Three Dimensional Dynamic Model Based Wind Field Reconstruction from Lidar Data

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Abstract. Using the inflowing horizontal and vertical wind shears for individual pitch controller is a promising method if blade bending measurements are not available. Due to the limited information provided by a lidar system the reconstruction of shears in real-time is a challenging task especially for the horizontal shear in the presence of changing wind direction. The internal model principle has shown to be a promising approach to estimate the shears and directions in 10 minutes averages with real measurement data. The static model based wind vector field reconstruction is extended in this work taking into account a dynamic reconstruction model based on Taylor’s Frozen Turbulence Hypothesis. The presented method provides time series over several seconds of the wind speed, shears and direction, which can be directly used in advanced optimal preview control. Therefore, this work is an important step towards the application of preview individual blade pitch control under realistic wind conditions.

The method is tested using a turbulent wind field and a detailed lidar simulator. For the simulation, the turbulent wind field structure is flowing towards the lidar system and is continuously misaligned with respect to the horizontal axis of the wind turbine. Taylor’s Frozen Turbulence Hypothesis is taken into account to model the wind evolution. For the reconstruction, the structure is discretized into several stages where each stage is reduced to an effective wind speed, superposed with a linear horizontal and vertical wind shear. Previous lidar measurements are shifted using again Taylor’s Hypothesis. The wind field reconstruction problem is then formulated as a nonlinear optimization problem, which minimizes the residual between the assumed wind model and the lidar measurements to obtain the misalignment angle and the effective wind speed and the wind shears for each stage. This method shows good results in reconstructing the wind characteristics of a three dimensional turbulent wind field in real-time, scanned by a lidar system with an optimized trajectory.

1. Introduction
In recent years lidar (Light-Detection-And-Ranging) technology has found its way into wind energy. A lot of research has been done in the field of lidar-assisted control of wind turbines for load reduction, decreasing rotor speed deviation, or increasing power production, see [1], [2], [3], [4], and was successfully tested in a field test, see [5], [6]. Lidar measurement technology is being continuously developed and nowadays, there are several devices for measuring the wind speed. To open the possibility for advanced control techniques which take wind characteristics into account, a reconstruction of the inflowing wind field is necessary to not only calculate the effective wind speed, but also linear wind shears and misalignment. For using predictive control techniques they have to be available in high resolution to take them into account, e.g. [7], [8] and [9]. Besides, for developing individual pitch feed forward controllers, a correct reconstruction of the shears is important.

This contribution presents an enhancement to [10] based on the idea presented in [11]. A dynamic nonlinear model is introduced which is used to reconstruct the wind field characteristics. Further, an
algorithm is introduced and an evaluation of the reconstruction algorithm is given. The method is tested in a simulation environment where a wind field structure is three-dimensionally scanned with a lidar.

The paper is arranged as follows: First, in Section 2 the wind field reconstruction problem is described. In Section 3, the simulation model and the reconstruction model are presented. Then, in Section 4 the reconstruction algorithm is introduced and the reconstruction results are presented in Section 5. Finally, a conclusion and an outlook is given in Section 6.

2. Problem Formulation

Although basic wind reconstruction can be done using only one fixed coordinate system, it is beneficial to consider a wind coordinate system for reconstruction methods. The inertial frame coordinate system, which is denoted by the subscript $I$, is used as the frame of reference. The wind field reconstruction methods aim to provide information about the wind within the $I$-system. The wind coordinate system is defined relative to the $I$-system and is denoted by the subscript $W$. It is used to describe the wind flow and is aligned with the mean wind direction regarding the $I$-system. The direction is defined by the horizontal misalignment angle $\alpha_H$ (azimuth or rotation around the $z$-axis) and the vertical misalignment angle $\alpha_V$ (elevation or rotation around the rotated $y$-axis), see Figure 1. The origin of the $W$-system is assumed to be at the origin of the $I$-system but can be set to any other position. Then, the transformation from the $W$-system into the $I$-system can be expressed by the rotational transformation

$$ T = T_{AZ} \cdot T_{EL} = \begin{bmatrix} \cos \alpha_H & -\sin \alpha_H & 0 \\ \sin \alpha_H & \cos \alpha_H & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos \alpha_V & 0 & \sin \alpha_V \\ 0 & 1 & 0 \\ -\sin \alpha_V & 0 & \cos \alpha_V \end{bmatrix}. $$

(1)

Coordinates in the $W$-system are transformed in the $I$-system by

$$ \begin{bmatrix} x_I \\ y_I \\ z_I \end{bmatrix} = T \begin{bmatrix} x_W \\ y_W \\ z_W \end{bmatrix}. $$

(2)

It is not possible to measure a three-dimensional wind vector with a single nacelle or spinner mounted lidar system utilizing only the line-of-sight wind speed. However, assumptions can be used to obtain an estimation, e.g.

