOWFA simulation. The wind turbine is aligned with the  wind direction. The lidar scanned in a  $7 \times 7$  grid at five distances from  $0.6D$  to  $1.4D$ . The wake center is estimated at the furthest scanning distance  $1.4D = 176.4\text{m}$



**Figure 9.** A second time evolution of the different estimated wind field and wake quantities. In this case, the wind turbine is misaligned with 30 deg and the wake is deflected. The lidar scanned in a  $7 \times 7$  grid at five distances from  $0.6D$  to  $1.4D$ . The wake center is estimated at the 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.



**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,  $\delta y_L$ , between the predicted output  $\tilde{y}$ , the measured output  $y_L$  and the desired output  $y_{L,des}$  to set the demanded yaw angle  $\gamma_{dem}$ .

### 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 wake deflection. For the wake model the assumptions of a constant  $c_T$  is made. Altogether, this yields an internal controller model  $\tilde{\Psi}$  of the reality  $\Psi$ :

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

with  $\gamma_{dem}$  the demanded yaw angle and  $d_{\text{Lidar}}$  the distance to the measurement location.

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

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

For the controller design, the time delay is approximated using the Padé approximation of time delays, see Skogestad and Postlethwaite (2005).

## 5 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, 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.

### 10 6.2.1 Controller

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

$$u = K_p \left( \Delta y_L + \frac{1}{T_i} \int \Delta y_L dt \right), \quad (18)$$

with the proportional gain  $K_p$  and the time constant  $T_i$ .

### 15 6.2.2 Filter

The wake propagation and the caused delay   a direct   of a yaw change and because of that one has to filter the measured feedback to prevent non-observable yaw actions. Since the delay  $\tau$  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

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

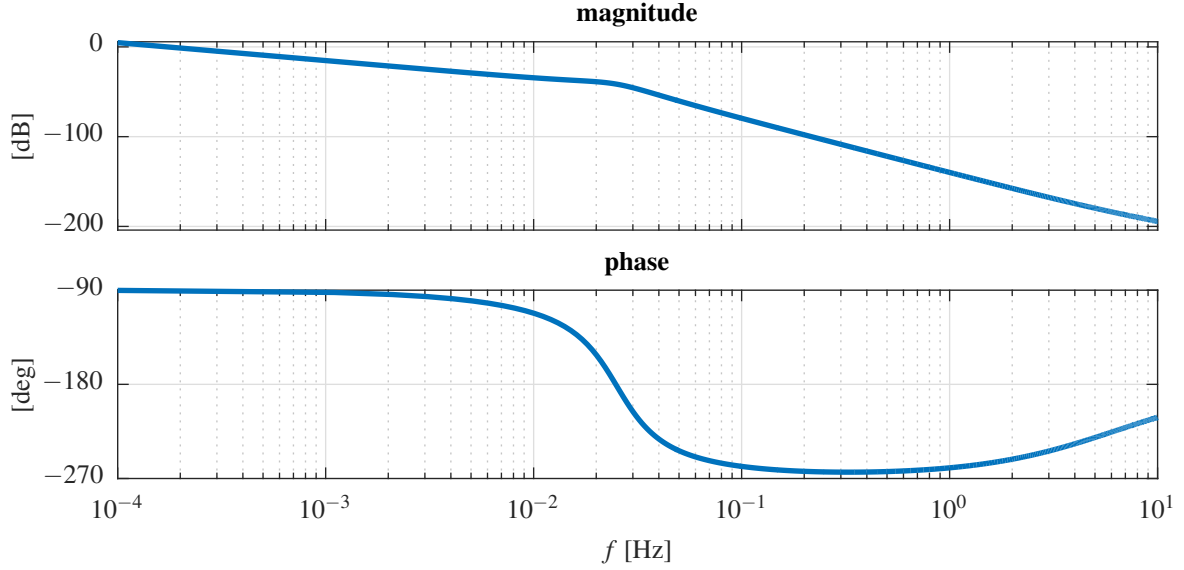
### 6.3.1 Controller analysis

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  $\tilde{\Psi}$ , the time delay approximation  $W$  and the filter  $F$ . Having merged all parts the

25 wake controller  $K$  is

$$K = \frac{F}{(1 + C \Psi (1 - F W))}. \quad (19)$$

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



**Figure 12.** Bode analysis of the designed controller  $K$ .

### 6.3.2 Closed-loop analysis

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

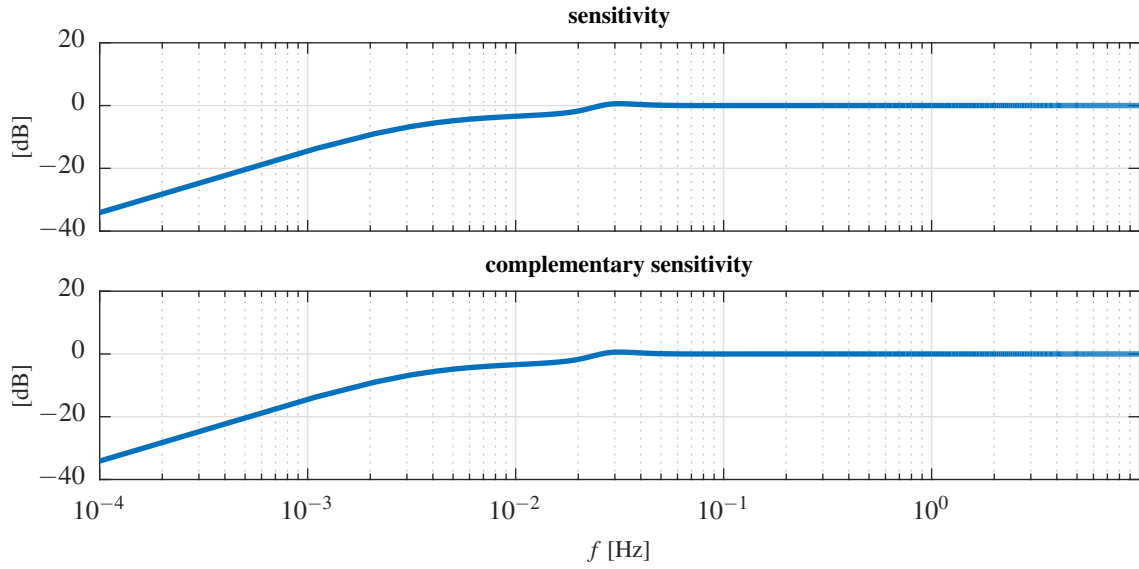
$$S = \frac{1}{1 + GK} \quad (20)$$

$$T = \frac{GK}{1 + GK}, \quad (21)$$

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

## 7 Conclusions

10 This paper introduces first a method which uses lidar measurements to estimate wind field parameters and 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. 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



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

appropriate controller is designed to meet the desired requirements. This enables the next step towards a closed-loop wake in a high fidelity simulation tool

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 robust controllers will be investigated. 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.

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