Lidar-Assisted Feedforward Individual Pitch Control to Compensate Wind Shear and Yawed Inflow

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Abstract. Lidar-assisted individual pitch control (IPC) has been investigated occasionally in recent years, focusing on the compensation of (vertical) wind shear as the main disturbance. Since yawed inflow might cause significant load fluctuations too, it is worth to compensate. Load patterns caused by yawed inflow significantly differ from those caused by wind shear, requiring a more sophisticated control algorithm. In this paper a lidar-assisted cyclic pitch feedforward control to compensate wind shear and yawed inflow is presented. The main objective is the analysis of the load patterns through a simplified aerodynamic model, which among other things focuses on a reasonable representation of the skewed wake effect. Establishing a suitable structure of the feedforward controller follows. The paper concludes with a comparison of fatigue load reductions achieved by three different controllers. Firstly, a well-known feedback individual pitch control; secondly, a feedforward controller for pure wind shear compensation and thirdly, this new feedforward controller to compensate wind shear and yawed inflow. The last two controllers use ideal lidar measurement chains.

1. Introduction

Individual pitch control (IPC) for load reduction has been discussed for almost two decades [1]. There are different approaches for feedback IPC controllers such as decentralized [2] or multivariable [3] control design. Field tests already have proven the effectiveness of load reduction [4]. However, the disadvantage of feedback IPC controllers is that changes of the asymmetric wind field are considered with delay, since the feedback is only reacting to impacts on the turbine dynamics after these impacts have already occurred. Therefore, lidar-assisted individual pitch control has been investigated occasionally in recent years [5–9].

Previous lidar-assisted feedforward approaches focus on the compensation of the wind shear, with vertical shear as the main reason for periodic load fluctuations on the rotor in normal operation. The supervisory control avoids high mean levels of (horizontal) yawed inflow by tracking the nacelle direction. Nevertheless dynamic changes are inevitable and even deviations of several degrees from the mean value are tolerated to avoid excessive loads of the azimuth drives. This causes significant load fluctuations too and is worth to compensate next to wind shear. Characteristic fluctuations of the blade loads per period (load patterns) caused by yawed inflow significantly differ from those caused by wind shear, requiring a more sophisticated control algorithm (contrary to [9]).

In this paper a lidar-assisted cyclic pitch feedforward control to compensate wind shear and yawed inflow both in horizontal and vertical direction is presented. In contrast to [8] no IPC feedback controller is added to the lidar-assisted feedforward controllers. Both IPC strategies need additional sensors in unequal price categories. For future industrial application a head-to-head comparison of
both strategies regarding their load reduction potential is of interest to evaluate whether the investment in a lidar system is worth its more expensive price.

Main objective of the paper is the analysis of the load patterns caused by shear and yawed inflow through a simplified aerodynamic model, which focuses among other things on a reasonable representation of the skewed wake effect. It is followed by establishing a suitable structure of the feedforward controller and the presentation of the ideal lidar measurement chain. The paper concludes with a comparison of fatigue load reductions for a Senvion 3 MW turbine achieved by three different controllers. Firstly, a well-known feedback individual pitch control compensating fluctuations one per rotation. Secondly, an already presented feedforward controller for pure wind shear compensation [9] and thirdly, this new feedforward controller to compensate wind shear and yawed inflow. Ideal lidar measurement chains are applied for both feedforward controllers.

2. Cyclic Pitch Feedforward Control
The inhomogeneous wind field is characterized by a horizontal mean wind speed \( \bar{v}_0 \) and four additional variables. The linear horizontal wind shear \( \delta_h \), the vertical wind shear \( \delta_v \), the horizontal inflow angle \( \alpha_h \) and vertical inflow angle \( \alpha_v \) as averages over the rotor or measuring area. A static compensation of both horizontal and vertical shear and yawed inflow effects by cyclic individual pitch is considered in this work.

