Performance evaluation of a blade-mounted LiDAR with dynamic versus fixed parameters through feedback-feedforward individual pitch and trailing edge flap control

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Abstract. This paper investigates combined feedback-feedforward control of a wind turbine using a blade-mounted telescope LiDAR sensor to measure the inflow wind speed. The objective of this paper is to evaluate the controller performance with fixed telescope parameters compared to the wind speed dependent dynamically changing telescope parameters. First the telescope parameters for both cases are determined, then the robust feedback controllers are extended with an inverse-based feedforward individual pitch and trailing edge flap controller to alleviate the 1P and 2P loads of the flapwise blade root bending moments. A minor performance degradation is observed with the fixed telescope parameters in comparison to the dynamic telescope parameters.

1. Introduction

LiDAR-based control has received significant attention, where mainly a hub or nacelle-mounted LiDAR is used for inflow wind speed measurements. Schlipf and Kühn [1] investigated the use of a nacelle-based LiDAR, where the wind measurement is applied as the input of a non-linear model predictive collective pitch controller. Bossanyi [2] and Kapp [3] applied LiDAR-based inflow wind speed measurement as a feedforward individual pitch control (IPC) input to actively mitigate the once per revolution (1P) frequency component of the flapwise blade root bending moment. They reported only marginal performance improvement with respect to the feedback controller case. To avoid uncertainties introduced by wind evolution, measurements should be taken close to the rotor [4]. However, due to large measurement angles with respect to the rotor axis when measuring close to the rotor using a hub or nacelle mounted LiDAR, a coherence degradation between the blade effective and measured wind speed is observed [4]. Hence, In this paper, a blade-mounted telescope is introduced on each blade, which is connected to a hub-based LiDAR system through fibre optics. This gives the possibility to measure closer to the wind turbine rotor without high measurement angles. Then the inflow wind speed measurement is used as an input of a feedforward individual pitch and trailing edge flap controller. Due to blade flexibility, varying rotor speed, blade pitch angle and wind speed, the optimal setup would
include a telescope on each blade such that the parameters e.g. focus distance, measurement angle can be changed online. A more robust solution for the vibration and lightning prone blade environment is to find fixed telescope parameters through optimisation, which are maintained over the whole operating range of the wind turbine. The objective of this paper is to evaluate the controller performance with fixed telescope parameters compared to the wind speed dependent dynamically changing telescope parameters. Keeping this objective in mind, it is considered reasonable to assume the validity of Taylor’s frozen turbulence hypothesis [5] for the inflow, while later investigations of this concept will take into account the wind evolution e.g. by large eddy simulation of the flow field.

2. Methodology
On each 80 m long blade of a 7.5 MW Type Class IA generic wind turbine [6], with rated wind and rotor speed of 10.9 m s$^{-1}$ and 10 rpm, a blade-mounted telescope and a movable trailing edge flap at the spanwise location of 66.4 m with a spanwise length of 10 m is introduced (Figure 1). Time-domain simulations are carried out for four mean wind speeds of 4, 9, 14, and 19 m s$^{-1}$, where turbulent wind conditions are set in accordance with DLC 1.2 of the IEC 61400-1 ed.3 standard [7] using the high-fidelity aeroelastic simulation code HAWC2 [8]. Wind shear and tower shadow are also taken into account. Two telescope setups are considered: (1) dynamic telescope parameters (DTP), where the parameters can vary in accordance with the wind turbine operating point, and (2) fixed telescope parameters (FTP), where the telescope parameters are fixed during installation for the entire wind turbine operating range. For these two cases, the telescope parameters are determined through optimisations and two corresponding feedforward controllers are also investigated. The feedforward control gains and the optimal time of when to apply the feedforward control signals are analysed for the four chosen wind speeds.

