Field Testing of Flatness-Based Feedforward Control on the CART2

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1 Introduction

Nacelle-based lidar systems are offering a good opportunity for new wind turbine control strategies, since inflowing wind information can be used in the controller. The benefits of lidar-assisted collective pitch feedforward control have been presented over the last years and was successfully demonstrated in several field testings, latest results see [1, 2]. This controller yields an improved rotor speed regulation and a reduction of structural loads above rated wind speed. While lidar-assisted control using only the generator torque is less promising [3, 4], multivariable controller such as Model Predictive Control [5] or flatness-based feedforward control [6] can yield further control performance below rated wind speed.

This paper presents the results from a field testing of a flatness-based feedforward controller in 2015.

2 Approach

2.1 Controller Design

Flatness is a system property introduced by [7]: A system is flat if a so-called flat output exists such that all system states and inputs can be explicitly expressed in terms of the flat output and a finite number of its derivatives. This property can be used to impose dynamics of a nonlinear system.

In [6] a Simplified Low Order Wind turbine (SLOW) is presented, which is flat with respect to the rotor speed and tower top displacement. Further, a feedforward controller is derived, which minimizes the tower motion and thus is denoted Tower EQUILibirum Accommodation (TEQUILA). Trajectories of rotor speed and tower movement are continuously designed during operation and translated into trajectories for the pitch angle and generator torque. Feedforward updates are then transferred to a baseline feedback controller, which is designed such that rated power is reached at 10 m/s [2].

For the field testing, the flatness-based feedforward controller is designed for the CART2 assuming perfect wind preview and compared to the feedback controller only and with additional collective pitch feedforward control [2]. For this purpose, a full aero-elastic model (FAST) is disturbed by an Extreme Operating Gust (EOG) at 10 m/s, see Figure 1. The simulations show that not only rotor over speed can be avoided, but the tower oscillation is also significantly reduced. In this case, the flatness-based feedforward controller performs significantly better than the collective pitch feedforward controller due to the initial gust below rated wind speed and the anti-windup.

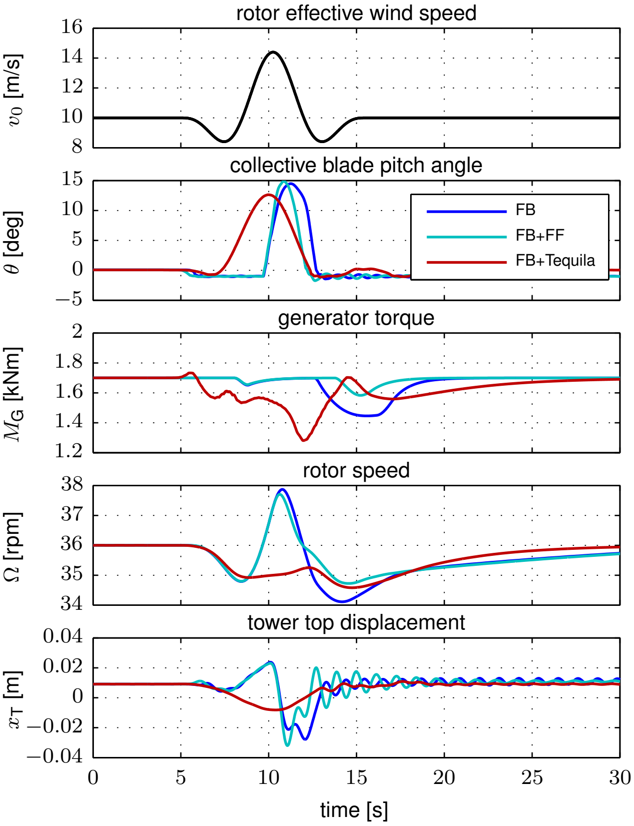

Figure 1: Reaction to an EOG in the case of perfect wind preview. Feedback controller only (dark blue), with additional feedforward (light blue) and additional flatness-based feedforward (red).

