Design and Evaluation of a Lidar-Based Feedforward Controller for the INNWIND.EU 10 MW Wind Turbine

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1 Abstract

For the development of the next generation of multi megawatt wind turbines, advanced control concepts are one of the major tasks. Reduction of fatigue and extreme loading could help to improve the overall design process and make plants more cost effective. This work deals with the application of the promising methodology of feedforward control using nacelle-based lidar sensor measurements on a 10 MW wind turbine concept. After lidar data processing has been described, the feedforward controller is designed such that disturbances from the changing wind speed to the generator speed are compensated by adding an update to the collective pitch rate signal of the normal feedback controller. The evaluation of the feedforward controller is done in two steps: Firstly, simulations using perfect lidar data measurements are applied to check the robustness of the controller against model uncertainties. After that, simulations with realistic lidar measurements are investigated. To improve control performance, the scanning configuration of the used lidar system is optimized. Over all it can be shown that lidar-assisted control leads to significant load reductions, especially in the full load region of the 10 MW turbine.

Keywords: Nacelle-Based Lidar, Feedforward Control, Scanning Trajectory Optimization, 10 MW Wind Turbine

2 Introduction

Nowadays, gaining electrical energy and reducing the Cost of Energy from wind turbines is still a challenging task. Especially for offshore wind farms the design and manufacture of even larger plants, that are able to operate in deeper and farther sites, is a common goal. The overall objective of the INNWIND.EU project is the development of a highly innovative design concept of a beyond-state-of-the-art 10–20 MW offshore wind turbine. This includes light weight rotor concepts with adaptive characteristics, innovative drive train concepts with super-conducting or Pseudo Magnetic Direct Drive generators and standard mass-produced towers and substructures designed for water depths of 50 m and beyond. Furthermore, floating concepts are taken into account and they have been demonstrated and tested with downscaled models in wave tanks. One of the main key targets is to beat the cubic law of weight and cost of conventional upscaling methods. A total of 27 European partners, both industrial establishments and research facilities, are meeting these challenges at the moment [1].

To achieve these targets in an appropriate and effective way, advanced controls are a major issue. Part of a work package in INNWIND.EU is the development of methodologies for feedforward control strategies using innovative measurements and sensors for reducing the impact of fatigue and extreme loading of large wind turbines. The present work shows how the control performance of the multi megawatt wind turbines can be improved by nacelle-based lidar-assisted control. This could be a contribution to make offshore wind energy more cost effective.

3 Approach

Within the first phase of INNWIND.EU a reference turbine was developed by upscaling the NREL 5 MW turbine [2], using the classical rules for geometrical similarities. It is a 10 MW traditional three-bladed, upwind turbine designed for offshore siting for an IEC class 1A wind climate. The hub height is 119 m and the rotor diameter is 178.3 m. For the overall dimensions and characteristics of this wind turbine, the conditions made in the upscaling process and the complete aerodynamic and aeroelastic model, please refer to [3]. One main goal of the reference turbine is to have a specification in such a detail that all project partners have a comparable simulation base, which is the starting point for their various investigations.

The reference turbine is a variable speed plant, where the collective blade pitch angle as well as the electromagnetic generator torque are used to operate the turbine in partial and full load region. The controller itself is based on classical proportional-integral feedback theory and is described in [4]. Furthermore, additional filters have been applied to mitigate rotor speed dependent influences and gain schedul-

