Control Engineering Practice 80 (2018) 105–115

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Data-driven repetitive control: Wind tunnel experiments under turbulent conditions

Joeri Frederik [a,*], Lars Kröger [b], Gerd Gülker [b], Jan-Willem van Wingerden [a]

[a] Delft Center of Systems & Control (DCSC), Department of Mechanical, Maritime and Materials Engineering (3mE), Delft University of Technology, Mekelweg 2, 2628CD Delft, The Netherlands

[b] ForWind - Institute of Physics, University of Oldenburg, 26111 Oldenburg, Germany

ARTICLE INFO

Keywords:
Data-driven control
Individual pitch control
Load alleviation
Repetitive control
Subspace identification
Wind energy
Active grid
Wind tunnel experiments

ABSTRACT

A commonly applied method to reduce the cost of wind energy, is alleviating the periodic loads on turbine blades using Individual Pitch Control (IPC). In this paper, a data-driven IPC methodology called Subspace Predictive Repetitive Control (SPRC) is employed. The effectiveness of SPRC will be demonstrated on a scaled 2-bladed wind turbine. An open-jet wind tunnel with an innovative active grid is employed to generate reproducible turbulent wind conditions. A significant load reduction with limited actuator duty is achieved even under these high turbulent conditions. Furthermore, it will be demonstrated that SPRC is able to adapt to changing operating conditions.

1. Introduction

In the quest to make the cost of wind energy increasingly competitive with conventional energy sources such as fossil fuels, wind turbine structures become increasingly larger and more slender in order to increase their rated power (Van Kuik & Peinke, 2016). Consequently, the loads experienced by the blades of turbines also increase, and it becomes of vital importance to mitigate these loads.

The majority of dynamic loads on wind turbine rotors have a periodic nature, caused by wind shear, tower shadow, gravity and partial wake overlap from upwind turbines (Bossanyi, 2003). To reduce these deterministic loads, Individual Pitch Control (IPC) is a method receiving an increasing amount of attention (Barlas & van Kuik, 2010). In IPC, the pitch angle of each blade is, as the name suggests, controlled individually to decrease the out-of-plane bending moments. This method is relatively easy to implement, since modern wind turbines already have individual pitch capabilities, as well as measurements of the bending moments. By applying periodic pitch angles to the blades on top of the collective pitch, significant load alleviations can be achieved (Bossanyi, 2003).

Many different IPC approaches are studied in literature. Initially, the focus was mainly on controlling the load occurring once per rotation (1P) using Linear Quadratic Gaussian (LQG) controllers to solve the multiple-input multiple-output (MIMO) problem (Bossanyi, 2000; Selvam, Kanev, van Wingerden, van Engelen, & Verhaegen, 2009). However, since the 1P loads are symmetric, these loads do not cause the largest loads on the non-rotating parts of the wind turbine structure. These parts experience the largest loads at the blade passing frequency NP, with N the number of blades of the turbine, Bossanyi (2005). One method of alleviating these NP loads is by applying the Coleman transformation (Bir, 2008), which transforms the loads into a static reference frame. This allows the use of simple linear single-input single-output (SISO) control methods, such as PI-controllers (Bossanyi, 2005; Van Solingen et al., 2015).

An important downside of IPC is the substantial increase of the pitch actuator duty cycle. Subsequently, the wear on the bearings of the blades is also increased. In the proposed IPC methods, this effect could be enlarged at higher wind turbulence intensities, as these methods might attempt to also control the non-deterministic loads. However, this is a research area that has not yet received a lot of attention. Furthermore, the mentioned IPC algorithms assume a constant operating conditions, and are usually not able to adapt to changing rotor velocities.

A novel IPC methodology that deals with both these problems is proposed in Navalkar, van Wingerden, van Solingen, Oomen, Pasterkamp, & van Kuik (2014). This methodology called Subspace Predictive Repetitive Control (SPRC) and combines subspace identification (Van der Veen, van Wingerden, Bergamasco, Lovera, & Verhaegen, 2013) with repetitive control. By using measurement data to do online identification, the model can be refined during operation. Furthermore, the

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[*] Corresponding author.
E-mail address: j.a.frederik@tudelft.nl (J. Frederik).

https://doi.org/10.1016/j.conengprac.2018.08.011
Received 16 March 2018; Received in revised form 12 June 2018; Accepted 16 August 2018

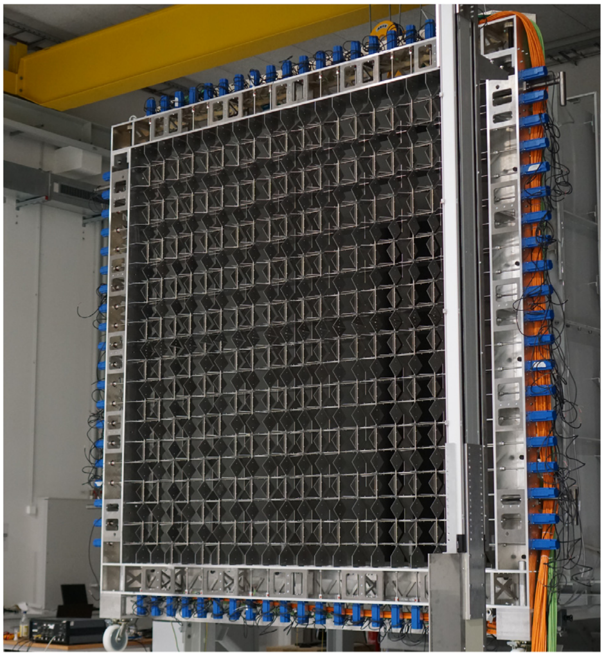

Fig. 1. The active grid mounted on the 3×3 m wind tunnel inlet in open test section configuration.

repetitive control law targets only the specified deterministic loads, thus lowering the actuator duty cycle. SPRC shows promising results in simulations (Navalkar, van Wingerden, van Solingen, Oomen, Pasterkamp, & van Kuik, 2014) and in wind tunnel experiments with laminar flow conditions (Navalkar, van Solingen, & van Wingerden, 2015). These laminar flow conditions are however not a realistic representation of the wind conditions that a turbine in the field would experience.