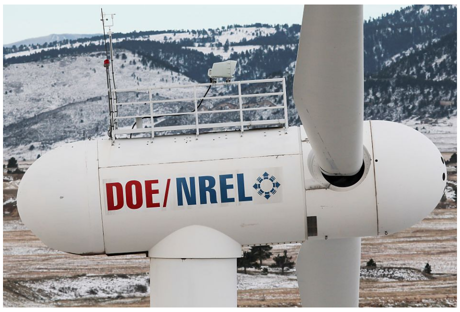

Figure 2: The 5-Beam Demonstrator installed on the nacelle of the CART2 at NREL. (Photo Credit: Lee Jay Fingersh, NREL 33621).

2.2 Lidar Data Processing Design

The dynamic wind field reconstruction and the adaptive filtering used in the field testing has been presented in [2]: The raw lidar data are condensed to an estimate of the rotor-effective wind speed. This signal is then filtered to remove all uncorrelated frequencies and synchronized with the turbine's reaction.

2.3 Tuning Lidar-Assisted Controller

The trajectory planning of the flatness-based controller is parameterized by five parameters (two time constants and three poles). Since only the rotor and tower motions of the turbine are shaped directly, the resulting collective pitch angle and generator torque trajectories can reach extreme values.

Here, the controller parameter have been tuned using the Hybrid Simulation technique introduced in [4] and the optimization suggested in [8]: Simultaneous measurement data from lidar and turbine are used to repeat a simulation with changing controller parameters. From the simulation results, a cost function is calculated from the standard deviation of the pitch angle, the damage equivalent loads on tower and shaft, and the generated energy relative to the feedback only case. The cost function is then minimized by standard Quasi-Newton methods to find the best parameters.

3 Field Testing Environment

The field testing took place at the National Renewable Energy Laboratory (NREL) in Colorado, USA. Since it is located next to the Rocky Mountains, NREL offers good conditions to perform many field tests.

The 2-bladed Controls Advanced Research Turbines (CART2) is operated by NREL and has a rotor diameter of $D = 42.7$ m, a hub height of 36.9 m, and during this campaign runs at a rated rotor speed of 36 rpm (see Figure 2). The CART2 is heavily instrumented with strain gauges, accelerometers, as well as a dedicated meteorological tower. Furthermore, a control system was developed and implemented in LabVIEW by NREL engineers and ties all of the mentioned sensing and actuation equipment into a single supervisory control and data aquisition (SCADA) system. This SCADA runs in real-time and runs the turbine's controller with in it at 400 Hz. This system offers engineers an easy way of implementing their own controller code as a DLL, which is loaded during compile-time by the LabVIEW SCADA system. In this work the DLL controller was created as an export using the MATLAB/Simulink coding environment.

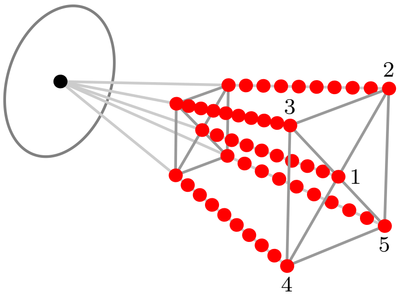

Figure 3: Measurement configuration of the AVENT lidar.

The 5-Beam Demonstrator Lidar is a flexible multi-range pulsed system designed by Avent Lidar Technology for the research and development of lidar-assisted turbine control. A unit was installed on the nacelle of the CART2 (see Figure 2) and measures at 10 configurable distances ahead of the rotor. At each distance, five line-of-sight measurements are taken sequentially within 1.25 s and are transferred to the CART-SCADA via an Ethernet connection in real time. The lidar measures in a square pattern configuration, with aperture cone angle of 45 degrees, and a central beam positioned horizontally. For the current setup at NREL on the CART2 turbine, the scan configuration has been optimized using the approach from [9] and distances from 50 m to 95 m ahead of the turbine were used.

The data from the lidar is processed on a separate real-time system and provided to the controller. The gateway offers a great flexibility in processing lidar and turbine data and in providing online visualization and parameter adjustment. It is part of the a generalized code development framework [2].

4 Initial Field Testing Results

The field test is set up so that the controller cycles between 5 minutes of running the normal baseline feedback controller and 5 minutes of combined flatness-based feedforward and feedback controller as described above. By cycling in this way, the two controllers are tested in wind conditions that are as similar as possible. Figure 4 shows exemplary 10 min of data. During the first 5 min, the flatness-based controller is active (feedforward gain $g_{\text{FF}} = 1$) and the turbine follows the designed trajectories (here only pitch angle and rotor speed are displayed). During the second 5 min, the flatness-based feedforward controller is switched off ($g_{\text{FF}} = 0$) and the turbine deviates from the desired trajectories.