2.1. Blade mounted LiDAR
To determine the optimal setup for the telescope, such as the focus distance, its position along the blade radius, and the orientation of the telescope on the blade, the blade effective wind speed ($u_{\text{eff}}$) is used. It is determined from the contribution of the horizontal wind speed on each blade segment to the flapwise blade root bending moment, where the horizontal wind speed component refers to the longitudinal wind speed in the rotor axis direction. The contribution depends on the radial distance ($r$) and the thrust coefficient ($C_T$) of the blade segment, and it is determined in accordance with Simley and Pao [4].

On each blade, a telescope is mounted which is connected to a hub-based continuous-wave LiDAR with fibre optical cables. The LiDAR samples the inflow wind speed in front of the wind turbine blade at a sampling frequency of 50 Hz. The measurements are used to control the next blade’s flap and pitch angle. The blade-mounted LiDAR simulates the volumetric measurement and takes into account the dynamics of the blade and tower, i.e., displacement, rotation and velocity in 3D space. The velocity induced by the blade rotation is considered in the LiDAR simulator as well. However, the rotational effect of the blade is not accounted for during the accumulation of a single measurement. The blade-mounted LiDAR simulator is implemented into HAWC2, where the coordinate systems and the telescope orientation are demonstrated in Figure 1. The line-of-sight wind speed ($u_{\text{los},i}$), measured on blade $i$, is defined as

$$u_{\text{los},i} = \frac{\int_{a_{\min}}^{a_{\max}} W(F,a) u_{p,i}(a) \, da}{\int_{a_{\min}}^{a_{\max}} W(F,a) \, da} \quad (1)$$
The one point measurement is

\[
    u_{p,i}(a) = \begin{bmatrix} u_{h,i}(a) \\ v_{h,i}(a) \\ w_{h,i}(a) \end{bmatrix} - \begin{bmatrix} \dot{x}_{l,h,i} \\ \dot{y}_{l,h,i} \\ \dot{z}_{l,h,i} \end{bmatrix}^T \begin{bmatrix} -\ell_{x,h,i} \\ -\ell_{y,h,i} \\ -\ell_{z,h,i} \end{bmatrix}
\]

where

\[
    F \text{ is the focus distance, } a \text{ is the range along the beam and } [u_{h,i} \ v_{h,i} \ w_{h,i}]^T \text{ is the wind speed vector along the laser beam expressed in the hub coordinate system.}
\]

The index \( i \) refers to the blade number. The \([\dot{x}_{l,h,i} \ \dot{y}_{l,h,i} \ \dot{z}_{l,h,i}]^T\) is the linear velocity vector of the LiDAR telescope expressed in the hub frame of reference. \([\ell_{x,h,i} \ \ell_{y,h,i} \ \ell_{z,h,i}]^T\) is the normalised vector of the laser beam in the hub coordinate system, and \( W(F, a) \) is the weighting function which is defined in accordance with Simley and Pao [4]

\[
    W(F, a) = \frac{1}{a^2 + \left(1 - \frac{a}{F}\right)^2 R_R^2}
\]

where \( R_R \) is the Rayleigh range. The limits \( a_{\text{min}} \) and \( a_{\text{max}} \), introduced in Equation (1), are the minimum and maximum range along the beam. For practical implementation of the LiDAR simulator, these values are chosen where \( W(F, a) = 0.02 \).

The \( x \)-axis of the hub coordinate system is oriented along the rotor axis and it rotates with the rotor. The high-fidelity aeroelastic simulation tool HAWC2 is capable of providing the full kinematical information, i.e., positions, orientations, linear and angular velocities, of any blade segments in the hub coordinate system. By assuming that the \( v_{h,i} \) and \( w_{h,i} \) components are close to zero, the wind speed parallel to the rotor shaft axis \( (u_{\text{est},i}) \) can be estimated as

\[
    u_{h,\text{est},i} = \frac{u_{\text{los},i} - \dot{y}_{l,h,i} \ell_{y,h,i} - \dot{z}_{l,h,i} \ell_{z,h,i}}{-\ell_{x,h,i}} + \dot{x}_{l,h,i}
\]

