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Methods for systematic tuning of wind turbine controllers

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Summary (max. 2000 char.):
Automated methods for wind turbine controller tuning can be useful to obtain a first estimation of the controller gains. Furthermore, these techniques can be employed within a multidisciplinary design procedure allowing for concurrent aeroservoelastic design. This report presents two methods to systematically tune the gains of the PI pitch controller of the Basic DTU Wind Energy Controller. The first method is based on pole-placement technique and the second on fatigue loads reduction. Both methods require linear models of a wind turbine that are obtained with HAWCStab2. These techniques are solved with numerical optimization.
The frequency placement method shows improvements compared to the state-of-the-art method but only when the model complexity is low. Tuning with load based method shows that different compromises between tower loads and rotor speed regulations can be achieved.

Contents

1 Introduction

Tuning of wind turbine controllers is an important and delicate step of the controller design. This process is often performed with manual trial and error iterations where the gains are changed until the response of the controlled system satisfies the requirements. Automated methods can be useful to obtain a first estimation of the controller tuning of a new wind turbine design since they do not require manual iterations and a detailed knowledge of the controller and of the effect of the gains on the response. Furthermore, systematic techniques can be employed within a multidisciplinary design procedure allowing for concurrent aeroservoelastic design.

In wind energy applications, a method to tune a wind turbine proportional integral PI controller with a pole-placement technique is presented by Øye [1]. This method can be used to tune the PI pitch controller and the PI generator torque controller. In this approach, the wind turbine is represented with a single degree of freedom model of the rigid body rotor rotation. The reduced turbine model is then connected with a simple model of the PI controller obtaining a formulation of the closed-loop system. The gains of the controller are then selected to obtain a desired frequency and damping of the mode associated with the controlled rotor rotation, the regulator mode. Because the model is represented by a second order equation, a closed system can be derived to obtain the gains analytically at one wind speed. In the case of the PI pitch controller, the gains are then modified with a gain-scheduling technique to account for the changes in the aerodynamic properties of the rotor when the wind speed changes. The gain-scheduling parameters can be obtained by polynomial fitting of aerodynamic properties of the rotor as function of the pitch angle. This method has the advantage of retrieving a controller tuning with a direct approach and no iterations. However, the simplified model sets some limits. As shown in the works by Hansen [2] and Tibaldi et al. [3], when the tuning obtained with the single degree of freedom model is used on a high-order wind turbine model, the position of the regulator mode does not satisfy the target requirements. The interaction with other wind turbine components leads, indeed, to a drift of the regulator mode frequency and a reduction of its damping. The filter on the rotor speed feed-back is largely responsible for the latter.

One of the main drawbacks of pole-placement techniques is that they require the selection a priori of the frequency and damping of the regulator mode. The former has to be selected somewhere below the first tower modes frequencies, the latter is usually selected close to a damping ratio of 70%. To obtain a method to tune a controller that is free from parameters chosen a priori, a procedure based on loads minimization can be employed. The tuning of a PI pitch controller involves the identification of a balance between tower loads and rotor rotational speed variations. The rotor speed should be as constant as possible to guarantee a regular power output. To achieve this quality in power production a high pitch activity is required to react quickly to the changes of the wind speed. On

the other hand, a high pitch activity affects also the aerodynamic thrust that is the main responsible for the longitudinal tower loadings. Therefore, an aggressive tuning has small rotor speed variations but high tower loading and a soft tuning leads to higher rotor speed variations and lower tower loads.

Two different methods for systematic controller tuning are here presented and discussed: a pole-placement technique of the regulator mode based on high-order models, and a method for fatigue loads reduction.

Both methods are based on linear high-order models of the wind turbine, therefore they do not require time domain simulations. The linearized models used in this investigation are obtained with the aeroservoelastic code HAWCStab2 [4]. Numerical optimization techniques need to be used in both approaches to obtain the set of tuning gains. The optimizations are all performed with a framework developed with OpenMDAO [5].

In the fatigue method, the load is evaluated in frequency domain from the transfer function of the linear model at different operational points. The technique to evaluate the fatigue is described in details by Tibaldi et al. [6].

The DTU Wind Energy 10 MW Reference Wind Turbine [7, 8, 9] is used throughout the investigation.

2 Methods and Models

This section contains a description of the methods and models used in this investigation.