In this section the simplified model of the turbine aerodynamics as a basis of the compensation design is first addressed. The description focuses on the modelling of the skewed wake effect, which is essential for considerations at yawed inflow. The analysis of load patterns caused by shear and yawed inflow follows, proceeding with a discussion about effects of full-span pitch control on the resulting blade root loads and local blade loads. The section ends with a description of the feedforward controller structure.

2.1. The simplified model
The design of the controller is model based and the Blade Element Momentum (BEM) theory is the basis of the simplified model. Influences of the blade structure as well as shaft tilt and rotor cone are neglected and the model is only limited to significant effects for static considerations

- Axial induction, correction of high values according to Spera in [10]
- Blade tip losses according to Prantl in [10]
- Skewed wake effect acc. to Glauert and Pitt & Peters [11] with a reduced scaling of 0.3 \( K \).

For the compensation of the yawed inflow a correct modelling of the skewed wake effect is essential. Yawed inflow – either horizontal or vertical – produces a skewed wake with angle \( \chi \) behind the rotor, which influences the wind conditions in the rotor area, e.g. the induction factor \( a \) according to the rotor azimuth angle \( \psi \). A basic formulation of the induction factor correction in each blade segment with relative radius \( \frac{r}{R} \) for the BEM theory was formulated by Glauert in 1926 for the autogyro. The correction is proportional to the basic induction \( a \). Thus, there is a large effect at high induction in partial load operation and a minor in full load operation. The scaling factor \( K \) by Pitt and Peters in 1981 fits well with helicopter experiments [12] and was adapted for complex wind turbine models using BEM such as FAST [13]

\[
a_{\text{skew}} = a \left[ 1 + K \left( \tan \frac{\chi_h}{2} \sin \psi + \tan \frac{\chi_v}{2} \cos \psi \right) \right] \quad \text{with} \quad K = \frac{15\pi \, r}{32 \, R}.
\]

The scaling of the effect is disputed, but has a big impact on the load pattern as shown in Figure 1. A bigger scaling factor leads to a bigger load fluctuation and a bigger phase shift of the maximum load.
Measurements of the skewed wake effect are rare and it is difficult to evaluate the effect exactly. A comparison with FAST, not using BEM theories but the advanced Generalized Wake Model, suggest a scaling around 0.5 $K$. Field tests on small turbines by Eggers et al. [14] in 2000 recommend a reduced scaling of 0.5 $K$ or even smaller. These studies confirm the results of measurements performed by the authors. Blade loads of a 3 MW Senvion wind turbine in extreme yawed inflow were logged in partial load operation, where the induction and the skewed wake effect are large. It indicates a scaling factor of 0.3 $K$, which is implemented in the simplified model subsequently. Compared with equation 1 or FAST using BEM theories, the impact of the skewed wake effect on the load patterns is significantly smaller.

![Figure 1: Relative out-of-plane moment at the blade root $M_y/M_{y,max}$ over rotor azimuth angle $\psi$ with different scaling of the skewed wake effect at $v_0 = 8$ m/s, $a_h = 10$ deg and no wind shear.](image)

A successful implementation of the feedforward controller requires a proper representation of the load fluctuations (amplitude and phase relation) caused by the four wind field variables in full load operation by the simplified model. The model is verified successfully with Senvion’s version of the simulation tool Flex5, originally developed by Stig Øye. Flex5 uses BEM theory including dynamic inflow for the aerodynamic calculation. Simulating a reduced model with stiff structure, no shaft tilt and blade cone angle and no tower shadow in Flex5, the blade loads of both models match very well in quality and quantity. Although the skewed wake effect in Flex5 is not modelled according to equation 1, it shows the same minor impact and fits quite well to the reduced scaling of 0.3 $K$. Comparing the simplified model to Flex5 with default settings, there are some deviations in the load fluctuations. Main reasons are the shaft tilt – which could be taken into account as vertical yawed inflow by the compensation –, blade deflection and tower shadow. The impacts decrease with increasing wind velocity. Thus, the accordance is adequate for full load operation.