(i) no vertical and no horizontal wind component
With the second assumption (and the wind vectors can be individually calculated by:

\[ v_{\text{los},1} = \frac{x_{1,i}}{f_i} u_{1,i} \quad \text{and} \quad v_{\text{los},2} = \frac{x_{2,i}}{f_2} u_{2,i} \] (4)

and the wind vectors can be individually calculated by:

\[
\begin{bmatrix}
  u_{1,i} \\
v_{1,i} \\
w_{1,i}
\end{bmatrix} = \begin{bmatrix}
  \frac{f_i}{n_1} v_{\text{los},1} \\
  0 \\
  0
\end{bmatrix}
\quad \text{and} \quad
\begin{bmatrix}
  u_{2,i} \\
v_{2,i} \\
w_{2,i}
\end{bmatrix} = \begin{bmatrix}
  \frac{f_i}{n_2} v_{\text{los},2} \\
  0 \\
  0
\end{bmatrix}.
\] (5)

With the second assumption \( (u_{1,i} = u_{2,i} = u, v_{1,i} = v_{2,i} = v \text{ and } w_{1,i} = 0) \) the longitudinal and lateral wind component can then be calculated using Equation (3):

\[
\begin{bmatrix}
  u \\
v
\end{bmatrix} = A^{-1} \begin{bmatrix}
  v_{\text{los},1} \\
v_{\text{los},2}
\end{bmatrix}
\quad \text{with} \quad
\begin{bmatrix}
  v_{\text{los},1} \\
v_{\text{los},2}
\end{bmatrix} = \begin{bmatrix}
  \frac{x_{1,i}}{f_1} & \frac{y_{1,i}}{f_1} & \frac{z_{1,i}}{f_1} \\
  \frac{x_{2,i}}{f_2} & \frac{y_{2,i}}{f_2} & \frac{z_{2,i}}{f_2}
\end{bmatrix} \begin{bmatrix}
  u \\
v
\end{bmatrix}. \] (6)

A dilemma ("Cyclops Dilemma") exists, if the lidar is used for yaw and cyclic pitch control at the same time: If the first assumption is used to calculate the horizontal wind shear, perfect alignment is assumed. If the second assumption is used to obtain the misalignment, homogeneous flow is assumed. To overcome this dilemma the model has to be adjusted to cover the following wind field characteristics: effective wind speed, horizontal and vertical linear shear, and misalignment. This work offers a possible solution to this problem.

3. Modeling the Systems - Wind Field and Lidar Measurement

In the following section, first the wind field model and the lidar model used for simulation are presented. Then, the simplified wind field model and lidar model are described. These are used for reconstructing the wind characteristics.

3.1. Wind Field Model for Simulation

The wind field structure used for simulation is a vector field flowing towards the lidar. However, a large eddy simulation model would be more realistic, because it can consider wind evolution models based on Navier-Stokes equations. In this studies assumptions, which are also made for aero-elastic simulation, are used. We assume that Taylor’s Frozen Hypothesis (see [12]) holds and that the wind field is flowing with mean wind speed in wind direction. With respect to the inertial coordinate system, the wind field structure is continuously yawed and pitched. In Figure 1 the model of the wind field structure is depicted. In the following section, the lidar model is presented. This model is used for the simulation to obtain line-of-sight lidar data from the wind field structure.
3.2. Lidar Model for Simulation

To obtain lidar data the wind field which is subject to reconstruction is scanned three-dimensionally with the lidar simulator presented in [13]. The line-of-sight wind speed $v_{\text{los}, i}$ measured at a point $[x_{i,i}, y_{i,i}, z_{i,i}]^T$ with focus distance $f_i = \sqrt{x_{i,i}^2 + y_{i,i}^2 + z_{i,i}^2}$ is obtained by the equation

$$v_{\text{los}, i} = \frac{1}{f_i} \int_{-\infty}^{\infty} (x_{i,j}u_{a,j} + y_{i,j}v_{a,j} + z_{i,j}w_{a,j}) f_L(a) \, da.$$  \hspace{1cm} (7)

