

Iterative Feedback Tuning of an LPV Feedforward Controller for Wind Turbine Load Alleviation^{*}

Sachin T. Navalkar^{*} Jan-Willem van Wingerden^{*}

^{*} Delft Center for Systems and Control, Delft University of Technology,
2628 CD, Delft, the Netherlands (e-mail: S.T.Navalkar@tudelft.nl).

Abstract: Modern wind turbines incorporate active control techniques such as Individual Pitch Control (IPC) to reduce lifetime dynamic loads. However, system identification and controller design are typically difficult for turbine load control on account of the LPV nature of the system and disturbance. This challenge is addressed by extending the data-based Iterative Feedback Tuning (IFT) technique to systems with LPV output matrices, controlled with a parameterised feedforward controller LPV in output matrices. In order to compensate for the parameter-varying nature of the plant, controller and disturbance, and to estimate the IFT cost gradients in an unbiased manner, an increased number of experiments is required. Such an LPV controller, tuned and tested in a high-fidelity simulation environment, is able to show enhanced load reductions as compared to an LTI controller.

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1. INTRODUCTION

One of the fundamental roadblocks to the wide-scale deployment of wind energy, especially offshore, is the cost related to the manufacture and maintenance of mechanical components that are required to withstand severe dynamic loading over the turbine lifetime. To counter the effects of loads, induced primarily by the time-varying wind field, modern turbines often include active load feedback controllers, such as the Individual Pitch Controller (IPC) that counters wind loading by a cyclic motion of the blades along their longitudinal axes, as in Bossanyi (2003), Bossanyi et al. (2013). There has been an increase in recent years in exploring the use of feedforward measurements for enhancing load control and mitigating stability problems, Selvam et al. (2009), Laks et al. (2011).

In these references, a non-linear coördinate transformation is used along with PI control for IPC control. Such controllers show substantial load reductions, however the PI parameters have to be manually tuned and the output often has to be phase-shifted by a specific angle for load minimisation. Furthermore, such a controller only addresses one load peak, and additional peak reduction demands increased controller complexity, van Engelen (2006). Also, the LPV nature of the plant, Manwell et al. (2002), is usually ignored by IPC controllers. Finally, system modelling for PI controller optimisation is difficult and entails large uncertainties since turbine dynamics vary due to manufacturing discrepancies and location-specific factors.

As such, wind speed-varying data-driven controllers for IPC have been considered in recent literature, Navalkar et al. (2014), which combines online system identification and controller design. Iterative Feedback Tuning (IFT), Hjalmarsson (2002), forms another suitable data-based alternative that skips the identification step and uses experimental data to estimate the gradient of the performance-related cost criterion and thereby tune a parameterised controller. Limited knowledge of system behaviour is required by IFT and it can be used to tune the parameters of low-order and fixed-structure controllers for optimal performance in many practical applications, Gevers (2002).

A major limitation here is that the system during each experiment is taken to be LTI, and reidentification and retuning is required for changed operating conditions. Wind turbine dynamics are LPV and depend on the wind speed; IFT would yield a tuned LTI controller that is suboptimal in the operating range. Parameter variations can be dealt with as a bounded uncertainty, van der Velden et al. (2014), or by designing a switching controller, Koumboulis et al. (2007). A full LPV extension to IFT has been developed in Navalkar et al. (2015), however it requires a large number of experiments for parameter tuning. The structure of the LPV problem is required to be exploited to make the method practically tractable.

The main contribution is twofold: first, IFT is developed for systems with LPV output matrices, subject to LPV disturbances, for tuning a feedforward controller that can also be LPV in output matrices. The theory will be applied for the load control of wind turbines and both tuning and controller validation will be done in a high-fidelity simulation environment used for turbine (controller) certification.

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Table 1. INNWIND D121 Reference Wind Turbine, Bak et al. (2013)

Description	Symbol	Value
Rated power	P_{rated}	10 MW
Rotor diameter	d_{ro}	178.3 m
Cut-in wind speed	v_{cutin}	4 m/s
Rated wind speed	v_{rated}	11.4 m/s
Cut-out wind speed	v_{cutout}	25 m/s
Rated rotational rotor speed	Ω_{ro}	9.6 rpm
Gearbox ratio	ν	50.0
Pitch-rate limit	$\dot{\theta}_{\text{limit}}$	$10^\circ/\text{s}$

In the next section, the simulation environment and the reference turbine model will be described. The theoretical framework for the IFT tuning of feedforward controllers for LPV systems will be presented in Section III. In Section IV, IFT-LPV will be applied for load control of the reference turbine and the conclusions will be discussed in the last section.