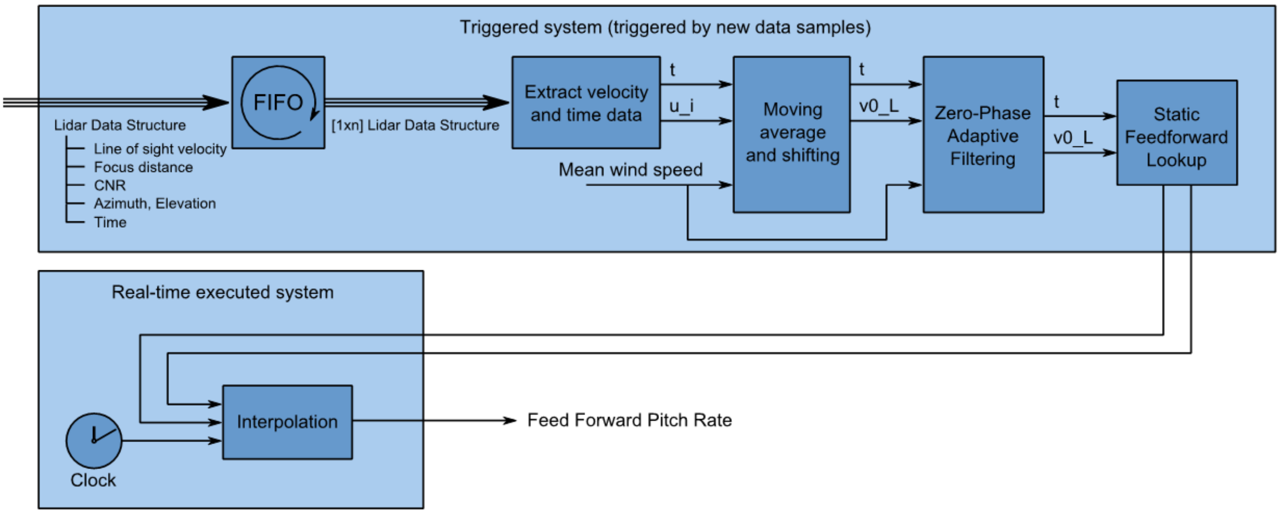

Figure 1: Schematic view of the lidar data processing for providing an estimate of the rotor effective wind speed v_{0L} to the feedforward controller.

ing techniques are handeling the effects of changing dynamics because of different wind speeds.

Due to this turbine dynamics, a variation in the approaching wind field can only be compensated by the feedback controller when its impact already has happened. To overcome this limits of feedback control, which is based on the principle of action and reaction, lidar technology is able to measure in front of the rotor – preview information of the wind becomes available. With this information, the control strategy can be adapted in terms of increasing power production and especially with regard to load reduction.

Lidar-assisted control concepts have shown their advantages and have already been successfully implemented and tested on mid-scale research wind turbines [5], [6]. In the present work, approaches and methodologies of feedforward control by means of using a nacelle-based lidar system as a sensor, are transferred to large multi megawatt wind turbines. All the applied concepts are based on [7]. Another extensive overview of turbine-mounted lidar control applications is given in [8]

4 Lidar-Assisted Control

4.1 Data Processing and Simulation Environment

When lidar technology is used for control it is very important to provide a signal of the rotor effective wind speed v_0, which is the wind speed affecting the turbine. An estimate of the rotor effective wind speed, v_{0L}, has to be provided by the lidar device respectively its data processing. This signal has to be well correlated with v_0 and furthermore it has to be filtered out of uncorrelated frequencies to avoid inducing loads by unnecessary control actions.

Processing lidar data in an correct and effective way is a crucial part even before the actual feedforward controller is designed. For this purpose, a lidar data precessing library has been developed, which functionality could be summarized as follows: Each lidar data sample is saved in a n-sample-long FIFO (first in first out) buffer, which provides the whole series of data samples, according to its previously set size. This structure can consist of raw data from the applied lidar system like the measured line-o-sight velocity, focus distance, carrier-to-noise ratio (CNR) as well as azimuth and elevation angle of the laser beam. From this data, time series of lidar measurements can be extracted. After correction, averaging, time shifting and filtering the signal, a preview of the rotor effective wind speed v_{0L} can be obtained. For a more detailed description of the individual processing steps, please refer to [7]. The whole ”processing pipeline” from raw lidar data to the feedforward control signal, which is added to the normal feedback signal, is depicted in Figure 1.

An advantage of using entire time series of lidar data instead of scalar measurements is that zero-phase filtering can be applied. This removes the necessity of compensating for phase shifts caused by dynamic filtering in the signal and also eases further processing steps like differentiation because noncausal filters can be implemented. As an additional benefit, model-predictive controllers can be fed with disturbance preview or, if an estimated rotor effective wind speed by plant data is calculated in the same way (using FIFO-buffers), an online cross correlation can be programmed, providing the time shift between the rotor plane and measurement planes.