The weighting function $f_L(a)$ at the distance $a$ to the focus point depends on the used lidar technology (pulsed or continuous wave). Here, following the considerations of [14], a normalized Gaussian shape weighting function representing a pulsed lidar with a full width at half maximum of 30m is used. Further, the wind vector $[u_{a,i}, v_{a,i}, w_{a,i}]^T$ is an evaluation of the wind field at:

$$[x_{a,i}, y_{a,i}, z_{a,i}] = [x_{i,i}, y_{i,i}, z_{i,i}] + \frac{a}{f_i} [x_{i,i}, y_{i,i}, z_{i,i}].$$  \hspace{1cm} (8)

The simulation algorithm can be stated as follows:

(i) At time $t_i$: Transform the lidar measurement coordinates in the wind coordinate system using the actual misalignment angles $\theta_V(t_i)$ and $\theta_H(t_i)$.

(ii) Shift the wind field structure using Taylor’s Frozen Turbulence Hypothesis.

(iii) Evaluate the lidar measurement equation in the three-dimensional wind field structure.

(iv) Return the obtained line-of-sight wind speed $v_{\text{los}, i}$.

3.3. Wind Field Model for Reconstruction

Simplifications and assumptions are made to obtain a wind field model which is used for reconstruction. We want to describe the wind field with the following characteristics: effective wind speed, horizontal and vertical linear shear, and the misalignment angle. For this reason, we assume that the wind field
Figure 3: Reduced multi-stage wind field model. The wind field model consists of three stages with different effective wind speeds, linear vertical and horizontal shears and is rotated with $\alpha_H$ and $\alpha_V$ around the horizontal and vertical axis, respectively.

structure to be discretized into several stages, only has a longitudinal wind component $u_W$. The wind component $u_W$ consists of an effective wind speed, a horizontal and a vertical linear shear. Further, the wind field structure is yawed and pitched with respect to the inertial coordinate system. To cope with the dynamic behavior of the wind, Taylor’s Frozen Turbulence Hypothesis is taken into account. Using this assumption the actual position of a wind speed measurement is

$$x_{i,W,\text{shifted}} = x_{i,W} + \Delta x = x_{i,W} + v_{\text{mean}} \Delta t,$$

where $v_{\text{mean}}$ is the mean wind speed and $\Delta t$ is the time difference between the $i$-th measurement and the reconstruction. Here, other dynamic models can be used in further research. For a circular lidar scan trajectory this leads to a helix, which can be seen in Figure 4. The wind speed at a defined point $[x_{i,W}, y_{i,W}, z_{i,W}]$ in the wind field at time $t_i$ is then defined in the wind field coordinate system by

$$\begin{bmatrix} u_{i,W} \\ v_{i,W} \\ w_{i,W} \end{bmatrix} = \begin{bmatrix} v_{0,j} + \delta_{H,j} y_{i,W} + \delta_{V,j} z_{i,W} \\ 0 \\ 0 \end{bmatrix}, \quad j \text{ such that } x_{j,W} \leq x_{i,W,\text{shifted}} < x_{j+1,W},$$

where $v_{0,j}$ is the effective wind speed and $\delta_{H,j}$ and $\delta_{V,j}$ the horizontal and vertical wind shear, respectively, at stage $j$ (see [1], [10]). To obtain the wind field with respect to the inertial coordinates the coordinate transformation (1) is applied. Figure 3 shows the wind field model which is used for reconstruction with three stages, including three effective wind speeds, horizontal and vertical linear shears, respectively.

3.4. Lidar Model for Reconstruction

As already pointed out in Equation (3) the lidar measurements can be modeled by a point measurement in the wind field. Then, the wind vector is projected onto the normalized laser vector with the focus distance $f_i = \frac{x_{i,j}^2 + y_{i,j}^2 + z_{i,j}^2}{f_i}$. In the inertial coordinate system this yields

$$v_{\text{los},i,j} = \frac{1}{f_i} \left(x_{i,j} u_{i,j} + y_{i,j} v_{i,j} + z_{i,j} w_{i,j}\right).$$

In the following section the wind field reconstruction algorithm is presented and described in detail.
Figure 4: How past measurements are moved in time according to Taylor.

| Parameters of the scanned pattern used for reconstruction: |
|-----------------------------------------------------------|
| max distance | 70m       |
| min distance | 14m       |
| half opening angle | 45°  |
| number of measurement distances | 5         |
| number of points | 30        |
| time for one full scan | 1 s       |

Table 1: Trajectory parameters.