In estimating the wind speed, it is assumed that the velocity, displacement, and rotation of the blade segment are known, and therefore the measured line-of-sight wind speed can be corrected.
2.2. LiDAR setup optimisation

The estimated wind speed parallel to the rotor shaft axis \( (u_{h,est}) \), based on the telescope measurement mounted on blade \( i \) is used to control the blade pitch and trailing edge flap angle of the next blade, namely blade \( i - 1 \). Hence, the objective is to find the best coherence between the estimated wind speed parallel to the rotor shaft axis \( (u_{h,est}) \), based on the telescope measurement mounted on blade \( i \), and the blade effective wind speed \( (u_{bef}) \) estimated on blade \( i - 1 \). For simplification the blade number from the indexes are neglected. The coherence and the phase shift of the two signals are used to determine the optimal setup of the LiDAR, such as the position along the blade radius \( (R) \), the rotation around the z-axis \( (\gamma_i) \), and the focus distance \( (F) \). The objective function is defined as

\[
\min_{R,F,\gamma_i} J(u_{bef}, u_{h,est})
\]

where

\[
J(u_{bef}, u_{h,est}) = \frac{\int_0^{f_{\text{max}}} (S_{u_{bef}u_{h,est}}(f))^2 \left| \frac{\varphi_{u_{bef},u_{h,est}}(f)}{\gamma_{u_{bef},u_{h,est}}(f)} \right| df}{\int_0^{f_{\text{max}}} (S_{u_{bef}u_{h,est}}(f))^2 df}
\]

where \( f_{\text{max}} \) is the maximal frequency of interest. The cost function, \( J(u_{bef}, u_{h,est}) \), is formulated in order to minimize the ratio of the phase shift \( \varphi_{u_{bef},u_{h,est}} \) and coherence \( \gamma_{u_{bef},u_{h,est}} \) between \( u_{bef} \) and \( u_{h,est} \). This ratio is weighted by the square of the power spectral density, \( S_{u_{bef}u_{h,est}}(f) \), of \( u_{bef} \) to emphasize the frequencies where the individual pitch control (IPC) and trailing edge flap control (TEFC) should be active. In the DTP case, for each of the selected wind speeds, 4, 9, 14, and 19 m s\(^{-1} \), the telescope parameters are found through optimisation. This setup provides an upper bound on achievable performance. In the FTP case, to find the optimal parameters for the entire operation range, the objective function from Equation (6) is weighted with the damage equivalent load magnitude of the flapwise blade root bending moment \( (DEL(j)) \), as calculated for the reference baseline controller case (denoted REF), and with the probability of the mean wind speed occurrence \( (p(j)) \). The weighted \( (J_w) \) objective function is

\[
J_w = \left[ \sum_{j=\text{u}_{\text{min}}}^{\text{u}_{\text{max}}} \left( p(j) \cdot \text{DEL}(j)^m \cdot J(u_{bef}(j), u_{h,est}(j)) \right) \right]^{\frac{1}{m}}
\]

where \( m \) is the Wöhler exponent of the S-N curve, a value of 13 is further used.

For both cases, simulations are carried out for time intervals of 10 minutes. The findings are plotted in Figure 2. Figure 2 highlights, that the expected DTP values and the DTP values found through the optimisation do not fully match. This is because the expected value estimation is based on the assumptions that (a) the blade is rigid, (b) laminar inflow with wind shear is considered, and (c) the pitch angle is constant, which is not the case when there is turbulent inflow. Although there are drifts between the expected and optimal values, the tendency remains the same for the four evaluated wind speeds. The values found for the FTP case are very close to the values found for the 14 m s\(^{-1} \) wind speed in the DTP case. This is also expected due to how the objective function is defined in Equation (7).