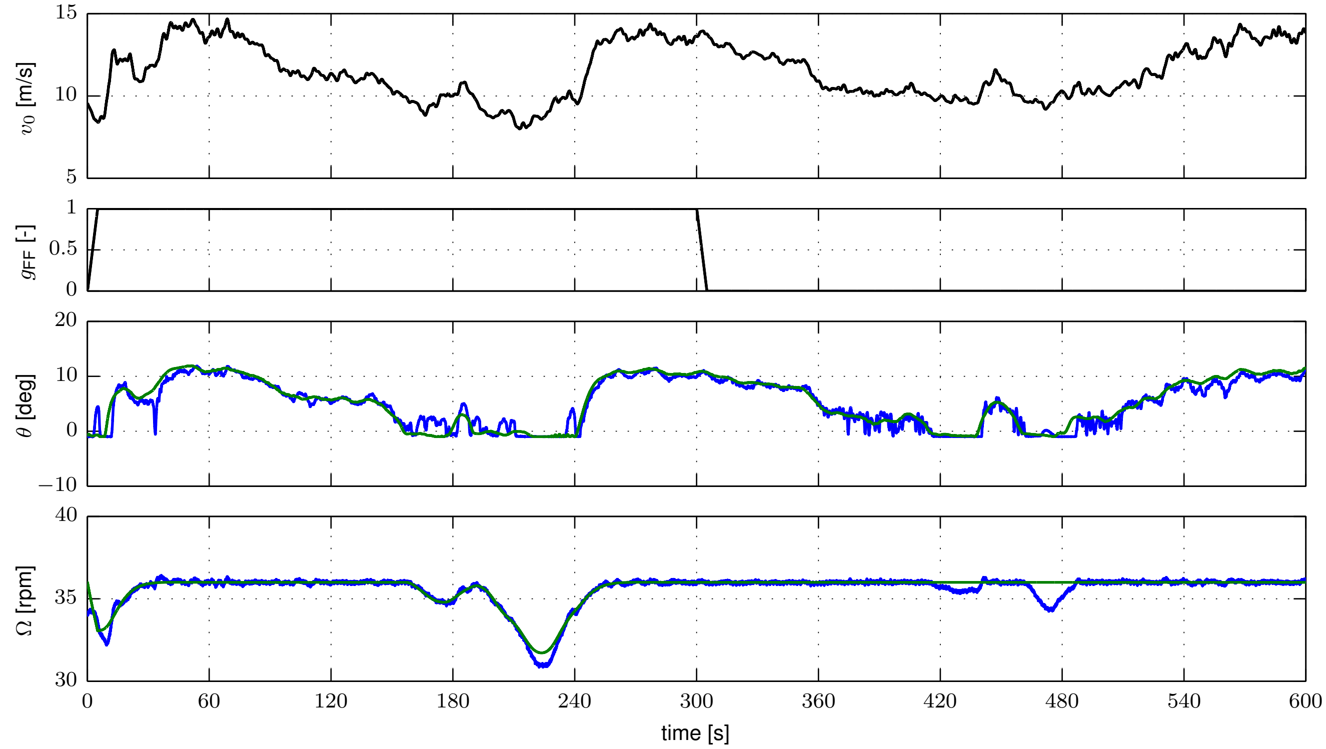

Figure 4: Field testing data: lidar measurement, feedforward gain, collective pitch angle and rotor speed. Desired value from trajectory planning (green) and measured value (blue).

5 Conclusions

In this work, field testing results from a flatness-based feedforward controller are presented. This lidar-assisted controller provides a feedforward update of the collective pitch angle and generator torque and is designed to reduce the tower motion in the transition between partial and full load operation. Although a more detailed analysis of the data is necessary to evaluate the benefit in control performance, the initial results show that the turbine follows the desired trajectories and thus can be considered as a proof-of-concept of multivariable feedforward control.

6 Learning Objectives

1. How can we design a multivariable feedforward controller to reduce rotor speed variations and tower motion?
2. How can we combine the controller with a real lidar system and tune it?
3. What are the benefits in a realistic environment?

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