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Frederik, J., Kröger, L., Peinke, J., Hölling, M., & Van Wingerden, J. W. (2018). Validating subspace predictive repetitive control under turbulent wind conditions with wind tunnel experiment. In *Journal of Physics: Conference Series: The Science of Making Torque from Wind (TORQUE 2018)* (Vol. 1037). (Journal of Physics: Conference Series). Institute of Physics Publishing. <https://doi.org/10.1088/1742-6596/1037/3/032008>

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To cite this article: Joeri Frederik *et al* 2018 *J. Phys.: Conf. Ser.* **1037** 032008

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Validating subspace predictive repetitive control under turbulent wind conditions with wind tunnel experiment

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Abstract. To reduce the cost of wind energy, it is essential to reduce loads on turbine blades to increase lifetime and decrease maintenance cost. To achieve this, Individual Pitch Control (IPC) received an increasing amount of attention in recent years. In this paper, a data-driven IPC algorithm called Subspace Predictive Repetitive Control (SPRC) is used to alleviate periodic loads on a scaled 2-bladed wind turbine in turbulent wind conditions. These wind conditions are created in an open-jet wind tunnel with an active grid, enabling unique reproducible high turbulent wind conditions. Significant load reductions are achieved even under these high turbulent conditions.

1. Introduction

As the size of wind turbines is ever increasing [1], it is of increasing importance to alleviate loads on the turbines to reduce maintenance costs and decrease the Levelized Cost Of Energy (LCOE). The dynamic loads on blades and other turbine components are dominated by the frequency of the rotor speed (1P) and its harmonics (2P, 3P, etc.). Using Individual Pitch Control (IPC), these varying loads can be reduced [2], with little to no loss of power production [3].

A novel implementation of IPC for load reductions is Subspace Predictive Repetitive Control (SPRC), which combines subspace identification [4] with repetitive control. This algorithm has shown promising results in a simulation environment [5] and in low-turbulence wind tunnel experiments [6]. However, no research has yet been conducted with SPRC in more realistic wind conditions. In this paper, it is shown that similar results can be obtained under higher turbulent conditions. These conditions are obtained using an open jet wind tunnel mounted with a novel active grid at the Oldenburg University [7].

In the following section, the control methodology of SPRC as well as Conventional IPC (CIPC), which will be used as a comparison, will be discussed shortly. Section 3 will describe the testing environment, followed by a section discussing the results. Finally, the conclusions will be given in the final section.



2. Control methodology

In this section, the design of the controllers used to alleviate the periodic loads on turbine blades is briefly discussed. Conventional IPC [2] is used as a reference implementation, such that the performance of SPRC can be evaluated.

In Conventional IPC, the Coleman Transformations [8] are used to transform the blade loads to a non-rotating reference frame. Subsequently, a notch filter is used to remove the 1P loads.

In SPRC, subspace identification is combined with repetitive control using basis functions to reduce the dimensionality of the problem. This control scheme is given in Figure 1. SPRC determines the control input u , in this case the individual pitch angles, based on the system output y , *i.e.* the blade loads. Figure 1 gives a schematic representation of the SPRC algorithm. In this figure, U_k and Y_k represent the input and output vectors lifted over period P at time instant k respectively, \mathcal{A} and \mathcal{B} are the system matrices of the lifted system and $\hat{\bullet}$ indicates an estimate.

An inverse QR algorithm [9] is used to estimate the system matrices. Notice that a basis function projection is used to transform U and Y into the lower-dimensional θ and \bar{Y} respectively. This is done by exploiting the fact that most of the energy content of the disturbance signal are at the frequencies 1P and its multiples. Considering the bandwidth of the pitch motors, only the 1P and 2P loads are considered, resulting in the following transformation matrix:

$$\phi = \begin{bmatrix} \sin \frac{2\pi}{P} & \cos \frac{2\pi}{P} & \sin \frac{4\pi}{P} & \cos \frac{4\pi}{P} \\ \sin \frac{4\pi}{P} & \cos \frac{4\pi}{P} & \sin \frac{8\pi}{P} & \cos \frac{8\pi}{P} \\ \vdots & \vdots & \vdots & \vdots \\ \sin 2\pi & \cos 2\pi & \sin 4\pi & \cos 4\pi \end{bmatrix} \otimes I_r \quad (1)$$