These alterations pave the way for an easy implementation of a variety of algorithms. Simulations have shown that for reasonable FIFO buffer sizes, e.g. in the range of 2-3 minutes, memory usage increases about 150 kB and a modern CPU can still do all necessary operations within milliseconds.

For testing and evaluation of the lidar-based feedforward controller, the lidar simulator of DNV GL's *Bladed* (version 4.5) is used in this work. With this module it is possible to measure wind velocities upstream by mounting several types of lidar systems (pulsed, continuous wave) at different positions (nacelle, spinner, blade) of the turbine. The user is able to specify the number of lidar beams and its focal distances. A weighting function, which describes the weighting of the wind velocities from arround the focal points, can be defined for averaging the measurements along the beams. Furthermore, different scanning techniques like fixed position, circular scanning or rosette scanning can be selected. Together with a full aero-elastic model of the 10 MW reference turbine implemented in *Bladed*, it is possible to perform several feedforward control strategies.

In terms of all coding issues regarding data processing and controller development, a control-engineer-friendly *Simulink*-based framework has been developed, where feedback, feedforward and supervisory are implemented. This framework could also provide other project partners with a compiled controller DLL. Thus, it enables them to run simulations with different aeroelastic codes using the *Bladed*-style interface for external controllers.

4.2 Feedforward Controller for Perfect Wind Preview

The feedforward controller is based on [9] and provides a collective pitch rate update to the conventional feedback controller above rated wind speed to reduce rotor speed variations. To cancel out the effect of the wind speed on the rotor speed, the aerodynamic torque needs to be held constant. For a simple nonlinear model of the wind turbine, this can be achieved by adjusting the pitch angle Θ along a static pitch curve, which is obtained by steady state simulations.

In a first step, the robustness of the feedforward controller against model uncertainties is investigated by disturbing the full aero-elastic model with coherent wind and assuming perfect knowledge of the rotor effective wind speed v_0. Therefore, the *Bladed* lidar simulator is set to staring mode with one laser beam pointing in straight ahead direction. Figure 2 shows the results of this case for an Extreme Operating Gust (EOG) at 25 m/s. As it can be seen, perfect wind preview leads to significant improvements in control performance. Compared to the feedback (FB) baseline controller (dark blue line), the overshoot of the rotor speed Ω can be reduced to a vanishingly small amount by the additional feedforward (FF) controller (light blue line). With respect to load reductions it can be seen that the oscillation of the tower base fore-aft bending moment $M_{y\mathrm{T}}$ is minimized, which will result in decreasing tower loads.

This evaluation leads to the conclusion that the used feedforward controller is able cancel out the effects from changes in rotor effective wind speed to rotor speed almost completely when perfect wind preview is assumed. This effect can be shown over the entire full load region, whereas the controller achieves better performance at higher wind speeds.

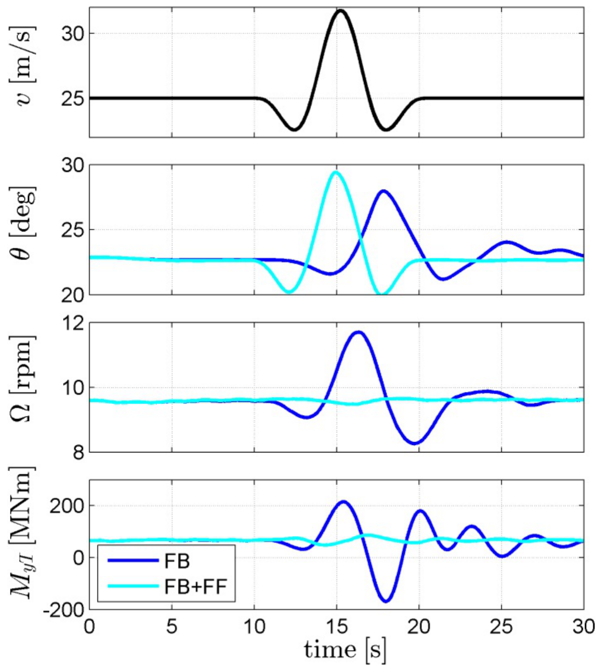

Figure 2: Response of the INNWIND.EU 10 MW wind turbine to an EOG at 25 m/s in case of perfect lidar measurement using DNV GL's *Bladed*.