2.1 Controller Gains

This investigation focuses on the gains of the proportional integral (PI) pitch controller on the rotor speed feedback of the Basic DTU Wind Energy Controller [10]. However, both methods are general and can be applied to any linearized controller.

The controller gains are defined as:

$$k_P = k_{P,0}\, \eta_K + k_{P,0,\Omega}\, \eta_K\, \eta_{K,\Omega} \qquad\qquad k_I = k_{I,0}\, \eta_K \qquad (2.1)$$

where $k_{P,0}$, $k_{P,0,\Omega}$, and $k_{I,0}$ are constant gains, and η_K and $\eta_{K,\Omega}$ are gain-scheduling parameters function of the low-pass filtered measurement of the pitch angle. The gain-scheduling parameters are defined as:

$$\frac{1}{\eta_K} = 1 + \frac{\Theta}{K_1} + \frac{\Theta^2}{K_2} \qquad\qquad \eta_{K,\Omega} = 1 + \frac{\Theta}{K_{1,\Omega}} + \frac{\Theta^2}{K_{2,\Omega}} \qquad (2.2)$$

where Θ is the pitch angle and K_1, K_2, $K_{1,\Omega}$, and $K_{2,\Omega}$ are constant.

The parameters K_1, K_2, $K_{1,\Omega}$, and $K_{2,\Omega}$ define the gain-scheduling. The gain-scheduling is required to take into account the changes in the aerodynamic characteristics of the rotor above rated wind speed and to achieve uniform controller performances.

The gain-scheduling parameters can be estimated analytically by fitting of the steady state aerodynamic gain and the aerodynamic damping. The aerodynamic gain is the partial derivative of the aerodynamic torque with respect to the pitch angle, the aerodynamic damping is the partial derivative of the aerodynamic torque with respect to the rotational speed. These derivatives are derived as quasi-steady gradients from the velocity triangles and derivatives of profile coefficients along the blade span, and not from the gradients of the power coefficient surface which would include the slow effect of dynamic inflow [11].

The scheduling technique implemented in the Basic DTU Wind Energy controller follows the one proposed by Øye [1] and extended in Tibaldi et al [3].

2.2 Numerical Pole-placement Technique

When tuning a controller with a pole-placement technique, the frequency and damping of the mode associated with the controlled rotor rotation, the regulator mode, are imposed to specific values, chosen a-priori, adjusting the the controller gains. To achieve this, linear models of the wind turbine in closed-loop are required to compute the frequencies and dampings from the eigenvalues.

This method requires two models, a full high-order model (evaluation model) and a reduced model (tuning model). The full high-order model is used to evaluate the quality of the tuning. The reduced model is employed in the tuning procedure to obtain the gains.

If the reduced model employed is very simple, an analytical formulation of all the controller parameters can be derived. An analytical formulation allows to directly compute the controller gains without iterative methods. However, when the model used for the placement has a higher order, numerical methods need to be used to estimate the gains. Better performances should be achieved on the full high-order model because the differences between the tuning model and the evaluation model are smaller. On the other hand when the tuning model has many states, the identification and selection of the regulator mode among all the modes is not trivial.

2.3 Fatigue-based Method

There are two main drawbacks when performing numerical optimization based on loads evaluated with nonlinear aeroservoelastic simulations: the computational time and the uncertainty of the results due to the stochastic turbulent wind. Time domain simulations are usually very time consuming to be integrated in a design procedure, especially if they are performed at each cost function evaluation. Since an optimization can require several hundreds of cost function evaluations, the computational time of the objective should be limited, so that a solution can be achieved within an acceptable time. When loads are evaluated from simulations with turbulent inflow the amount of turbulent seeds that are used can significantly affect the design and alter the convergence of the algorithm. An investigation on the uncertainty of the results is presented by Tibaldi et al. [12].

In this work, the loads are evaluated with a frequency domain method so that the limitations mentioned above are partially overcome. The method utilizes a linear model of the wind turbine in closed-loop configuration to compute the transfer function from the wind input to a desired sensor. The transfer function is then combined with the power spectra of the wind to obtain the power spectra of the output. A spectral method is finally applied to the output to obtain an estimation of the fatigue damage of the sensor. A detailed description of the method is presented by Tibaldi et al.[6]. An application of the method is shown by Zahle et al.[13].