2. SIMULATION ENVIRONMENT AND TURBINE MODEL

In this section, the high-fidelity simulation environment is described, and the model of the 10 MW reference turbine is presented. Further, the specific turbine loading conditions that require active control are described.

2.1 Simulation Environment

The simulation software GH BladedTM will be used for testing if IFT can be used to tune an LPV feedforward IPC controller. Bladed is a fully non-linear turbine simulation environment used for load certification of new turbines. The turbine is represented by a multi-body model with flexible tower and blades. The response of the turbine to different turbulent wind profiles can be validated. Blade-element momentum theory, Manwell et al. (2002), with wake corrections and dynamic stall is used to describe the aerostructural interaction. Bladed has been used in literature for comparing turbine load controllers, Houtzager et al. (2013).

2.2 Wind Turbine Model

The wind turbine that is modelled in GH Bladed and used for investigating IFT-LPV is the Innwind 10 MW reference wind turbine, Bak et al. (2013). Its characteristics are given in Table 1. The non-linear turbine model has 69 states and the linearised dynamics from blade pitch to blade loads for different wind speeds are shown in Fig. 1. The turbine has a rotor diameter of 178.3 m, and it is considered to be representative of commercial turbines for which the controller will be developed in this paper. This turbine is also equipped with a baseline power controller in closed-loop, Manwell et al. (2002); which controls the generator speed and aerodynamic torque for power production. This controller is standard and will not be described in further detail. The load controller to be developed is completely decoupled from this baseline controller and focusses only on reducing turbine loads.

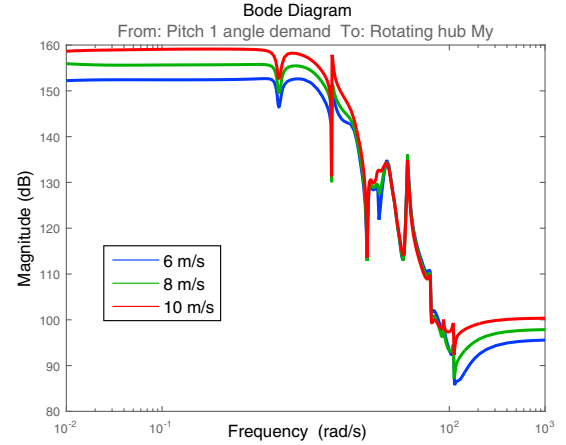


Fig. 1. Linearised dynamics, blade pitch to blade loads.

2.3 Load Control for Wind Turbines

The dominant turbine load peaks occur at its rotational speed, 1P, and its harmonics 2P, 3P, ... The loads are caused by tower shadow, wind shear, rotational sampling of turbulence and imbalances, Manwell et al. (2002). Since the turbine operates at different rotational speeds, the peak frequencies also change, as does the load magnitude.

Since the blade loads are caused by the wind varying over one rotation, they can be counteracted by pitching each blade over the rotation. For three blades, each blade need to be pitched 120° out of phase, this is Individual Pitch Control (IPC), which is needed to be tuned optimally.

Blade pitch produces an aerodynamic force that compensates the load variation and its authority hence depends on the wind speed. So, the turbine system can be approximated by a state-space model with an LPV input matrix (B LPV). The system is considered to be quasi-SISO: the three blade pitch angles are constrained to be equal in magnitude and 120° out of phase. For this SISO system, the LPV dependency can be shifted from the input matrix B to the output matrices C and D .

Further, the LPV parameter is the wind speed, which can be measured but not controlled. Due to this LPV nature of the problem, direct IFT methods do not show optimal performance, and an LPV IPC controller is needed.

3. THEORETICAL FRAMEWORK

The objective here is to develop an IFT-LPV framework for feedforward control for systems LPV in the output matrices. This condition significantly reduces the number of experiments required and makes it tractable in real time. The block diagram is shown in Fig. 2. The plant G is LPV in its output matrices which depend upon the scheduling parameter μ . The control input u is shaped by the feedforward controller $C(\rho)$ which is also LPV in its output matrices and depends on the parameters ρ which will now be tuned. The auxiliary input q will be used for the IFT experiments. The reference r is a disturbance generator based on the measured azimuth. The output y is to be minimised, and it is perturbed by the disturbance $v(\mu)$, which depends on μ .

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