4.3 Lidar Scanning Trajectory Optimization

It is not possible to fulfill the upper scenario in reality because the rotor effective wind speed cannot be measured perfectly. Normally, the lidar system is only able to estimate a signal of the rotor effective wind speed $v_{0\mathrm{L}}$ out of a turbulent inflowing wind field. How well this wind speed can be predicted depends on several different effects, which are mostly connected to each other. This could be done by calculation of the correlation for the available scan parameters and using its optimum.

One goal of this work is to find the optimal scanning trajectory for a nacelle-based lidar system. Therefore, a scanning lidar system is considered, which has been developed by Stuttgart Wind Energy (SWE) at the university of Stuttgart. It is able to set the laser beam directions freely and measure at five points per direction in different flexible distances. Various scanning trajectories could be applied. For more characteristics and specifications refer to [10]. From this circumstance it can be seen that there is no "the" optimum scanning trajectory. It always depends on the present application respectively lidar system and general conditions.

To find the optimal scanning trajectory for this application, a constrained optimization problem has been defined. It consists of a cost function that describes what should be optimized. In this case the correlation coefficient ρ_{LR} is used, which is a measure how well the obtained signal from the lidar system for the rotor effective wind speed $v_{0\mathrm{L}}$ is correlated to the rotor effective wind speed v_0 of the turbine. The parameters which can be changed, the optimiation variables, are depending on the used lidar system. For the SWE-

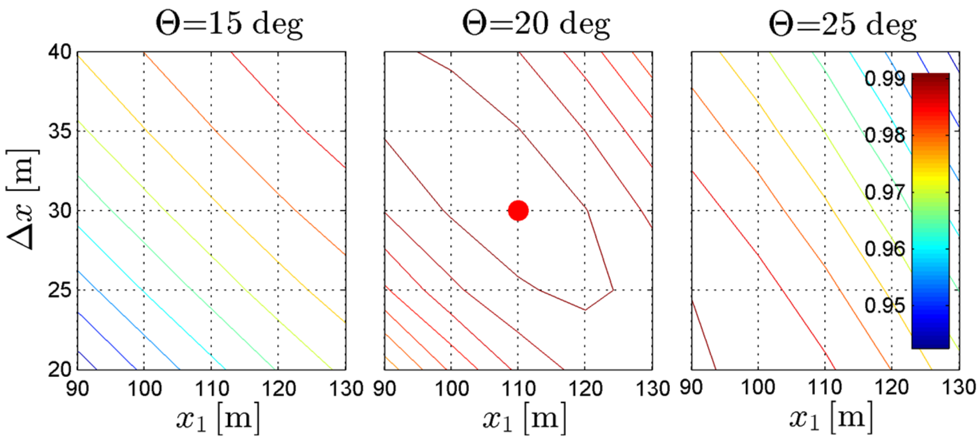

Figure 3: Optimized correlation coefficient ρ_{LR} between v_{0L} and v_0: Optimal setup: $x_1 = 110m$, $\Delta x = 30m$, $\Theta = 20°$.

Scanning-Lidar the distance of the first scan x_1, the spacing between the scan planes Δx and the scanning angle Θ are reasonable choices. At last, constraints for the optimization problem have to be defined. On the one hand lidar specific constraints – like number of scanning points on the circles, total scan time, maximum scanning angle, minimum first distance, maximum last distance – have to be taken into account. On the other hand controller specific constraints – e.g. the preview time caused by pitch angle actuator dynamics – have to be considered to provide the feedforward signal in the right time to the controller.