2.2. Analysis of load patterns

To avoid energy losses and an extreme increase of pitch activity, the controller is only active in full load operation and load patterns are only analyzed here. Figure 2 shows examples of load patterns for two variables of the wind field, vertical wind shear and horizontal yawed inflow. Steady conditions are assumed at each blade angle. At vertical wind shear (a) the maximum moment always appears at 0°, when the blade is up. The amplitude of the load fluctuations is almost the same for all wind speeds. In contrast, at horizontal yawed inflow the maximum moment appears around 180° at 12 m/s near rated wind speed, disappears around 16 m/s and has a reversed sign at high wind speeds.
Figure 2: Load patterns of the out-of-plane moment at the blade root $M_y$ over rotor azimuth angle $\psi$ in full load operation, relative to the maximum moment in Figure 2a.

a) Linear vertical shear of 0.0415 1/s.  
b) Horizontal yawed inflow of 10 deg.

Figure 3 provides an explanation for this phenomenon. The angle of attack $\alpha$, the resulting velocity $v_{res}$ at the rotor plane and the lift coefficient $c_l$ at a certain point in the last third of the blade – representing the most efficient part of the blade – are plotted over the rotor azimuth angle $\psi$. Contrary to shear conditions (not depicted), the angle of attack and the resulting velocity run opposed. At low wind speeds the angle of attack and the lift coefficient only change slightly. As a consequence, the changes of the resulting velocity dominate the out-of-plane moment, depicted in Figure 2b, with $M_y \sim v_{res}^2 c_l$. At higher wind speeds the angle of attack and the lift coefficient change more significantly, now dominating $M_y$.

Figure 3: Angle of attack $\alpha$, resulting velocity $v_{res}$ and lift coefficient $c_l$ over rotor azimuth angle $\psi$ at a certain point in the last third of the blade at horizontal yawed inflow of 10 deg in full load operation.

A closer look at Figure 2a visualizes the influence of the skewed wake effect. There is a phase shift of the maximum moment from expected 180° to 190° for 12 m/s. At higher wind speeds and related lower induction the influence is very low.

The load patterns for horizontal wind shear and vertical yawed inflow are shifted by 90° in each case.
2.3. Effect of full-span pitch control on blade root and local blade loads

Full-span pitch control is state of the art and is considered in this study. Obviously, it allows a compensation of the resulting moments at the blade root. Beyond that it is interesting how the loads in each blade segment are influenced.

In Figure 4 the out-of-plane moment $\Delta M_y$ for each 1 m blade segment over the blade radius is depicted for linear vertical shear (a) and horizontal yawed inflow (b) at $v_0 = 20$ m/s. At rotor azimuth angle $\psi = 90^\circ$ the blade is not influenced by both mentioned wind field variables referred to as reference load case. The blade loads increase and decrease mostly when the blade is up at $0^\circ$ and down at $180^\circ$. With individual full-span pitch control (IPC) the blade root load fluctuations are compensated ideally. It is interesting to notice that full-span pitch control also compensates the segmental fluctuations when wind shear occurs. In case of yawed inflow the segmental blade loads do not meet the reference load case exactly. Here, either a compensation of blade root fluctuations or segmental fluctuations by choosing another suitable IPC feedforward control-law are possible. Probably, future segmental-span pitch control will meet the requirement of the resulting blade root and local blade load reduction.

![Figure 4: Segmental out-of-plane moment $\Delta M_y$ relative to the max. segmental moment in Figure 4a over relative blade radius $r/R$, $v_0 = 20$ m/s, no and ideal compensation (IPC) of the blade root fluctuations at $\psi = 0$ deg and $\psi = 180$ deg as an example of extreme conditions.

a) Linear vertical shear of $\delta_v = 0.0415$ 1/s. b) Horizontal yawed inflow of $\alpha_h = 10$ deg.]