Loads evaluated with this approach should also be verified with nonlinear time domain simulations. In this work the aeroservoelastic code HAWC2 [14, 15] is used for this purpose.

2.4 Linear Models

The open-loop wind turbine models are obtained with HAWCStab2, a tool developed at DTU Wind Energy. HAWCStab2 is an improved version of HAWCStab [16] with a different kinematic formulation. The model is an analytical linearization of a nonlinear finite beam element model using a co-rotational element formulation. The beam model is coupled with an unsteady blade element momentum model of the blade aerodynamics including shed vorticity, dynamic stall, and dynamic inflow [17]. A validation and analysis of the open-loop performances are provided by Sønderby and Hansen [18] for a version of HAWCStab2 without the present dynamic inflow model.

In this investigation, the linearized controller equations are implemented in a Python routine and evaluated each time the controller gains are changed. The controller model is a simplified linearization of the Basic DTU Wind Energy Controller, described by Hansen and Henriksen [10]. A description of the linear controller is presented by Tibaldi et al. [6].

2.5 Optimization Problems

The numerical optimization problems that are solved are defined as:

$$\begin{aligned} \underset{\boldsymbol{x}}{\text{minimize}} \quad & f(\boldsymbol{x}) \\ \text{subject to} \quad & \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0} \end{aligned} \tag{2.3}$$

A scalar nonlinear cost function f is minimized changing a set of variables $\boldsymbol{x}$. The variables are the normalized gains $k_{P,0}$, $k_{I,0}$, and $k_{P,0,\Omega}$ and the gain-scheduling parameters K_1, K_2, $K_{1,\Omega}$, and $K_{2,\Omega}$. All these variables are normalized by the initial value used in the optimization and obtained with the single degree of freedom model proposed by Øye [1].

The objectives function used for the pole-placement differs from the one used for the fatigue-based tuning.

The objective of the pole-placement is to achieve uniform performances throughout the rated region, therefore the regulator mode is required to have same frequency and damping at all wind speeds. The regulator mode is identified at each wind speed selecting the mode that has the smallest error, defined as:

$$e_i = \sqrt{\left(\frac{\boldsymbol{\omega}_i - \tilde{\omega}}{\tilde{\omega}}\right)^2 + \left(\frac{\boldsymbol{\xi}_i - \tilde{\xi}}{\tilde{\xi}}\right)^2} \tag{2.4}$$

where ω_i and ξ_i are the system modes frequency and damping ratio at the wind speed with index i and $\tilde{\omega}_i$ and $\tilde{\xi}_i$ are the target regulator mode frequency and damping ratio. Before computing the error e_i, the modes with a damping ratio higher than $98\,\%$ are removed from the set of the system modes.

The objective function f is defined as the norm of the frequency and damping error with respect to the target values

$$f = \sqrt{\sum_i^n \left(\frac{\omega_i - \tilde{\omega}}{\tilde{\omega}}\right)^2 + \sum_i^n \left(\frac{\xi_i - \tilde{\xi}}{\tilde{\xi}}\right)^2} \tag{2.5}$$

where ω_i and ξ_i are the regulator mode frequency and damping ratio at the wind speed with index i and $\tilde{\omega}_i$ and $\tilde{\xi}_i$ are the target regulator mode frequency and damping ratio. No weight is considered between the errors on the frequencies and the damping ratios because they are here considered of equal importance.

The objective of the fatigue-based optimization is to minimize the fatigue damage load of the tower base longitudinal bending moment.

$$f = \sqrt{\frac{1}{n} \sum_i^n \left(\frac{del_i}{\tilde{del}_i}\right)^2} \tag{2.6}$$

where del_i is the damage fatigue load at the wind speed with index i, and $\tilde{del}_i$ is the load of the same sensor of the initial design.

The pole-placement problem does not contain any constraints. The fatigue-based optimization has a constraint that bounds the variations of the rotor speed standard deviation not to increase compared to the reference initial value, and a constraint to avoid the damping ratio of the regulator mode to be higher than a fixed value. The damping ratio is evaluated on a single degree of freedom model of the wind turbine. The constraints are added to avoid the optimization to increase excessively the damping of the regulator mode, that would lead to a slow rotor speed regulation.