In this paper, experiments will be presented that form the next vital step in assessing the relevance of SPRC as an IPC algorithm. Using the open jet wind tunnel of ForWind at the University of Oldenburg, which is equipped with a novel active grid, realistic turbulent wind conditions can be created. Furthermore, the active grid makes it possible to reproduce these conditions, thus enabling an evaluation of different control methodologies. Preliminary results of these experiments are shown in Frederik, Kröger, Hölling, Peinke, & van Wingerden (2018). Modifications to the SPRC algorithm are proposed that make it possible to achieve superior performance compared to other IPC methodologies. Compared to Frederik, Kröger, Hölling, Peinke, & van Wingerden (2018), results showing the capabilities of SPRC to adapt to changing operating conditions in a turbulent flow field will be presented.

The structure of this paper is as follows: in Section 2, the experimental setup is described. This section contains a description of the flow conditions as created by the active grid 2.1, a description of the wind turbine 2.2, and an overview of the real-time environment 2.3. Section 3 covers the SPRC algorithm and its modifications, and Section 4 will then show the results of this algorithm subject to turbulent wind conditions. Finally, conclusions will be drawn in Section 5.

2. Test setup

In this section, the test setup used to conduct the experiments is described. First, the wind tunnel equipped with the novel active grid will be explained, followed by a description of the two-bladed control-oriented wind turbine. Finally, an overview of the real-time environment will be given.

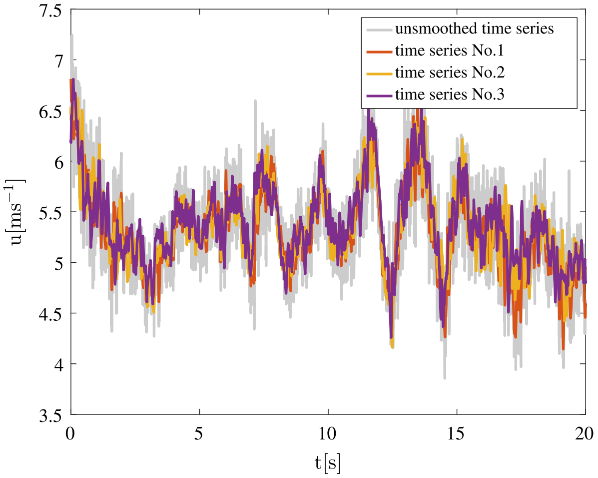

Fig. 2. Three exemplary wind speed time series generated by the Lidar excitation protocol smoothed by a moving average filter for a better comparison. An unfiltered wind speed time series is shown as reference in light gray.

2.1. Active grid

The experiments shown in this paper have been conducted in a low-speed wind tunnel of the University of Oldenburg. This tunnel has a cross section of 3×3 m and can reach wind speeds up to 30 m/s. On the inlet of this tunnel, an active grid is mounted as shown in Fig. 1. This active grid consists of 20 servomotors at each side that are connected to an axis mounted with rigid square flaps, as introduced by Makita (1991). Consequently, the 80 different axes of the active grid can be actuated individually. The change of the angle γ of the rigid square flaps with respect to the inflowing wind results in either a blockage or a deflection of the inflow.

By dynamically varying γ over time, various turbulent flow fields with specific characteristics such as atmospheric turbulence can be generated at certain positions in the test section (Heißelmann, Peinke, & Hölling, 2016; Knebel, Kittel, & Peinke, 2011). A comprehensive overview of the work in active grid research can be found in the review article of Mydlarski (2017). By repeating a predefined dynamic sequence of input angles γ, defined as an excitation protocol, it is possible to accurately reproduce turbulent flow fields.

To validate the new control concepts of the model wind turbine in turbulent conditions and to validate the reproducibility of the inflow, the flow field acting on the wind turbine is characterized. This was realized using a 2D hotwire system by Dantec Dynamics. This sensor consists of a thin wire suspended between two prongs and measures the wind speed and direction. An x-wire of the type 55P51 was used and operated at a sampling rate of 20 kHz with a low-pass filter at 10 kHz. For the data acquisition an 18-bit National Instruments A/D converter was used. These sensors were used to measure the wind speed at the location of the hub of the model turbine at 20 mesh sizes (3 m) distance to the active grid. Additionally, the hotwire was shifted 1 m to either side to determine differences in the flow field in the range of the wind turbine diameter.

Using the active grid described above, different wind conditions can be created. In this paper, the active grid was used in four different modes: two static and two active cases. For the static cases, the angle of attack of the active grid flaps was set to a constant angle of 0° , corresponding to the orientation of the flaps with minimal blockage, and 45°. In the active cases, two excitation protocols were used. The first one, called the Lidar mode, is based on Lidar measured atmospheric wind data and creates a wind field with intermittent behavior. The second one, called the gusts mode, is creating a mexican hat-like wind field with single gusts.