2.4. Structure of the feedforward control

According to [6] a sinusoidal individual blade angle compensates the fluctuations of $M_y$ for each wind field variable sufficiently: Optimal blade angles $\beta_{\text{opt}}$ for each rotor azimuth angle $\psi$ are determined by stationary simulations. They can be approximated by a cosine function of the azimuth angle, including a phase shift $\Delta \psi$, and a compensation amplitude $a$:

$$\beta_{\text{opt}}(\psi) \approx a \cos(\psi + \Delta \psi).$$

(2)

The compensation amplitude $a$ and the phase shift $\Delta \psi$ are optimized numerically for different $v_0$ and each of the wind field variables. The upper part of Figure 5 depicts a slight (ignorable) dependence of the compensation amplitude on the mean wind speed for wind shear and a strong one for yawed inflow. Furthermore a linear correlation between the magnitude of the wind field variable and the compensation amplitude appears, considered by the coefficients $c_{\text{amp,}v}(v_0)$ and $c_{\text{amp,}\alpha}(v_0)$ in equation 3. The phase shift in the lower part of Figure 5 only depends on the mean wind speed.
Figure 5: Amplitude $a$ and phase shift $\Delta \psi$ according to mean wind velocity $v_0$.

a) Linear vertical shear of $\delta_v = 0.02075 \text{1/s}$.

b) Horizontal yawed inflow of $\alpha_h = 5 \text{deg}$.

Further investigations show an almost linear superposition of load fluctuations caused by a simultaneous occurrence of different wind field characteristics. And, for example, the fluctuations caused by vertical wind shear could be compensated by intentionally yawing of the turbine. The feedforward pitch angles $\beta_{FF,i}$ of the $i$ blades are calculated as follows:

$$
\beta_{FF,i} = \delta_v c_{\text{amp},\delta}(v_0) \cos(\Delta \psi_\delta(v_0) + \psi_i) \\
+ \delta_h c_{\text{amp},\delta}(v_0) \sin(\Delta \psi_\delta(v_0) + \psi_i) \\
+ \alpha_h c_{\text{amp},\delta}(v_0) \cos(\Delta \psi_\alpha(v_0) + \psi_i) \\
+ \alpha_v c_{\text{amp},\delta}(v_0) \sin(\Delta \psi_\alpha(v_0) + \psi_i).
$$

The control structure used is depicted in Figure 6. Since the feedforward IPC is only active in full load operation, its combination with the baseline collective pitch controller is shown. It is important to note that no IPC feedback controller is added to the feedforward controller. The baseline collective pitch controller is only responsible to adjust the generator speed $\omega_g$ (output $y$) to the reference generator speed $\omega_{g,\text{ref}}$ (set point $w$). The turbine and its output $y$ are influenced in two different ways. The overall blade angles (control input $u$) act via the reference transfer function $G(s)$ and the inhomogeneous wind field (disturbance $d$) acts via the disturbance transfer function $G_{d}(s)$. The aim of the feedforward controller is to compensate the disturbance as good as possible — so strictly speaking it is not a feedforward control but a disturbance compensation.

Figure 6: Structure of the feedforward control loop.
In this study an ideal lidar measurement chain is considered. The measurement chain gets the full wind field information with any look-ahead time $T$ and all wind field variables are calculated as described in the following section 3. Based on these variables the static feedforward controller calculates the feedforward pitch angles $\beta_{FF,1}$, $\beta_{FF,2}$ and $\beta_{FF,3}$ using equation 3. There is no collective pitch feedforward control as the mean wind speed $v_0$ is only used to scale the feedforward controller. Afterwards the feedforward pitch angles are delayed by $t < T$. $t$ takes the prediction time and pitch dynamics into account in such a way, that the pitch moves early enough to overcome pitch dynamics. Finally the feedforward pitch angles are added to the collective pitch signal of the baseline controller.