With these considerations the constrained optimization problem is formulated as follows:

$$\max_{x_1,\Delta x,\Theta} \rho_{\mathrm{LR}} = \frac{\sigma^2_{\mathrm{LR}}}{\sigma_{\mathrm{LL}}\sigma_{\mathrm{RR}}} \quad (1)$$

where

$$\sigma^2_{\mathrm{LR}} = \int_{-\infty}^{\infty} S_{\mathrm{LR}} df \quad (2)$$

is the covariance between the lidar and the rotor signal and the cross spectrum of the rotor effective wind speed v_0 and the estimation from the lidar $v_{0\mathrm{L}}$ is defined by

$$S_{\mathrm{LR}} = \mathcal{F}\{v_{0\mathrm{L}}\}\mathcal{F}^*\{v_0\} \quad (3)$$

where $\mathcal{F}\{\cdot\}$ is the Fourier transform of a signal and $\mathcal{F}^*\{\cdot\}$ is its complex conjugate. σ_{LL} is the standard deviation of the auto spectrum of the lidar signal and σ_{RR} is the standard deviation of the auto spectrum of the rotor signal, calculated respectively.

The constraint optimization problem for the SWE-Scanning-Lidar is calculated by a brute force optimization algorithm. The impact of all variables and the optimal setup (red dot) is shown in Figure 3. Furthermore, this scanning configuration is displayed for $n = 20$ measuring points on a circular scanning trajectory in Figure 4.

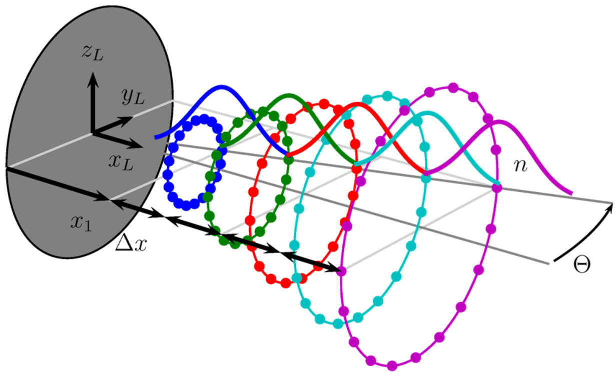

Figure 4: Visualization of an optimal scanning trajectory for the SWE-Lidar and the INNWIND.EU 10 MW wind turbine.

4.4 Feedforward Controller for Realistic Lidar Measurements

The promising results of Section 4.2 should be confirmed now by performing a detailed load analysis in case of realistic wind speed lidar measurements out of a turbulent wind field.

Firstly, the performance of the feedforward controller using the optimized scanning trajectory can be observed by analyzing the Power Spectral Densities (PSD) of relevant signals. For example, Figure 5 shows a significant reduction of the disturbances to the rotor speed Ω in case of the feedforward controlled 10 MW wind turbine at 16 m/s turbulent wind, mainly at lower frequencies. Considering the integral of the PSDs, the standard deviation σ, the improvements caused by the feedforward controller are quantified in the following table:

Table 1: Reduction of standard deviations of the rotor speed Ω, pitch angle Θ and tower base fore-aft bending moment $M_{y\mathrm{T}}$.

	$\sigma(\Omega)$	$\sigma(\Theta)$	$\sigma(M_{y\mathrm{T}})$
FB + FF	-68%	-22%	-28%

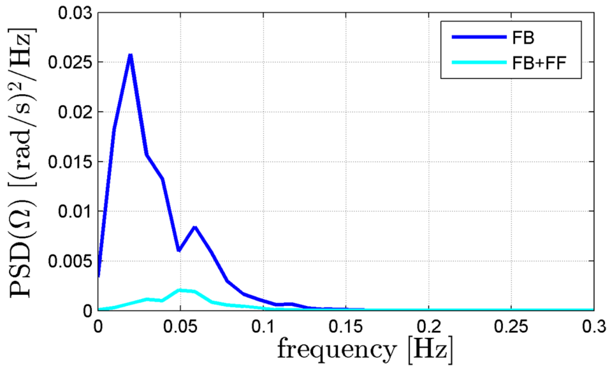

Figure 5: Power Spectral Density of a 1 h simulation at 16 m/s (Turbulence: Class A).