4. Wind Field Reconstruction Algorithm

The presented wind field reconstruction method was inspired by the internal model principle, [15]. The basic idea is to use a model to obtain the best estimation of the desired unknown inputs of the model. This is done by minimizing the error between measurements and the predicted output. For linear cases this can be done using the inverse matrix for a quadratic problem and using the pseudoinverse for non quadratic problems. In our reconstruction case the complete model is a set of nonlinear equations which can be solved numerically using least-square techniques. With the wind field model described in Section 3.3 and the lidar measurement model of Section 3.4, the internal model for the estimation is given. Inserting the wind model (10) in the lidar measurement equation (11) yields in the $W$-system

$$\hat{v}_{los,i} = \frac{1}{f_i}(x_{i,W} u_i,W)$$  \hspace{1cm} (12)

for the associated stage $j$.

Thus, the reconstruction problem can be written as

$$\min_s \sum_i^m K_i \left( v_{los,i} - \hat{v}_{los,i}(s,x_{i,I},y_{i,I},z_{i,I}) \right)^2,$$  \hspace{1cm} (13)

where $m$ measurements are considered for the reconstruction and $\hat{v}_{los,i}(s,x_{i,I},y_{i,I},z_{i,I})$ is the adequate estimation at the desired lidar measurement position. $[x_{i,I},y_{i,I},z_{i,I}]$ at time $t_i$. In $s = [v_{0,1,...,n}, \delta v_{1,1,...,n}, \delta H_{1,1,...,n}, \alpha_H, \alpha_V]$ the estimated wind field characteristic are concatenated, where $n$ is the number of reconstruction stages. With $K_i$ a possibility for either weighting measurements to cope with wind evolution or weighting them with respect to their information quality and importance for the reconstruction, as outlined in [16], is given. Here, $K_i = 1$ is used to weight all measurements equally.

The full wind field reconstruction algorithm can be stated as follows:

(i) At time $t_i$: Concatenate all lidar measurements with the associated measurement position and time information.

(ii) Apply Taylor’s Frozen Turbulence Hypothesis to the measurements.

(iii) Use the shifted positions to extract the relevant measurements, meaning $x_{i,W,\text{shifted}} \leq x_{W,\text{min}}$.

(iv) Solve the nonlinear set of equations as described in (13).

In the following section the reconstruction method is evaluated and reconstructed results are presented.
5. Reconstruction Results
In the first part, the lidar trajectory is described and the basic conditions for the simulation are stated. Then, reconstruction results are presented. The results of a reconstruction with a hub-height wind field are shown to demonstrate the applicability of the reconstruction concept. Second, a reconstruction of a turbulent wind field is presented and the robustness is discussed. To show the necessity of an adequate wind field model, the results are compared to the static linear wind field reconstruction method which assumes perfect alignment, $\alpha_{HH} = 0^\circ$. The method is presented and described in [10].

5.1. Simulation Environment
The trajectory which is used for scanning the wind field to obtain lidar measurements is a circular trajectory with five measurement distances, a half opening angle of $45^\circ$ and a maximum distance of 70 m. An overview of all trajectory parameters is given in Table 1. Although this trajectory is not applicable to current scanning lidar devices, these results present possibilities of wind field reconstruction and try to motivate further development of lidar devices. In the following case studies, the wind field changes its horizontal misalignment $\alpha_H$ between $\pm 10^\circ$. The vertical misalignment is set to $\alpha_V = 0^\circ$ in simulation and reconstruction.

5.2. Hub-height Wind Field Model Reconstruction
To demonstrate the functionality of the idea of the dynamic model based wind field reconstruction, a so called hub-height wind field is used, see [17]. Therefore, the effective wind speed and the horizontal and vertical linear shears are extracted from a turbulent Class C IEC Kaimal wind field with mean wind speed $v_{mean} = 16\ m/s$ and a turbulence intensity of 13% created with TurbSim, [17]. Then, they are condensed to a hub-height wind field with

$$u_{t,W}(t_i) = v_{0,HH}(t_i) + \delta_{H,HH}(t_i)y_{t,W} + \delta_{V,HH}(t_i)z_{t,W}, \quad (14)$$

