Comparison of Feedback and Ideal and Realistic Lidar-Assisted Feedforward Individual Pitch Control

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1. Introduction

Individual pitch control (IPC) for load reduction has been discussed for almost two decades [1]. There are different approaches for feedback IPC controllers such as decentralised [2] or multivariable [3] control design. Field tests already prove the effectiveness of load reduction [4]. However, the disadvantage of feedback IPC controllers is that changes of the asymmetric wind field are considered with delay, since the feedback is only reacting to impacts on the turbine dynamics after these impacts have already occurred. For this reason, lidar-assisted individual pitch control has been investigated occasionally in recent years [5-8].

Both – feedback und feedforward – IPC strategies need additional sensors. The feedback controller uses structural load measurements, whereas the feedforward controller needs preview wind information, which is typically provided by lidar devices. In order to evaluate the efficiency of different measurement values a comparison by simulation of both strategies regarding their load reduction is reasonable. Especially, for the lidar-assisted feedforward control it is essential to take a realistic measurement chain into account both to prove whether the algorithm is suitable and whether there are still appreciable load reductions.

In this paper a lidar-assisted cyclic pitch feedforward control is presented. The main objective is its parametrization through a simplified aerodynamic model. Furthermore, a realistic measurement chain is described.

In simulation studies load reductions by a feedback controller, an ideal and a realistic lidar-assisted feedforward controller compensating load fluctuations once per rotation are determined for a Senvion 3.4M104 wind turbine.

2. Cyclic Pitch Feedforward Control

According to [5] the inhomogeneous wind field is characterized by a horizontal mean wind speed v_0, a linear horizontal shear δ_H and a linear vertical shear δ_V as an average over the rotor or measuring area. A static compensation of both horizontal and vertical shear effects by cyclic individual pitch is designed in this work.

The compensation is based on a simplified model of turbine aerodynamics. Optimal blade angles β_{opt} for each azimuth angle φ are determined numerically by stationary simulations. β_{opt} can be modeled as a cosine function of the azimuth angle with an optimal amplitude amp_{opt}. The optimal blade angle and amplitude are depicted in Fig. 1. Due to nonlinear aerodynamics β_{opt} has no perfect, but almost a sinusoidal shape. The optimal amplitude only changes slightly with the azimuth angle respectively. For a simplified modelling of β_{opt} the amplitude can be considered constant.

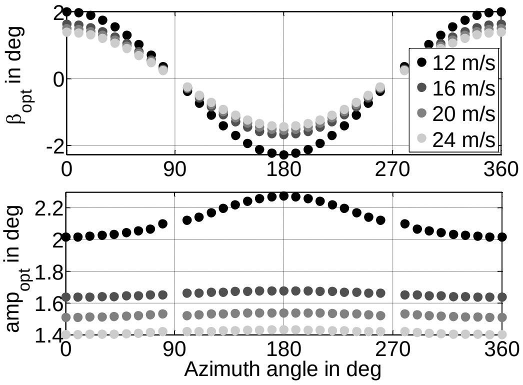

Fig. 1: Optimal blade angle and optimal amplitude to compensate a linear vertical shear of 0.0415 1/s for different mean wind speeds.

Numerous numerical optimizations for different mean wind speeds and shear were made. There is a slight dependence of β_{opt} and amp_{opt} respectively on the mean wind speed. Further a linear correlation between shear and β_{opt} / amp_{opt} appears. This correlation is considered by the constant shear amplitude coefficient c_{amp} as a division of amplitude and shear.

Considering the almost constant optimal amplitude, the dependence of the amplitude on the mean wind speed and the linear correlation of amplitude and shear, the feedforward pitch angles β_{FF} are calculated by:

$$\beta_{FF} = \delta_V \cdot c_{amp}(v_0) \cdot \cos(\varphi) + \delta_H \cdot c_{amp}(v_0) \cdot \sin(\varphi).$$

For implementation a look-up-table for c_{amp} is used.

The feedforward pitch angles are added to the collective pitch signal of the baseline controller.

3. Lidar Simulation and Wind Field Reconstruction

The simulation of a realistic reconstruction of wind characteristics by means of lidar measurements includes:

- Simulation of the lidar measurements including volume measurement,
- Wind field reconstruction based on line-of-sight wind speeds,
- Indirectly accounting for wind evolution by filtering the reconstructed wind field characteristics.

Filtering the reconstructed wind field characteristics, which are then used as controller inputs, has two effects: First to eliminate unrealistic high frequency fluctuations due to the application of Taylor's hypothesis of frozen turbulence in simulation. Second, to eliminate frequencies that are not correlated for a specific rotor and lidar measurement configuration. By means of SWE's analytical model for the correlation between a lidar measurement and a wind turbine rotor [9], it is possible to determine an optimal trajectory for a given lidar device. Additionally, the filter parameters can be calculated with the analytical model.

In the simulations of this work a pulsed lidar with several points in serveral focus distances is used.

In contrast, the ideal lidar-assisted feedforward controller uses unfiltered averages of v_0, δ_H and δ_V directly calculated from the wind field over the rotor area as inputs.

4. Simulation Results

Simulations are done in Flex5 with full stochastic wind fields and a Senvion 3.4M104 wind turbine model. Damage equivalent loads (DEL) are calculated for IEC2A.

For better comparability feedback and feedforward controller both focus only on the compensation of load fluctuations once per rotation. Fig. 2 shows the load reductions for the different control concepts compared to a baseline controller:

A: Baseline collective pitch speed controller (BL),
B: Feedback individual pitch controller with cyclic 1P signals similar to [10] + BL,
C: Lidar-assisted feedforward individual pitch controller with ideal measurement in the rotor area + BL,
D: Lidar-assisted feedforward individual pitch controller with realistic measurement and wind field reconstruction + BL.

Contrary to [5] no IPC feedback controller is added to the lidar-assisted feedforward controllers.

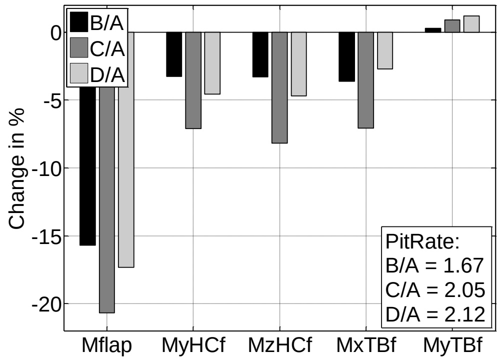

Fig. 2: Change of DEL for IEC2A, A: Baseline controller, B: Feedback IPC, C: Feedforward IPC ideal, D: Feedforward IPC realistic, IPC only active above rated wind speed.

In contrast to the IPC feedback (B), the feedforward controllers (C, D) have no information about fluctuating loads that are not caused by the wind field, e.g. the rotor imbalance, which is considered in the simulation. Still, the prediction of the wind field covers the main part such that substantial loads like flapwise blade root moment (Myflap) and hub center tilt (MyHCf) and yaw moment (MzHCf) considerably decrease compared to the feedback controller. The weighted mean pitch rate (PitRate) increases. Obviously, load reductions are lower for the realistic lidar-assisted controller. Nevertheless, the feedforward control algorithm is suitable and the load reductions are in the range of or even stronger than the reductions by the feedback controller.

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