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Systematic tuning of fixed structure speed and active tower damping controllers using H∞ norm criteria in the frequency domain

Introduction

If collective pitch is used for both rotor speed control and active tower damping of a wind turbine, control design effectively becomes a multivariable problem. Speed control and axial tower motion are highly coupled, as changes in pitch angle always influence both the aerodynamic thrust and the aerodynamic torque acting on the rotor. Modern control design methods, in principle, can optimize both control loops in parallel once the overall optimization criterion is defined, e.g. [1]. This, however, requires proper weighting of different control objectives as a starting point, which in many cases is not obvious. In many cases, the problem of controller parameter tuning is simply shifted towards tuning of weighting matrices or weighting functions.

Furthermore the resulting MIMO-controllers are not very transparent and, depending on the control design model, may be of high order. In practice, this may be causing problems for gain scheduling or pitch actuator saturation / controller switching between part-load and full load.

In practical application, separate control loops for speed control and tower damping are commonly chosen. The controller terms typically consist of simple PID schemes or filters that are designed in an iterative procedure. In many cases, an existing speed controller is augmented with an additional control loop for active tower damping [2]. Clearly, this approach will not result in an optimal controller parameterization regarding both speed control and tower fatigue objectives.

Approach

The approach taken in this paper is to apply a pragmatic multivariable control design to a controller with predefined i.e. fixed structure. The advantages of a simple and transparent controller structure should be combined with those of a systematic multivariable control design.

The chosen speed controller is of PD type. Tower damping is achieved with a derivative term to suppress steady state measurement offsets, combined with second order filter low pass filter. Both controllers act on the collective pitch rate reference value.

The assumed control objective in this study is:

> For a given wind spectrum,
> minimize the fatigue damage related to the fore-aft tower bending moment
> while keeping the rotor speed deviations below a defined threshold.

Since information on the wind field is typically given in the frequency domain, an H∞-norm based approach is chosen. The original control objectives are translated into weighting functions. While some authors propose numerical optimization of weighting function parameters, see e.g. Ozdemir [3], in this paper the dependency between weighting function parameters and the original control objectives should be made transparent. For this purpose, tower bending fatigue and maximum speed deviations must be related to the frequency domain properties of the wind turbine, i.e. the shape of the closed loop transfer functions.

Fatigue due to tower fore-aft bending can be estimated directly based on the PSD of the bending moment signal using the Dirlik-method. Also the maximum speed deviations can be estimated based on the PSD of the rotor speed signal using the Rice-method for estimating the probability distribution of maximum amplitudes of a normally distributed signal [5]. The controller evaluation for optimization is thus efficiently carried out in the frequency domain without any time domain simulations.

In the first step, full-order H∞ control design is carried out as a reference, using the *hinfsyn* function in MATLAB [6]. The applied types of weighting functions are shown in Figure 2. The weighting function for pitch rate is directly related to speed and acceleration limits of the pitch actuation system. The free parameters of the weighting functions for rotor speed W_Om (gain and corner frequency) and tower acceleration W_aT (gain) are chosen in order to shape the closed loop transfer functions in a desired way.

If tower bending fatigue is compared for different controllers with same maximum rotor speed deviation (Rice-estimate), it turns out that controllers with larger integrator time constants achieves lower fatigue damage values, compare Figure 1. As a consequence, pure D-control (acting on pitch rate reference) seems to be most suitable if steady state rotor speed deviations can be tolerated. If zero steady state speed deviation is required, a desired integrator time constant can be specified.