where $\phi \in \mathbb{R}^{P \times 4r}$ is the transformation matrix, with P the rotation period and r the number of inputs. Then, the inputs U_k are determined using

$$U_k = \phi \theta_j \quad (2)$$

with θ_j a vector of length $4r$. By using this transformation, only these $4r$ parameters θ that determine the amplitude and phase of the pitch angles need to be optimized. Furthermore, this transformation limits the frequency content of the pitch signals to the 1P and 2P frequencies. This combination makes SPRC an IPC algorithm that is both effective and efficient. A full description of the SPRC algorithm can be found in [10].

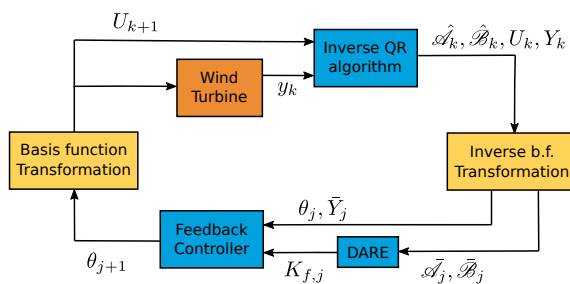


Figure 1. A schematic representation of the SPRC algorithm. Discrete Algebraic Riccati Equations (DARE) are used to find the state feedback gain $K_{f,j}$. The obtained input θ_{j+1} is transformed into the future pitch input U_{k+1} .

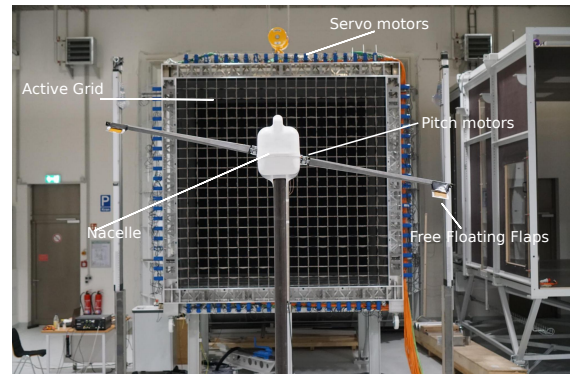


Figure 2. Picture of the experimental setup showing the two-bladed turbine in front of the open jet wind tunnel with active grid.

3. Testing environment

The wind turbine used for these experiments is a two-bladed variable speed wind turbine with a rotor diameter of 2 m, previously described in [5]. The blades of this turbine can be pitched individually through servomotors that connect the blades with the hub. The Out of Plane (OoP) bending moments are measured using piezo patches at the root of both blades. The blades are also equipped with free floating flaps that can be bent using piezobenders, however these have not been used in the experiments shown here.

Figure 2 shows the turbine in front of the open-jet wind tunnel at the Oldenburg University. This tunnel has a cross section of 3 by 3 meter and for these experiments is fitted with an active grid of 80 servomotors that each control one axis within the grid. The axes are mounted with rigid square flaps as described in [11]. By dynamically varying the angle of these axes over time, different turbulent flow fields can be generated [12]. In this way, a reproducible, time-varying, turbulent wind profile can be created to test control algorithms in realistic conditions. An extensive review of the wind conditions created by the active grid is presented in [7].

Making use of the active grid, two different wind Turbulence Intensity (TI) profiles are created: a low (TI: 2.5%) and a high turbulent (8.8%) case. In the low-TI case, the flaps of the grid are set in line with the wind direction to have minimal blockage, and will henceforth be called the open protocol. In the high-TI case, the axes are rotated in such a way that Lidar measured atmospheric wind data is imitated. This mode will therefore be called the Lidar protocol.