2.3. Multiple input, multiple output (MIMO) feedback controller

For control development, a simplified wind turbine model from Ungurán and Kühn [9] is used. The model is transformed into the non-rotating frame of reference applying the multiblade...
Figure 2: The found optimal focus distance, position, and orientation of the blade mounted telescope. The markers correspond to the DTP case carried out for the four chosen mean wind speeds (4, 9, 14, and 19 m s\(^{-1}\)). The lines correspond to the FTP case. The dashed lines represent the expected DTP values based on steady state simulations.

coordinate transformation in accordance with Vali et al. \[10\]. Lu et al. \[11\] analysed the multiblade coordinate transformation (MBCT) dynamics. They showed that by taking into account the MBCT during the \(H_\infty\) controller development, a higher load reductions can be achieved in comparison to controller proposed by Bossanyi \[12\]. Hence, in this work, \(H_\infty\) controllers are developed taking into account the MBCT dynamics. The controller is based on the methodology proposed by Glover and McFarlane \[13,14\], which requires the selection of pre- and post-weighting functions, namely \(W_1(s)\) and \(W_2(s)\), respectively, leading to the shaped plant as follows

\[
G_{\text{shaped}}(s) = W_2(s) G_{\text{wt}}(s) W_1(s) 
\] (8)

Controllers are designed for the operating points defined with wind speeds of 4, 9, 14, and 19 m s\(^{-1}\). The post-compensator \((W_2,\text{IPC}(s))\) is selected as 1 and the pre-compensator \((W_1,\text{IPC}(s))\) for the IPC acting on the 1P loads is selected as a combination of an integrator, DC gain of the inverted wind turbine transfer function, and a second-order Butterworth low-pass filter.

\[
W_1,\text{IPC}(s) = \frac{0.5}{s} G_{\text{wt,IPC}}^{-1}(0) \frac{0.2562}{s^2 + 0.7159 s + 0.2562} 
\] (9)

The only parameter varying with the operation point is the DC gain of the inverted wind turbine transfer function. The pre-compensator function for TEFC acting on the 2P loads is selected in a similar manner except for the integrator term. The trailing edge flap size is only 12.5% of the total blade radius, and it is placed close to the blade span. Considering actuator constraints for such a trailing edge flap, it is not possible to fully compensate the 2P component of the blade root bending moments. To avoid excessive actuator usage, the pre-compensator is selected as a combination of a proportional gain, DC gain of the inverted wind turbine transfer function, and a second-order Butterworth low-pass filter.

\[
W_1,\text{TEFC}(s) = 2 G_{\text{wt,TEFC}}^{-1}(0) \frac{0.2562}{s^2 + 0.7159 s + 0.2562} 
\] (10)

This leads to the sensitivity functions plotted in Figures 3 and 4 where the maximal singular values are 2.53 dB and 1.44 dB for the IPC acting on 1P and TEFC acting on 2P, respectively, which is under 6 dB, as recommended by Skogestad \[14\]. The plots show, that the bandwidth increases as the wind speed increases, this is because 1P and 2P frequencies vary with the rotor speed.
Figure 3: Sensitivity functions for the feedback IPC acting on the 1P frequency.

Figure 4: Sensitivity functions for the feedback TEFC acting on the 2P frequency.

Figure 5: Feedforward control implementation, where the inputs \( u_{h,\text{est},1} \), \( u_{h,\text{est},2} \), \( u_{h,\text{est},3} \) are the estimated wind speeds parallel to the rotor shaft axis and the outputs are the blade pitch angles \( \beta_1 \), \( \beta_2 \), \( \beta_3 \). The feedforward controller \( K_{\text{ff}} \) is implemented in the non-rotation frame of reference. Multi-blade coordinate transformation \( T \) is applied to the inputs and inverse transformation \( T^{-1} \) to the output. \( u_{dd,1} \), \( u_{dd,2} \), \( u_{dd,3} \) are the delayed estimated wind speeds.