2.6 Optimization Framework

The optimizations performed in this investigation are carried out with a framework based on the open-source tool OpenMDAO (Open-source Multidisciplinary Design, Analysis, and Optimization framework) [5, 19, 20, 21]. OpenMDAO provides an interface and tools to help setting up MDAO problems, managing directly data and work flows.

The framework is coupled with the optimization package PyOpt [22] that includes a large variety of optimization algorithms, here the algorithm SNOPT [23, 24] is used.

An application of the framework used to interface OpenMDAO with HAWCStab2 is described by Zahle et al. [13].

3 Results

3.1 Pole-placement

This section shows results of the pole-placement obtained with five different models with increasing order. The five models used for the tuning are:

SDOF single degree of freedom or two states model of the rigid rotor rotation as described by Øye [1];

Model 1 twelve states model including: the rigid rotor rotation, the second-order low pass filter on the rotor speed feedback, the second order band stop filter on the drivetrain frequency, and three second order models of the pitch actuators;

Model 2 same as *Model 1* with the addition of degrees of freedom for blade flexibility;

Model 3 same as *Model 2* with the addition of state variables for the unsteady blade aerodynamics;

Model 4 same as *Model 3* with the addition of state variables for dynamic inflow.

All the gains are computed numerically, except for *SDOF* model. All the linearized models are obtained at the same steady operational conditions that are evaluated including blade deflection. In the case of models *SDOF* and *Model 1* the degrees of freedom associated with the blades deformations are removed after the computation of the steady states, i.e., the blades are deflected in the stationary steady state in an assumed uniform inflow, but vibrations about this mean operational state are neglected.

The target value of the natural frequency is $0.06\,\mathrm{Hz}$ and of the damping ratio is $70\,\%$. The frequencies and dampings are evaluated at five wind speeds in the objective function (Equation (2.5)), 11, 14, 17, 20, and $23\,\mathrm{m/s}$.

The size of the models used in the tuning differs significantly due to the different order. Therefore, the computational time required to reach a solution is different from model to model. The computations with models *Model 1* and *Model 2* last few seconds and 30 minutes respectively. On the other hand, the larger models *Model 3* and *Model 4* take approximately 2 and 3 hours, respectively.

Table 3.1 shows the variation of the controller gains obtained from the pole-placement method with the different models. The gains are normalized with respect to the gains obtained with the model *SDOF* that correspond to the initial solution of the optimization.

Figure 3.1 illustrates the proportional and integral gains of the controller obtained with the pole-placement method with the different models. The plotted gains are the actual PI

Table 3.1: Controller gains variation with respect to those obtained with model *SDOF*. *Model 1* (rigid turbine and filters), *Model 2* (filters and flexible rotor), *Model 3* (filters, flexible rotor, and unsteady aerodynamic), and *Model 4* (filters, flexible rotor, unsteady aerodynamic, and dynamic inflow).

	$k_{P,0}$	$k_{I,0}$	$k_{P,0,\Omega}$	K_1	K_2	$K_{1,\Omega}$	$K_{2,\Omega}$
SDOF	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Model 1	0.883	0.750	0.772	0.937	9.874	0.350	1.396
Model 2	0.631	0.465	0.582	2.484	1.630	0.298	1.290
Model 3	0.620	0.420	0.788	1.729	1.413	0.897	0.985
Model 4	0.570	0.580	0.689	1.435	1.349	1.196	1.052

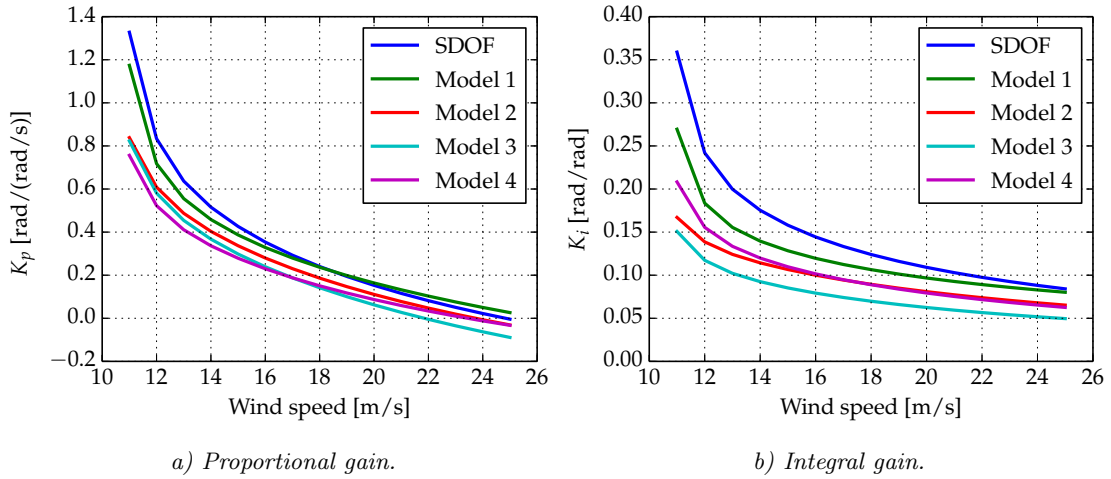a) *Proportional gain.* b) *Integral gain.*