3. Ideal Lidar Measurement Chain

In this study an ideal lidar measurement chain is considered. The basic benefits of an IPC feedforward controller with combined shear and yawed inflow compensation in contrast to a pure shear compensation are exposed more clearly than with additional measurement noise. Furthermore, working with a real measurement chain in a second step is avoided intentionally. While the wind field reconstruction of the mean wind speed and wind shear are considered in detail and work well under standard conditions (see [6]), both aspects are much more complicated for an extended wind field model including yawed inflow. There are promising approaches for the reconstruction of extended wind fields like [15]. But especially under yawed conditions the error of this estimation is actually too high for a successful application along with the IPC feedforward controller. Further investigations are necessary for an improvement of this reconstruction or an extension of a different approach with good prospects like [16]. Besides this, the lidar scan geometry is crucial to gather proper measurement data for a successful reconstruction. The correlation-model of Stuttgart Wind Energy [17] enables a half-analytic optimization of the scan geometry regarding a reconstruction of the mean wind speeds and wind shear, but it is not extended to yawed inflow up to now.

The ideal measurement chain uses spatial averages of $v_0$, $\delta_h$, $\delta_v$, $\alpha_h$ and $\alpha_v$ directly calculated from the wind field over the rotor area as inputs. To simplify matters and in absence of a suitable model, mean wind velocity and wind shear are calculated separately from yawed inflow, ignoring the mutual influence. Therefore, the calculated values are rather a good reference than real or ideal. The wind field variables $v_0$, $\delta_h$ and $\delta_v$ are derived from the direct inflow or $u$-components of the wind vector at the discrete $y$- and $z$-coordinates given by $n$ grid points of the wind field using the linear model in equation 4 via least square optimization in equation 5.

$$v_{u,j}(y_j, z_j) = v_0 + \delta_h y_j + \delta_v z_j. \quad (4)$$

$$\left(v_0, \delta_u, \delta_v\right) = \arg \min \sum_{j=1}^{n} \left(v_{u,j} - \left(v_0 + \delta_h y_j + \delta_v z_j\right)\right)^2 \quad (5)$$

The yawed inflow is calculated as the arithmetic mean value of all local inflow angles in the wind field spanned by the $u$- and $v$- components for horizontal inflow angle resp. $u$- and $w$- components for the vertical inflow angle.
Figure 7: Time series of the variables for a standard IEC2A wind field with a mean horizontal yawed inflow of 10°, used for the ideal lidar measurement chain.

Figure 7 shows the time series of the variables for a standard IEC2A wind field with a mean horizontal yawed inflow of 10°. It is an example for the wind fields used for the following simulation studies. They are full stochastic wind fields with turbulence intensity of class A. The turbulences create continuous variations of vertical and horizontal wind shear and yawed inflow. A constant vertical wind shear caused by the wind profile with a standard power exponent of 0.2 superimposes the variations. It is represented by a mean linear vertical wind shear of \( \approx 0.04 \, \text{1/s} \) in Figure 7. Besides this, a mean horizontal yawed inflow of 10° is considered, according to the IEC design requirements in [18], where yaw misalignment shall be taken into account in power production.

4. Simulation Results

This new feedforward controller, a feedforward controller for pure wind shear compensation and a feedback individual pitch controller are considered for the load comparison. Similar to [18] the feedback IPC consists of two independent PI-controllers to regulate two orthogonal moments, e.g. tilt and yaw moment, in the fixed coordinate system of the rotor hub. As a consequence thereof, blade load fluctuations once per period (1P) are reduced.

Thus, feedback and feedforward controller both focus only on the compensation of 1P load fluctuations for better comparability. A pitch velocity limitation of \( \pm 8.5°/s \) is implemented for all controllers. Contrary to [8] no IPC feedback controller is added to the lidar-assisted feedforward controllers. Furthermore there is no lidar feedforward collective part included.