2.4. Feedforward control

A model inverse based feedforward controller is developed in the non-rotating frame of reference, where the 1P or 2P (depending on the used transformation) is being transformed to 0P. Therefore, it is only necessary to actuate in low frequencies, below 3P, in the non-rotating frame of reference. Such a controller would have a high-frequency roll-off, hence only the DC gains of the inverse-based feedforward controller is considered, and a Butterworth low-pass filter is added to eliminate the actuation on higher frequencies, leading to the following transfer function

\[
K_{\text{ff}}(s) = (-G_{\text{wt,ff}}(s)^{-1}G_d(s))(0) \frac{0.741}{s^2 + 1.217s + 0.741}
\]  
(11)

The feedforward control development for 2P load reduction is done in a similar manner. The LiDAR based inflow wind speed measurement taken place from blade \( i \) is used as a control input of blade \( i - 1 \). Therefore, the measurement is delayed until the blade \( i - 1 \) reaches the azimuth position of blade \( i \). The delay is indicated as \( e^{-sT_{\text{id}}} \) in Figure 5 and calculated as

\[
T_{\text{id}} = T_p - T_s
\]  
(12)

where \( T_p \) is the preview time, based on the blade mounted LiDAR parameters, the steady-state wind turbine model, and the assumption that the frozen turbulent hypotheses holds. \( T_s \) is the time delay introduced by the wind turbine model and the feedforward controller. The time delay and feedforward control gains are varying in accordance to the mean wind speed measured with the blade mounted LiDAR system.

2.5. Feedforward control optimisation

Using the blade mounted telescope parameters found for the DTP case, the feedforward controller is validated. First, by using laminar inflow with wind shear, and secondly with
turbulent wind field, where the turbulent intensity is set as 5%. It is observed that the feedforward controller, without feedback, can achieve a similar or better load reduction at the wind turbine components as the feedback only case. However, when the considerably higher turbulence intensity is considered in accordance with the IEC 61400-1 ed.3 standard, it is observed that the feedforward controller has a negative effect mainly on the non-rotating components of the wind turbine. It is also observed that the trailing edge flap angle is saturated, leading to a distorted control signal. Furthermore, it is assumed that the wind speed measurement at only one radial position is equal to the blade effective wind speed. Therefore gain scaling factor \( (K_s(u_{\text{mean}})) \) and an additional time delay term \( (t_d(u_{\text{mean}})) \) is introduced into Equation (11) and Equation (12), respectively. For finding the optimal values, the following dimensionless objective function is introduced

\[
J_{\Delta DEL} = \Delta DEL_{\text{BRBM}} + \frac{\Delta DEL_{\text{Yaw}} + \Delta DEL_{\text{Tilt}}}{2}
\]  

where \( \Delta DEL_{\text{Yaw}}, \Delta DEL_{\text{Tilt}}, \) and \( \Delta DEL_{\text{BRBM}} \) are the achieved damage equivalent load reduction of the yaw, tilt, and flapwise blade root bending moments, respectively, in comparison
to the reference (REF) case.

Two optimisation cases are considered: (a) the DTP case, plotted in Figure 6a and (b) the FTP case, shown in Figure 6b. In the plots, the first row corresponds to the individual feedforward pitch control active at 1P (IPC 1P), and the second row represents the trailing edge flap control active at 2P (TEFC 2P). Each column refers to a mean horizontal wind speed case. For the DTP case, shown in Figure 6a, it is seen that the gains for the IPC active at 1P (IPC 1P) and for the trailing edge flap control active at 2P (TEFC 2P) have to be scaled down. The TEFC 2P gains are reduced further in comparison to IPC 1P in order to avoid actuator saturation. This is due to the difference in the controlled surface area and actuator constraints. The trailing edge flap operates at higher frequency, and therefore requires a high angle rate. Also larger angular amplitudes are needed compared to IPC 1P, because of the smaller controlled surface. This leads to saturated flap angles and to limited damage equivalent load reduction of the flapwise blade root bending moment. This has a negative effect on the non-rotating components of the wind turbine due to the cross-coupling between the yaw and tilt moments.