Figure 3.1: Proportional and integral gains. Comparison between the different models used for the tuning *SDOF* (rigid turbine), *Model 1* (rigid turbine and filters), *Model 2* (filters and flexible rotor), *Model 3* (filters, flexible rotor, and unsteady aerodynamic), and *Model 4* (filters, flexible rotor, unsteady aerodynamic, and dynamic inflow).

gains, described in Equation (2.1), therefore they include the gain-scheduling. For increasing wind speeds the aerodynamic damping increases, therefore, the proportional controller gain has to decrease for increasing wind speed to avoid the regulator mode damping to increase excessively. Similarly, also the integral gain has to decrease to keep the regulator mode frequency close to the desired values. When the model order is increased, the proportional gain is systematically decreased. On the other hand, the integral gain decreases for increasing model complexity except when the dynamic inflow model is included. In this case, the gain is higher than when only the dynamic stall is included (*Model 3*).

Figure 3.2 shows the damped frequency and damping ratio of the regulator mode of the models used for the tuning. The figure includes only the results of models *Model 1*, *Model 2*, *Model 3*, and *Model 4*, where the black dashed line is the target value. The results show the effectiveness of the optimization to minimize the cost function because the model used for the tuning and the evaluation are the same. The plots show that when the model is simple, and it has few degrees of freedom, the optimization finds a tuning that allows
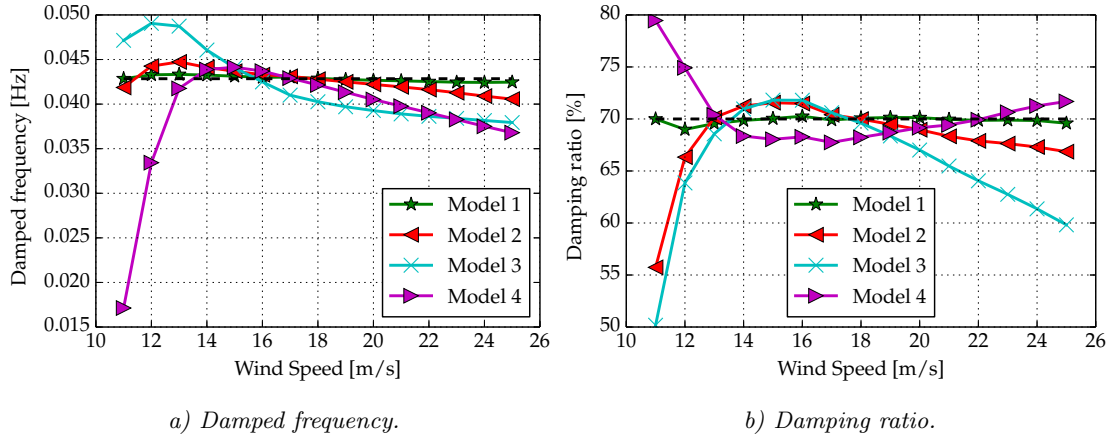
a) Damped frequency.   *b) Damping ratio.*

Figure 3.2: Regulator mode frequency and damping evaluated with model used for the tuning. Comparison between the tuning obtained with models *SDOF* (rigid turbine), *Model 1* (rigid turbine and filters), *Model 2* (filters and flexible rotor), *Model 3* (filters, flexible rotor, and unsteady aerodynamic), and *Model 4* (filters, flexible rotor, unsteady aerodynamic, and dynamic inflow). The black dashed lines are the target values.