Simulations are done in Flex5, which is already mentioned in section 2.1. Standard IEC2A wind fields with a mean horizontal yawed inflow of 10° as described in section 3 and a Senvion 3 MW turbine model with more than 100 m rotor diameter are chosen. Although IPC is only active above rated wind speed, the whole operation region is considered for load evaluation. Damage equivalent loads (DEL) are calculated for theses IEC2A conditions, using three different 10 minute simulations for each mean wind speed.

Figure 8 shows the load reductions for the different control concepts compared to a baseline controller. In contrast to the IPC feedback (B), the feedforward controllers (C, D) have no information about fluctuating loads that are not caused by the wind field, e.g. the rotor imbalance, which is considered in the simulation. Still, the prediction of the wind field (C, D) covers the main part such that substantial loads like flapwise blade root moment (\( M_{\text{flap}} \)), hub center tilt (\( M_{\text{yHC}} \)) and yaw moment
(\(M_{zHC}\)) considerably decrease compared to the feedback controller. Lateral tower base loads (\(M_{xTB}\)) are reduced and longitudinal loads (\(M_{yTB}\)) are increased slightly. The drawback is an increased pitch activity; the weighted mean pitch rate increases from 166 % to almost 200 % with regard to the baseline controller.

An additional compensation of the yawed inflow (C) reduces the blade loads by a few extra percent, while the hub center loads remain unchanged. Lateral tower loads are reduced slightly, the longitudinal tower loads do not change. A slightly reduced pitch activity accompanies the load changes. For the chosen wind conditions with a mean horizontal yawed inflow of 10° the impacts of wind shear and yawed inflow on the blade loads partly compensate each other. The knowledge of all disturbance components avoids unnecessary and wrong pitch activity.

![Figure 8](image.png)

**Figure 8:** Change of DEL for IEC2A, IPC only active in full load operation.

5. Conclusion

In this paper a lidar-assisted cyclic pitch feedforward control to compensate wind shear and yawed inflow in horizontal and vertical direction is presented. The conception of the feedforward controller is based on a simplified aerodynamic model especially taking the skewed wake effect into account. Yawed inflow produces a skewed wake behind the rotor, which influences the wind conditions in the rotor area, e.g. the induction factor \(\alpha\) according to the rotor azimuth angle \(\psi\) and might cause substantial phase shifts of the load patterns. Due to measurements performed by the authors the scaling of the skewed wake effect is reduced to 0.3 \(K\) in contrast to [11] or [13]. Thereby the phase shift in the relevant full load operation is rather small and could be neglected.

Main objective of the paper is the analysis of the load patterns caused by shear and yawed inflow. Contrary to wind shear, load patterns caused by yawed inflow are strongly dependent on the operating point of the turbine. The linear correlation between the wind field variables and amplitude of the compensating sine function and an almost linear superposition of fluctuations caused by different wind field variables allow a simple and practicable implementation of the individual pitch control algorithm. It is interesting to notice that this full-span pitch control not only compensates the load fluctuation at the blade root, but in all segments of the blade when wind shear occurs. Here, either a compensation of blade root fluctuations or segmental fluctuations by choosing another suitable IPC feedforward control-law are possible. Another remarkable side effect bases on the almost linear superposition of the sinusoidal blade load fluctuations caused by different wind field variables. Thus, intentionally yawing of the turbine allows the compensation of vertical wind shear effects alternatively to individual pitch control.
The new feedforward controller is tested on Flex5 simulations with standard IEC2A wind fields with a mean horizontal yawed inflow of 10° and an ideal lidar measurement chain. The study shows some further load reductions of this new controller compared to only shear compensation for a Senvion 3 MW turbine. Compared with the IPC feedback controller both feedforward controllers have decreased substantial loads with the drawback of increased pitch activity in common.

Further studies should address the implementation of a real measurement chain. For this purpose developments of the reconstruction of extended wind field models including yawed inflow and concepts for the optimization of the lidar scan geometry are inevitable.

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