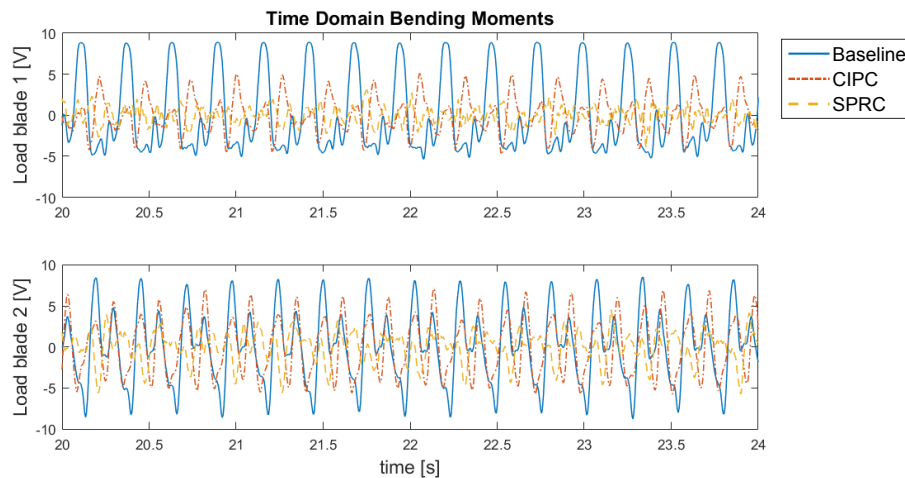


Figure 3. Root OoP bending moments of both blades with low TI (2.5%) and a wind speed of 5 m/s for the three control methodologies: no control (—), CIPC (— · —) and SPRC (— —).

4. Results

The SPRC methodology has been tested using different inflow velocities and turbulence intensities (TI's). In this paper, the results with an inflow speed of 5 m/s (230 rpm) are shown for the open protocol and the Lidar protocol. The SPRC algorithm will be compared to the benchmark Conventional IPC to evaluate the performance.

Figure 3 shows the measured OoP bending moments of both blades for the open protocol. The blades are pitched at 15° , resulting in a rotational velocity of 230 rpm. The baseline case of no control clearly shows the periodic behavior of the loads over time, with the 1P load dominating. Note that, as can be seen in Figure 3, the load signals of blades 1 and 2 are not symmetric. Due to imperfections in the wind turbine, significant differences between both blades can occur.

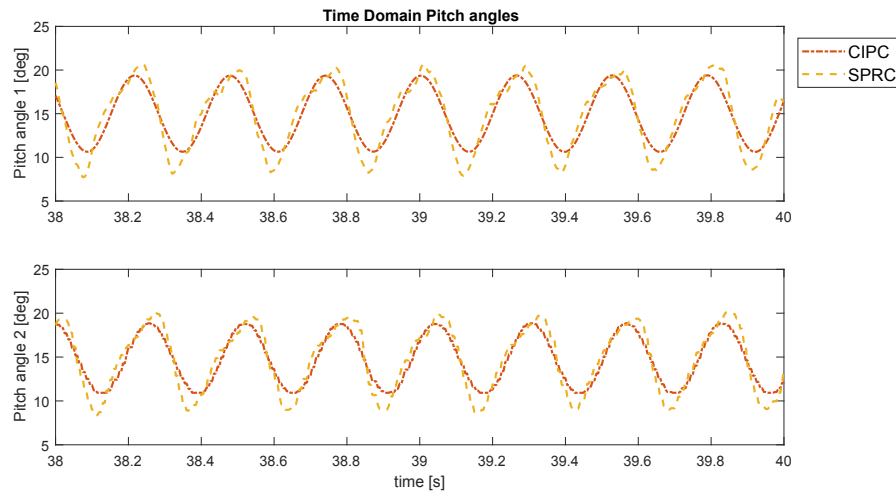


Figure 4. Pitch activity for the 5 m/s open protocol experiment. Shown are the pitch angles for the two IPC control methodologies: CIPC (— · —) and SPRC (— — —).

A significant reduction of this load is achieved by both Conventional IPC and SPRC. This is confirmed when the variance of the load signals is calculated: the variance of the loads with CIPC is approximately 60% lower compared to the baseline case, and SPRC even achieves a 86% reduction.