By default, a time delay is introduced to the system, which is the time of the wind propagation from the measured position to the blade. Yet, an additional time delay is required to be introduced into the system, it is found that this time delay has more effect on the DEL reduction of the non-rotating components. Although the additional time delay varies between 0.5 s and 0.75 s for IPC 1P, it can still be chosen as a constant value for all the wind speeds, due to the flatness of the objective function around the optimal value (Figures 6a and 6b). The same does not apply for TEFC 2P, where this value ranges between 0.05 s and 0.8 s. However, one constant value can be chosen for below-rated wind speed, and one for above-rated wind speed, but further investigation is required to see how the optimal values evolve around other operation points. For the FTP case, shown in Figure 6b, a similar trend is observed. The IPC 1P and TEFC 2P gain scaling factor can still be chosen as a linear function. Nevertheless, for TEFC 2P at $19 \text{m s}^{-1}$, the optimal gain scaling factor is almost zero. In the DTP case it is found that the optimal focus distance is 36.0 m at $19 \text{m s}^{-1}$ mean horizontal wind speed. However, for the FTP case, it is fixed at 24.3 m. Due to the feedforward controller design, the LiDAR preview time ($T_p$) is almost equal to the time delay introduced by the feedforward controller and the system ($T_s$). Either the focus distance needs to be increased or the time delay introduced by the feedforward controller needs to be reduced, which can be done by increasing the cut-off frequency of the second-order low-pass filter.

3. Results and discussion

Using the previously determined telescope and feedforward control parameters, the performance of the feedback-feedforward controllers are assessed through the damage equivalent load evaluation on several wind turbine components. The results are compared to the reference case (REF), where only the torque and collective pitch control are active, and summarised in Table 1. Three cases are considered. In the first case only the feedback controller (FB) is enabled. Secondly, the combined feedback-feedforward controller with dynamic telescope parameters is investigated (FB-FF DTP). Finally, the combined feedback-feedforward controller with fixed telescope parameters is investigated (FB-FF FTP). All the cases are compared to the reference case. The acronyms of b.r.b. and T.b. correspond to the blade root bending and the tower bottom, respectively. A negative value means a damage equivalent load reduction, while a positive value denotes a damage equivalent load increase in comparison to the reference case.

All three controller setups achieve major load reduction. In general the two FB-FF controllers provide load reduction in a similar order of magnitude, shown in Table 1. By comparing the combined feedback-feedforward controller with dynamic telescope parameters (FB-FF DTP) with the feedback only case (FB), only a minor load reduction is observed at the flapwise blade
Table 1: Damage equivalent load reduction for the mean wind speeds of 4, 9, 14 and 19 m s\(^{-1}\).

| Wind speed (m s\(^{-1}\)) | Case     | Flapwise b.r.b. (%) | Hub yaw (%) | Hub tilt (%) | T.b. fore-aft (%) | T.b. s2s (%) |
|--------------------------|----------|---------------------|-------------|--------------|-------------------|--------------|
| 4                        | FB       | -16.3               | -9.4        | -4.0         | 0.9               | 1.5          |
|                          | FB-FF DTP | -18.8               | -14.3       | -11.8        | -4.5              | -1.5         |
|                          | FB-FF FTP | -18.1               | -13.7       | -10.6        | -4.5              | -2.3         |
| 9                        | FB       | -15.8               | -19.7       | -19.6        | -2.1              | -9.8         |
|                          | FB-FF DTP | -15.8               | -18.9       | -24.5        | -3.5              | -6.1         |
|                          | FB-FF FTP | -15.5               | -18.6       | -23.9        | -2.8              | -7.4         |
| 14                       | FB       | -20.1               | -14.7       | -16.0        | -2.8              | 7.6          |
|                          | FB-FF DTP | -21.5               | -18.3       | -22.0        | -4.1              | 12.2         |
|                          | FB-FF FTP | -21.3               | -18.3       | -21.9        | -4.0              | 11.1         |
| 19                       | FB       | -18.1               | -8.2        | -8.4         | -1.1              | 1.6          |
|                          | FB-FF DTP | -17.8               | -12.4       | -13.8        | -2.0              | 7.0          |
|                          | FB-FF FTP | -17.8               | -11.6       | -11.6        | -1.4              | 5.8          |