the regulator mode to coincide with the target one. When the model used for the tuning has a high-order, the discrepancy between the target frequencies and dampings and the evaluated ones increases. *Model 2* is able to achieve a good fitting of the target frequency, however, at low wind speed, the damping ratio obtained is lower than desired. When the unsteady aerodynamic is included (*Model 3*), the maximum difference on the frequency is almost 10 %, and the damping decreases both at low and high wind speeds. These gaps can be related to the inability of the gain-scheduling function to better fit the turbine characteristics. The gain-scheduling assumes a certain shape function to compensate the variations of the wind turbine properties, that apparently is not sufficient to capture the physics of the high-order models. *Model 4* has a different behavior than the other models. The damping of this model is higher than the target one at low and high wind speeds. The higher damping at low wind speeds reduces significantly also the value of the damped frequency.

Figure 3.3 shows the damped frequency and damping ratio of the regulator mode of the full high-order model for different tuning. The figure compares the results of the tunings obtained with models *SDOF*, *Model 1*, *Model 2*, *Model 3*, and *Model 4*. All the models except from *Model 4* have the regulator mode with frequency and damping very different from the one evaluated with the same model as in the tuning (Figure 3.2). These differences illustrate the effects of the different model complexity on the controller dynamic. The tuning obtained with *Model 1* is not able to guarantee the position of the regulator mode once the dynamic is evaluated with the full high-order model. At the lowest wind speed, the frequency is more than twice the target value, and the damping is significantly lower. When the rotor speed filter is included in the model for the tuning, an important improvement is obtained compared to the *SDOF* model. Indeed, the damping increases at all wind speeds. Models *Model 2* and *Model 3* show the effects of considering the blades deflection and the dynamic stall model in the tuning process. Despite these two models are already with a
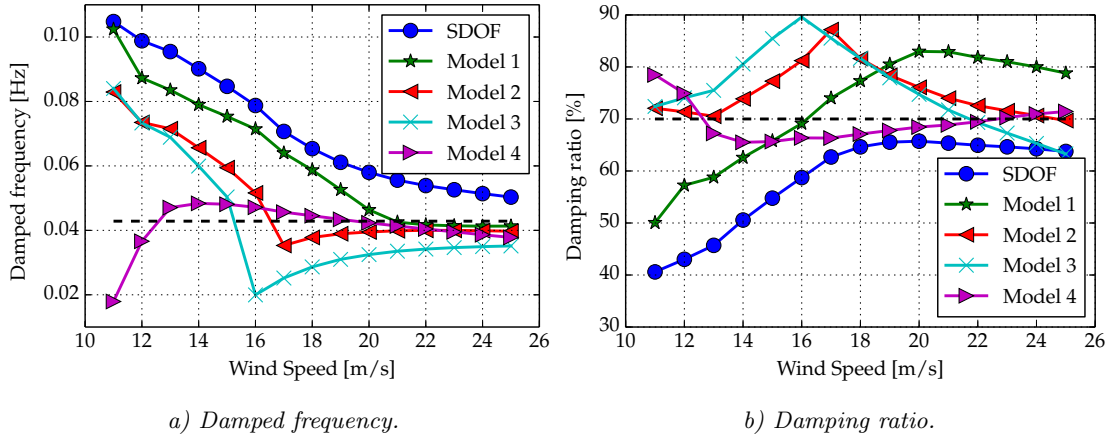
a) Damped frequency.

b) Damping ratio.

Figure 3.3: Regulator mode frequency and damping evaluated with the full high-order model. Comparison between the tuning obtained with models *SDOF* (rigid turbine), *Model 1* (rigid turbine and filters), *Model 2* (filters and flexible rotor), *Model 3* (filters, flexible rotor, and unsteady aerodynamic), and *Model 4* (filters, flexible rotor, unsteady aerodynamic, and dynamic inflow).

high detail, the placement of the regulator mode is still far from the target values. The main advantage of these models is the increase of the minimum damping ratio. However, the frequency is also reduced, especially when also the dynamic stall model is included, leading to a slow controller dynamic. The frequency and damping of models *Model 2* and *Model 3* are non-smooth between 15 m/s and 17 m/s. Only once a model of the dynamic inflow is included in the tuning procedure, the regulator mode frequency and damping are more uniform.