To compare the blade pitch activity with both control methodologies, Figure 4 shows the pitch angles for the interval of Figure 3. Both signals are quite identical, with similar frequencies and amplitudes. In this experiment, the pitch activity is marginally higher for SPRC: the variance of this signal is 2.4% higher than with CIPC. However, the considerable load reductions validate the slightly increased pitch activity.

With the high-TI Lidar protocol, a more irregular load pattern is observed, shown in Figure 5. Due to the turbulence, the loads clearly become more irregular. However, both

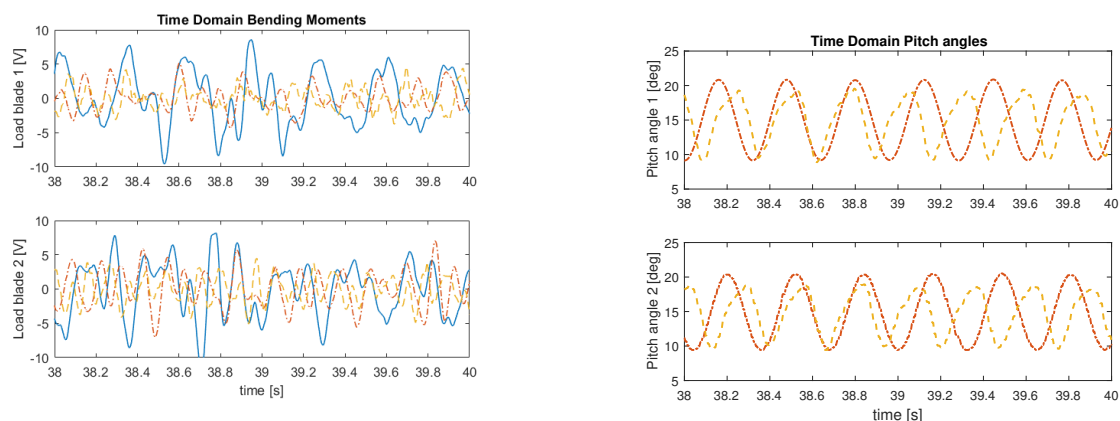


Figure 5. Root OoP bending moments of both blades with high TI (8.8%) and a wind speed of 5 m/s for the three control methodologies: no control (—), CIPC (— · —) and SPRC (— — —).

Figure 6. Pitch activity for the 5 m/s Lidar protocol experiment. Shown are the pitch angles for the two IPC control methodologies: CIPC (— · —) and SPRC (— — —).

control methodologies still achieve a load reduction, with SPRC again outperforming CIPC: it achieves a load variance reduction of 64%, compared to 55% with CIPC. Furthermore, Figure 6 shows that in these conditions, also the pitch signal is reduced with SPRC. The variance of the pitch signal determined with SPRC is 11% lower than of the CIPC pitch signal. Therefore, SPRC is able to achieve better performance with a lower control effort under these realistic wind conditions.

Evaluating the power spectral densities of the bending moments, shown in Figure 7, as expected shows peaks at the 1P, 2P and 3P frequencies. The top two plots show the blade loads for the open protocol. From these plots, it is clear that the 1P and 2P loads are reduced considerably by both CIPC and SPRC. The 1P load on blade 1 is almost completely removed by using SPRC, which also achieves an additional 2P load reduction on both blades compared to CIPC. Notice that with SPRC targeting the 1P and 2P loads, the 3P loads are now a considerable part of the total load magnitude.

With the Lidar protocol, the peaks associated with the rotational speed become wider, as the