For full-order H∞ design, a simple stepwise approach for adjusting the free weighting function parameters is proposed:

(1) Choose desired integrator time constant for speed response. The inverse value is takes as corner frequency of the speed weighting function W_Om. A large time constant will give the smallest tower fatigue damage in any case.
(2) For the gain of both speed and tower acceleration weighting function, start with the maximum value of the open loop transfer functions. After the first H∞ calculation, an approximate factor can be calculated between maximum step resonse v_Wind → Om_Rotor and the maximum rotor speed deviation for the given wind spectrum. This factor allows to choose the suitable gain of the rotor speed transfer function W_Om, which is then fully defined.
(3) Reduce gain of tower acceleration weighting function W_aT in sufficiently small steps and carry out H∞ design for each step until the maximum speed deviation equals the desired value.

Only (3) requires few iteration steps. The whole procedure could be easily automated.

In the second step, structured H∞ control design is carried out following the same design procedure for the prescribed controller structure. Here the *hinfstruct* function in Matlab is used [6], which applies non-smooth optimization to find the free parameters of the prescribed controller structure. Compare [7] for more detailed information on the method.

It reveals that for the chosen controller structure, very similiar results can be achieved as compared to the full-order H∞ design.

For full-order and structured H∞ design a 7th order wind turbine model is used, including 1st and 2nd axial tower bending mode, 1st collective flapwise blade bending mode and overall drivetrain inertia. To be more accurate, the resulting step responses and frequency domain performance indicators are computed based on a more detailed linear model including drivetrain torsion as well as more tower and blade modes. Finally the control design results are verified in nonlinear simulations.

In this abstract, a linearized wind turbine model for only on operating point is considered for control design. The approach, however, can be easily extended to a number of operating points. Gain-Scheduling between the different controllers is then quite straightforward because of the low order and the transparency of the prescribed controller structure.

Results and Conclusions

A pragmatic approach for parallel design of rotor speed control and active tower damping is proposed. The control design is carried out in the frequency domin and provides a high level of transparency to the control engineer. In detail, the following conclusion can be drawn:

- H_∞-criteria can be conveniently used to formulate relevant pitch control objectives in the frequency domain

- For the full order H_∞ control design, in principle, both speed control and active tower damping would be possible using only rotor speed feedback. For robustness reasons, however, omission of the tower to acceleration feedback is not a good idea.

- If both rotor speed and tower top acceleration feedback are used, structured control design can achieve similiar results as full order H_∞ controllers. The prescribed controller structure, however, is much more transparent and easier to handle in a practical arrangement including gain scheduling and handling of actuator saturations.

- For the speed controller, D-control (acting on pitch rate reference) seems to be most effective to minimize tower bending fatigue while restricting speed deviations to a prescribed threshold

- For a given turbine and wind spectrum, the maximum in closed loop step response v_Wind -> Om_Rotor seems to be a good estimate for the maximum speed deviation in turbulent wind conditions. This property may be used for choosing a suitable weighting function parameterization for H_∞-based control design.

Learning objectives

Structured H_∞ control design based on a given wind spectrum can be used as a systematic, transparent and efficient way for tuning the parameters of standard controllers for rotor speed control and active tower damping.