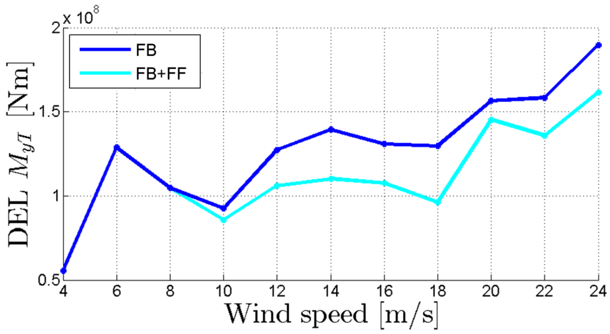

Figure 6: Lifetime-weighted DELs for the DLC 1.2 over mean wind speed.

Additionally, for the presented feedforward controller concept, a reduced set of load cases based on offshore standards is taken into account, which is representative to evaluate the simulation results and the control performance. This set of load cases includes fatigue cases, extreme load cases and fail cases. For more information refer to [11]. Considering Design Load Case (DLC) 1.2 for power production, the lifetime weighted Damage Equivalent Loads (DEL) of one of the most critical turbine parts, the tower base, have been derived. The reference cycle number at the calculation of the DELs is used $n = 2 \times 10^6$ and the Wöhler exponent of the tower is $m = 4$. Because the turbine does not operate at one specific wind speed throughout its lifetime, simulations are performed at different mean wind speeds and each simulation is weighted with its probability based on Weibull distribution. In Figure 6 this life time weighted DELs are shown over mean wind speeds from 4 m/s to 24 m/s with a stepsize of 2 m/s. It can be concluded that beginning at 8 m/s, decreasing DELs can be observed throughout the whole operating area of wind speeds.

Finally, the most important lifetime-weighted damage equivalent loads are summarized in Table 2.

Table 2: Lifetime weighted DELs for the DLC 1.2 simulations.

Lifetime Weighted DEL	FB [kNm]	FB + FF [%]
Rotating hub M_x	$4.89E+06$	-1.64
Stationary hub M_{yz}	$2.10E+07$	-0.33
Yaw bearing M_z	$2.79E+07$	-0.04
Blade root M_y	$3.31E+07$	-12.42
Tower top M_y	$2.04E+07$	-0.49
Tower base $M_{y\mathrm{T}}$	$8.33E+07$	-10.68

5 Conclusion and Outlook

This work shows the high potential for advanced lidar-based feedforward control of next generation wind turbines. Methodologies using nacelle-mounted lidar systems are successfully adapted to the INNWIND.EU 10 MW reference wind turbine. Compared to feedback controllers this work is showing promising results in reducing the impact of fatigue loading. The latter is one of the major starting points to make future design concepts of large multi megawatt rotors cost effective.

Taking all experiences into account after applying lidar-assisted control concepts to the INNWIND.EU 10 MW wind turbine, the most important learning objectives can be stated as follows:

- For high performance feedforward control, two requirements are crucial: Understanding lidar measurement principles thoroughly and combine it with proper control methods.
- The feedforward controller is designed with prefect wind preview such that all effects of the wind speed to the rotor speed are almost perfectly canceled out.
- Lidar configurations can be optimized to provide an optimal wind preview.
- The feedforward controller is combined with a lidar data processing, which fits the lidar estimate to the rotor-effective wind speed.
- Lidar-based feedforward control strategies show a promising potential in reducing fatigue loads independently of the feedback control.

In a similar study for a 5 MW wind turbine, comparable load reduction for tower base and blade root has been achieved [7]. It has to be investigated, if the benefits of lidar-assisted control might be even more attractive for 10 MW turbines, since the cost of lidar system will be the same while the load reduction might lead to larger cost reduction due the higher overall cost compared to 5 MW wind turbines. However, further work is necessary to investigate, if the benefits are still present, if more realistic simulations are done by including the wind evolution using the method presented in [12].

Within INNWIND.EU project several collective pitch feedforward controllers have been designed and tested. The acquired comparison results will be released in future publications. Furthermore, approaches in performing extreme load simulations under more realistic conditions and flatness-based feedforward control methods are showing encouraging results.

6 Acknowledgement

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