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

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1. Introduction

Nowadays, gaining electrical energy and reducing the Cost of Energy (CoE) from offshore wind farms is still a challenging task. To design and manufacture even larger wind turbines 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. Therefore, 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 task. The present work shows how the control performance of large multi megawatt wind turbines can be improved by lidar-assisted control. This could contribute to make offshore wind energy more cost effective.

2. Approach

Due to the turbine dynamics, a variation in the approaching wind field can only be compensated by the controller when its impact already has happened, making use of classical feedback control. 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 [2], [3]. In this work, the approach is transferred to large multi megawatt turbines. A methodology for feedforward control by means of using a nacelle-based lidar system as a sensor has been finalized [4], [5].

All investigations are carried out with a reference turbine, which is a three-bladed, upwind, medium speed drive, variable speed pitch-regulated offshore wind turbine that is mounted on a jacket structure at 50 m water depths and has a rated power of 10 MW [6]. The performance of the developed feedforward controller is compared to a reference baseline controller [7].

3. Main body of abstract

For all coding issues a control-engineer-friendly Simulink®-based framework is developed, where feedback, feedforward and supervisory controllers are implemented. This tool could also provide other project partners with a compiled controller DLL, which enables them to run simulations with different aeroelastic codes, e.g. GH Bladed®. The feedforward controller is based on [10] 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 along the static pitch curve.

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 wind.

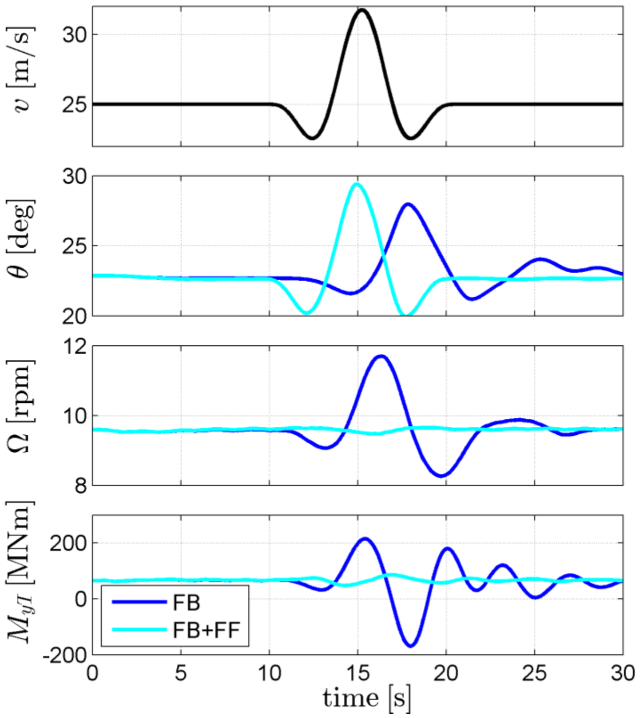

Figure 1: Response of the INNWIND.EU 10 MW wind turbine to an EOG in case of perfect lidar measurement. Feedback (FB), feedforward (FF); collective pitch angle (θ), rotor speed (Ω), tower base fore-aft bending moment (M_{yT}).

Figure 1 shows this case for an Extreme Operating Gust (EOG) at 25 m/s. Perfect wind preview leads to significant improvements in control performance. Compared to the baseline controller (dark blue line), the overshoot of the rotor speed Ω can be reduced to a vanishingly small amount by an additional feedforward controller (light blue line). Furthermore, the oscillation of the tower base fore-aft bending moment M_{yT} is minimized, which will result in decreasing tower loads.

However, the upper scenario is not realistic. Normally the lidar system has to provide a signal of a rotor-effective wind speed v_0 out of a turbulent inflowing wind field. Depending on different spatial averaging methods and measurement configurations, the correlation between lidar and rotor is varying. Thus, the robustness against measurement uncertainties is analyzed in a second step. Therefore, the lidar scan configuration is optimized to provide the best correlation in terms of coherence bandwidth by solving an optimization problem.