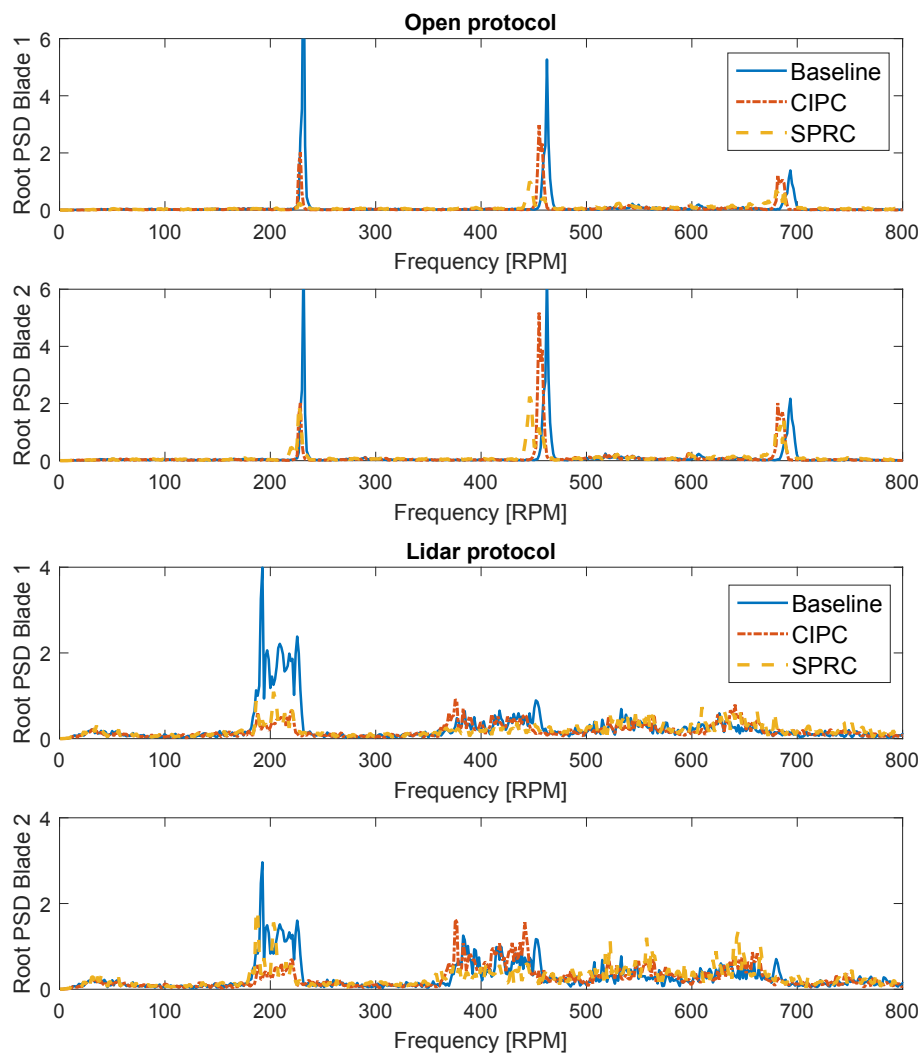


Figure 7. Square root of the power spectral density of the blade OoP bending moments with low TI (left) and high TI (right), for no control (—), CIPC (— · —) and SPRC (— · —).

rotor speed varies due to the turbulent inflow. Both CIPC and SPRC again achieve large load reductions for the 1P loads, but SPRC exhibits superior behavior at 2P. Based on Figures 5, 6 and 7, it can be concluded that SPRC successfully targets the 1P and 2P loads of the turbine in realistic high-turbulent wind conditions, while demanding a slightly lower actuator duty.

5. Conclusions

In this paper, the effectiveness of Subspace Predictive Repetitive Control (SPRC) has been proven when used for IPC in realistic high turbulent wind conditions. These conditions are created with a novel active grid mounted on an open-jet wind tunnel, which enables a fair comparison between different control methodologies. As a benchmark controller, Conventional IPC is used.

With SPRC, the dominant 1P and 2P dynamic loads can be vastly reduced, resulting in a significantly lower variance in the root out of plane bending moments. SPRC demonstrates the ability to reduce these loads further than achieved by Conventional IPC. In low turbulent wind conditions, SPRC performs 26 % better than CIPC, in high turbulent conditions 9 %.

For low turbulent wind conditions, superior blade load results are obtained at the cost of a slightly higher blade pitch activity. However, with a Turbulence Intensity (TI) of 8.8 %, a situation much more similar to full scale conditions, performance improvements are obtained alongside a reduction of the pitch activity. Subsequently, it can be concluded from these wind tunnel experiments that SPRC is a very promising control methodology for load alleviation on wind turbines.

Acknowledgments

This work was supported by the INNWIND.EU Project, an EU Consortium with Academic and Industrial Partnership for Innovations in Wind Energy.

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