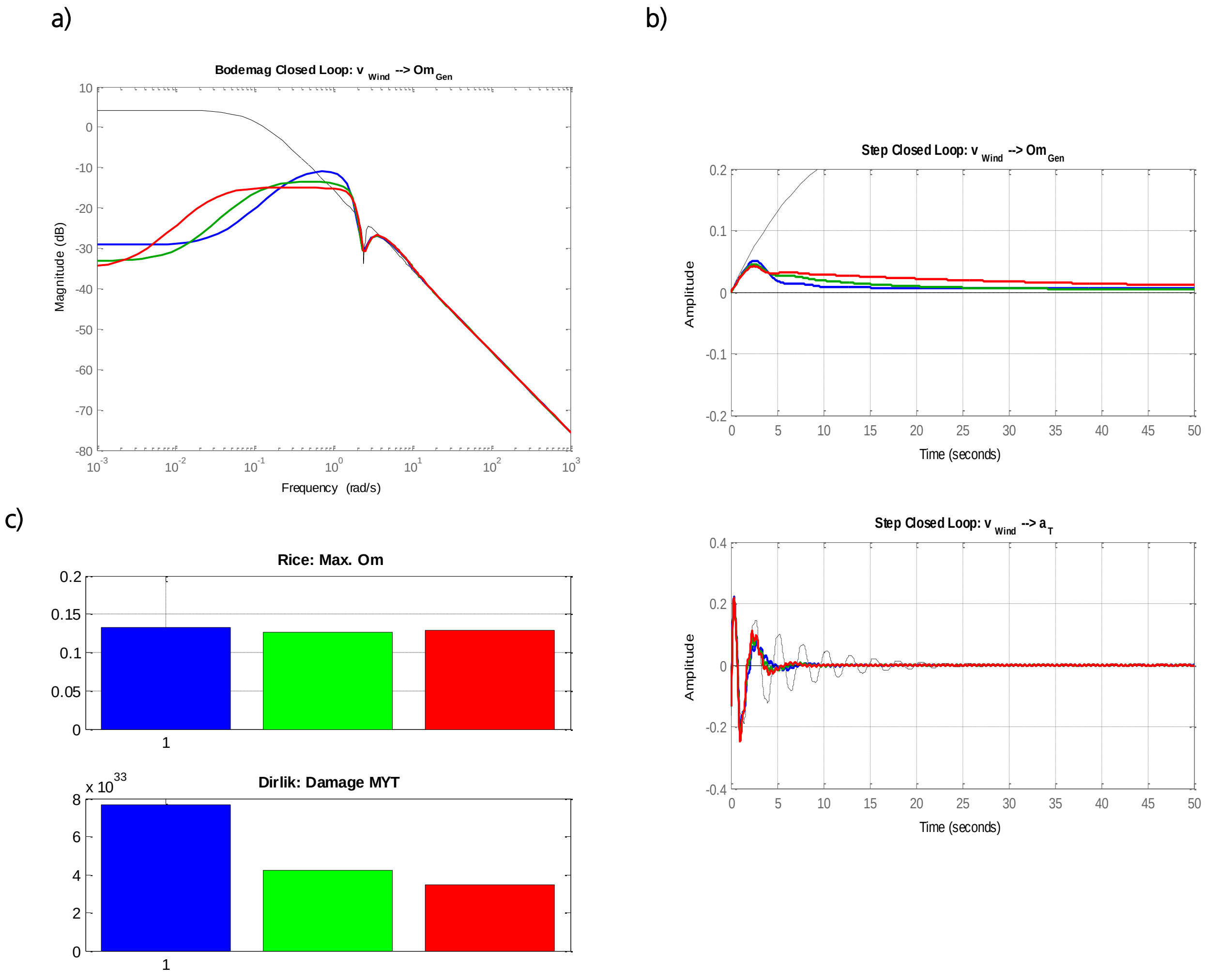

Figure 1: Comparison of 3 different full-order H∞-controllers with the same maximum speed deviation:

a) Bode magnitude plot from wind speed to rotor speed, black line: open loop

b) Step responses from wind speed to rotor speed (top) and tower top acceleration (bottom); black dotted line: open loop

c) Estimates of maximum rotor speed deviation (Rice) and tower bottom bending fatigue damage (Dirlik)