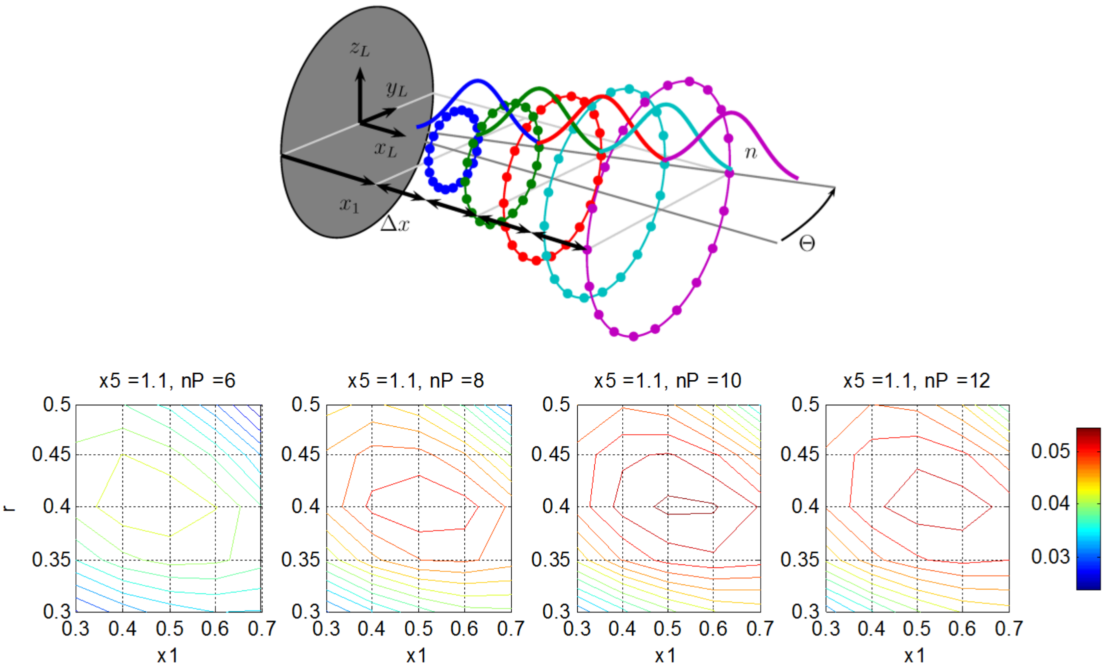

Figure 2: Visualization of a lidar scanning trajectory (top) and results of coherence bandwidth obtained by brute force optimization (bottom). x_1: distance of first circle; Δx: spacing of circles; θ: scanning angle; r: normalized circle radius; n: number of circle points.

Figure 2 shows an exemplary circular scanning trajectory and its optimization variables. In this optimization problem several lidar-specific as well as controller-specific constraints are taken into account. Figure 3 demonstrates results of the feedforward-controlled wind turbine in case of realistic wind speed measurements out of a turbulent wind field with an optimized scan trajectory. It clearly shows a beneficial effect on the Power Spectral Densities (PSD), where the disturbances to rotor speed Ω has been reduced, mainly at lower frequencies.

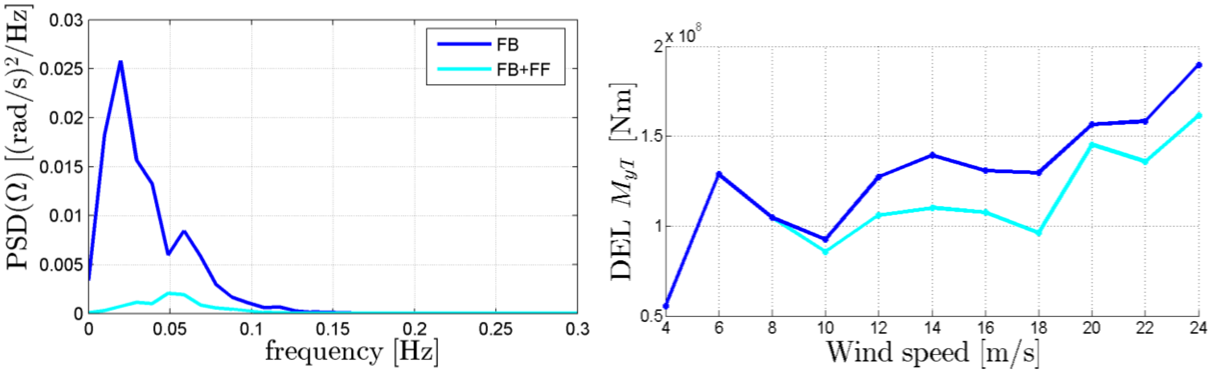

Figure 3: Feedforward control of the INNWIND.EU 10 MW wind turbine in case of realistic lidar measurement: Reduction of rotor speed PSD (left) and tower base bending moment DEL (right).

For the presented feedforward controller concepts 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. Considering Design Load Case (DLC) 1.2 for power production, the lifetime weighted Damage Equivalent Loads (DEL) of the most critical turbine parts, e.g. tower base or blade root, have been reduced up to 10%. In general, decreasing DELs can be observed throughout the whole operating area of wind speeds, see Figure 3 (left).

4. Conclusion

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.

In a similar study for a 5 MW wind turbine, comparable load reduction for tower base and blade root has been achieved [8]. This leads to the conclusion that 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 [9].

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.

5. Learning objectives

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.

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