where $v_{t,W} = 0$ and $w_{t,W} = 0$ for any grid point $[y_{t,W}, z_{t,W}]$ at time $t_i$. The effective wind speed $v_{0,HH}(t_i)$ and the horizontal and vertical linear shears $\delta_{H,HH}(t_i)$ and $\delta_{V,HH}(t_i)$ are obtained by solving the linear least-square problem

$$\min_s \left( m - As \right)$$

with

$$\begin{bmatrix} u_{W1} \\ \vdots \\ u_{Wn} \end{bmatrix} = \begin{bmatrix} 1 & y_{1,W} & z_{1,W} \\ \vdots \\ 1 & y_{n,W} & z_{n,W} \end{bmatrix} \begin{bmatrix} v_{0,HH}(t_i) \\ \delta_{H,HH}(t_i) \\ \delta_{V,HH}(t_i) \end{bmatrix} \quad (15)$$

for $n$ grid points across the rotor disk at time $t_i$. The misalignment changes continuously with

$$\alpha_H(t) = \alpha_{max} \sin(\omega_{\alpha}t) \quad (16)$$

where $\alpha_{max} = 10^\circ$ and $\omega_{\alpha} = \frac{2\pi}{600}$. The obtained wind field is then scanned with the lidar simulator to obtain the lidar measurement data. The reconstruction is shown in Figure 5. It is executed every second because of the chosen trajectory time $T_{scan} = 1s$. A very good correlation is achieved. However, because of the simplification made in the lidar measurement model for reconstruction in Equation (12) compared to the measurement principle of the lidar simulator in Equation (7) and the differences in the wind models, a perfect estimation is not possible. While for the simulation the wind field is continuously yawing, the misalignment angle is assumed to be constant in reconstruction.

5.3. Turbulent Wind Field Reconstruction
Having demonstrated the reconstruction method in a hub-height case, a turbulent Class C IEC Kaimal wind field with mean wind speed $v_{mean} = 16\ m/s$ and a turbulence intensity of 13% is now considered in
Figure 5: Reconstruction results for the nominal case, where a hub-height wind field is scanned with a simulated lidar system. The trajectory and the setting for the reconstruction is described in Table 1.

Figure 6: Reconstruction results for the realistic turbulent case, where a turbulent wind field is scanned with a simulated lidar system. The trajectory and the setting for the reconstruction is described in Table 1.
order to test the performance under more realistic conditions. The turbulent wind field is continuously yawing as described in (16). After having scanned the wind field with the lidar simulator the reconstruction is performed. The reconstruction result is shown in Figure 6. Furthermore, to evaluate the new reconstruction method, the linear method is also depicted in Figure 6. One can see the influence of the misalignment on the horizontal linear shear and thus the error which occurs by assuming perfect alignment in the linear method. Considering the coherence analysis presented in Figure 7 the reconstruction of the horizontal linear shear is heavily improved. Furthermore, the reconstruction of the vertical linear shear is also improved. The effective wind speed and the vertical shear are reconstructed well up to a frequency of 0.2 Hz (50%). Whereas the horizontal shear and the horizontal misalignment angle are reconstructed well up to 0.008 Hz and 0.012 Hz, respectively.

### 6. Conclusion and Outlook

An improved method to reconstruct effective wind speed, horizontal and vertical linear shear, and the misalignment angle out of lidar measurements is presented. The method is evaluated using a detailed lidar simulator, scanning in a three-dimensional wind field structure, which is flowing towards the turbine using Taylor’s Frozen Turbulence Hypothesis and with an continuously changing horizontal misalignment. The presented method reduces the wind field structure to the wind characteristics effective wind speed, horizontal and vertical linear shear, and horizontal misalignment. The wind characteristics are then reconstructed using the internal model principle. The reconstruction shows promising results at a low turbulence level, although the horizontal shear and the misalignment are reconstructed with less accuracy than the effective wind speed and the vertical shear. Further, a deeper investigation is necessary to analyze the influence of the reconstruction method, lidar measurements and chosen reconstruction parameter on the coherence and the reconstruction quality. However, the dynamic nonlinear model improves the reconstruction result considerably compared to the static linear model.

As a next step, a robustification of the least-square solution would help to cope with uncertainties in measurements and higher local turbulence. Uncertainties introduced by the wind evolution can be directly weighted according to wind evolution models. Furthermore, the analytic correlation model for lidar systems and wind turbines (see [16]) can be enhanced to obtain the coherences for horizontal and vertical linear shear and the misalignment angle. Further, the method can be applied to real lidar measurement data or to lidar measurement data obtained by a large eddy simulation.
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