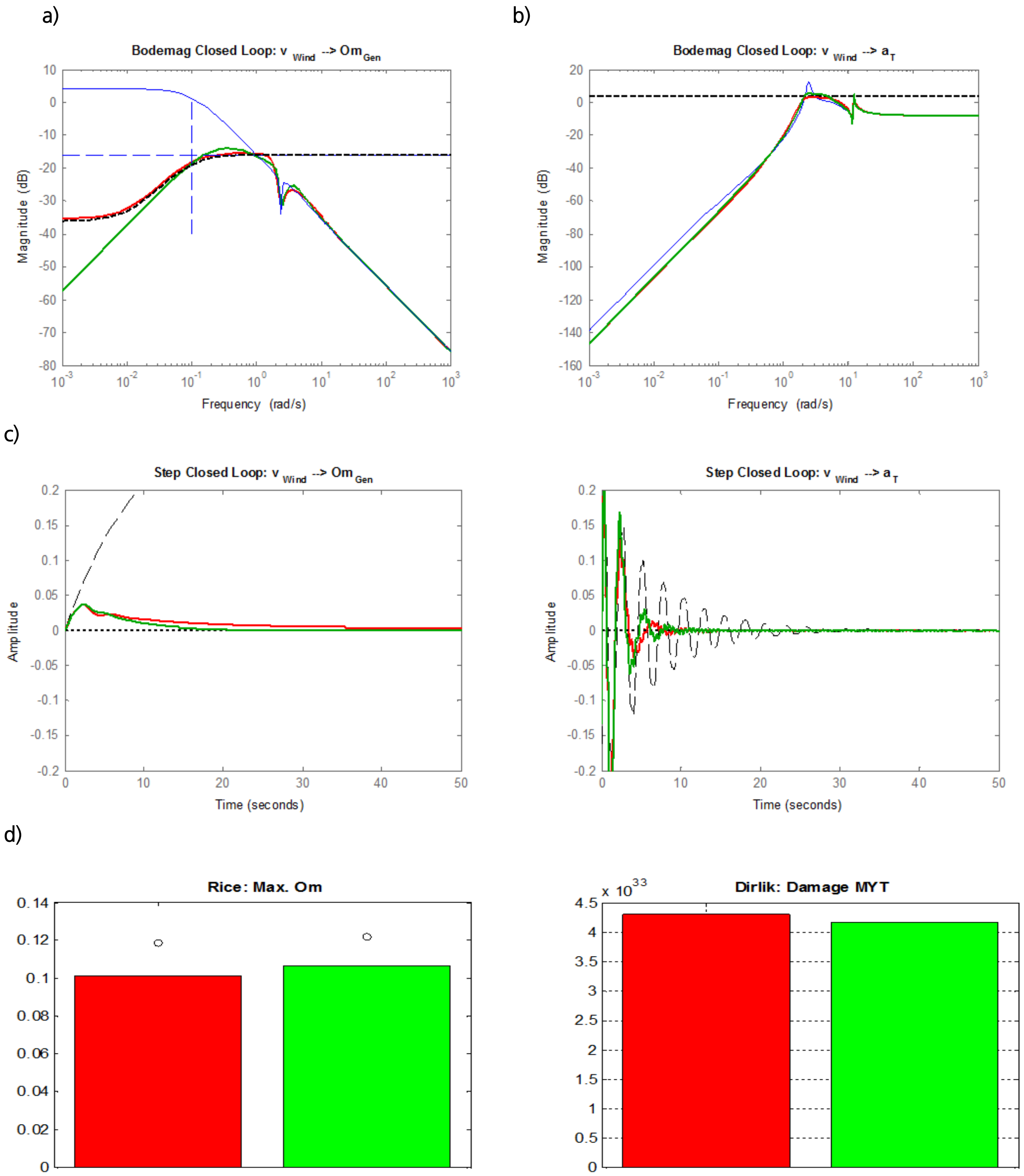

Figure 2: Comparison of full-order H∞-controller (red) and fixed structure controller (green)

a) Bode magnitude diagram from wind speed to rotor speed, blue: open loop, black dotted: weighting function W_Om

b) Bode magnitude diagram from wind speed to axial tower top acceleration, blue: open loop, black dotted: weighting function W_aT

c) Step responsed from wind speed to rotor speed (left) and tower top acceleration (right), black dotted: open loop

d) Estimates of maximum rotor speed deviation (Rice) and tower bottom bending fatigue damage (Dirlik)

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Abbreviations:

v_Wind: rotor effective wind speed
Om_Rotor: rotor speed
aT: axial tower top acceleration