root bending moment (Flapwise b.r.b.). Similar results were found by Bossanyi [2] and Kapp [3] by extending the feedback IPC, active on 1P of the flapwise blade root bending moment, with a feedforward controller. A higher damage equivalent load (DEL) reduction is observed at the non-rotating wind turbine components, except for the tower bottom side-to-side moments (T.b. s2s). The increased DEL at the tower top and tower bottom side-to-side moments are only an indirect effect of the controllers. This could be eliminated with a tower side-to-side controller. However, this is out of the scope of the paper. By comparing the DELs of feedback-feedforward controller with dynamic (FB-FF DTP) and fixed telescope parameters (FB-FF FTP) a slight negative impact is observed on the reduction of the flapwise blade root bending moment. The FB-FF FTP controller has a similar tendency as the FB-FF DTP controller, except the performance is usually slightly degraded, but in general a better load reduction is still achieved compared to the feedback controller (FB) case.

The blade mounted telescope system connected to a LiDAR is technologically viable [15] and the results of this study indicate promising load reduction. However, many issues need to be explored further before field tests. The assumption of Taylor’s frozen turbulence hypothesis and the induction zone is also not taken into account in the investigation. This would impact the measurement in a field test. Such uncertainties will be evaluated in large eddy simulation in combination with an actuator line representation of the rotor in the future. Perfect measurement, no measurement noise and drift, of the blade segment velocity, deflection, and orientation are assumed, which is then used to correct the LiDAR-based measurements. Placing sensors, such as distributed fibre optic sensors, can provide these quantities, but the additional sensors would increase the cost of the overall LiDAR system, making it less attractive for field implementations. One solution would be to use an observer to estimate the blade segment velocity and orientation from the already widely used wind turbine sensors, such as blade root bending moment measurement sensors.

4. Conclusion
This paper proposes a blade mounted telescope, connected to a hub-based LiDAR. The objective of this paper is to evaluate the controller performance for individual pitch control and trailing
edge flap control with respect to two concepts for adjusting the telescope parameters. The blade-mounted telescope is aligned to measure the component of the inflow wind field which is parallel to the rotor shaft axis. A blade-mounted telescope and LiDAR simulator are introduced into a high-fidelity aeroelastic simulation tool, where two cases are considered: (1) dynamic telescope parameters (DTP), where the parameters can vary in accordance with the wind turbine operating point and (2) fixed telescope parameters (FTP), where the telescope parameters are fixed during installation for the entire wind turbine operating range. Four horizontal mean wind speeds are investigated, two below and two above-rated wind speed. The results highlighted that the FTP setup offers a similar load reduction as the DTP setup around rated wind speeds and only a marginal performance loss near cut-in and cut-out wind speeds. Although slightly less damage equivalent loads (DEL) reduction is achieved with the FTP case with respect to the DTP case, still FTP offers a similar DEL reduction at the flapwise blade root bending moment and a higher DEL reduction at the non-rotating components with respect to the FB case. This motivates to use telescope with fixed parameters, however a special care has to be taken in the controller design in order to have enough preview time above rated wind speeds. The sensor concept could be applied also for other wind turbine and blade concepts e.g. with multiple flaps and telescopes where higher load reduction might be achieved.

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