To have a better understanding of the behavior of the regulator mode, the eigenvalues in its proximity are plotted in Figure 3.4. In the figure, the increasing marker size indicates increasing wind speed, with a wind step size of 0.3 m/s, and the different color distinguish the different tuning models. The regulator modes poles are those with an imaginary part close to 0.04 Hz at high wind speed. All the eigenvalues with an imaginary part lower than 0.005 Hz are associated with the dynamic inflow and dynamic stall models. An additional eigenvalue with an imaginary part close to 0.02 Hz is present. This pole is highly affected by the tuning and the dynamics of the inflow. The real part of the pole varies considerably when the wind speed increases, the mode is not present when frozen wake is assumed, and it is not so isolated from the other aerodynamic poles when the controller is not present. For models *SDOF* and *Model 1*, this eigenvalue has approximately a real part of −0.02 Hz and an imaginary part of 0.02 Hz at low wind speed, and for increasing wind speed its real part increases in absolute value. Interesting is the interaction of this mode with the regulator mode of model *Model 2*. When the real parts of this mode and the regulator mode are close to −0.06 Hz, the two poles attract each other and they separate again at higher wind speed. This interaction leads to the non smooth trend of the regulator mode damping of *Model 2* and *Model 3*, shown in Figure3.3. In the case of *Model 4*, this mode has a different behavior; it starts with a higher frequency and a real part close to −0.09 Hz and for increasing wind speeds its imaginary part decreases. This different behavior, compared with the two other models, raises the doubt on which mode is actually the regulator mode

for this tuning. Further investigations are required to better understand the nature of this additional mode and to identify which of these modes dominate the dynamic of the controller and therefore the dynamic of the rotor speed response.

From the investigation it appears that the dynamic inflow model, highly interacts with the regulator mode, affecting significantly the controller frequency and damping. Furthermore, if the dynamic inflow model is included in the tuning procedure, as for *Model 4*, the identification of the regulator mode among all the aeroservoelastic modes becomes non-trivial. Further effort should be spent to better understand the dynamics of the controller and dynamic inflow interaction and, therefore, better exploit this tuning technique.

3.2 Fatigue-based Method

This section presents the results of two test cases where the fatigue based method is used to tune the PI pitch controller.

The fatigue loads and the damping ratio are estimated and used in the objective function (Equation 2.6) and constraint at the wind speeds of 12, 14, 16, and 18 m/s. The cases have different constraints on the maximum damping ratio of the one degree of freedom model. In the first case, *Tuning 1*, the maximum damping ratio is 80 %, in the second case, *Tuning 2*, it is 95 %. *Tuning 1* achieves a objective function reduction of 1.01 %, *Tuning 2* of 2.06 %. Both solutions have the constraint on the rotor speed variation active at 12 m/s and the one on the damping ratio active at 18 m/s.

The gains obtained from this optimization are shown in Figure 3.5 and Table 3.2. Also the values of a reference tuning, that is the initial guess for the optimization, are illustrated. The reference tuning is obtained with pole-placement of a single degree of freedom model.
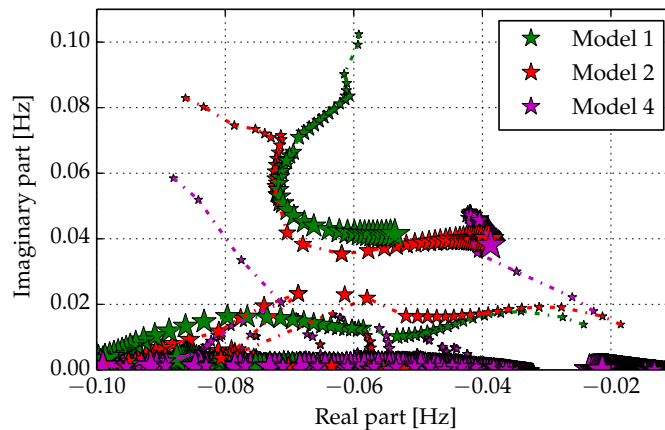

Figure 3.4: Full high-order model poles close to the regulator mode as function of the wind speed. Comparison between *Model 1* (rigid turbine and filters), *Model 2* (filters and flexible rotor), and *Model 4* (filters, flexible rotor, unsteady aerodynamic, and dynamic inflow). Increasing marker size means increasing wind speed. Wind step size: 0.3 m/s.

Table 3.2: Controller gains variation with respect to *Reference*. Comparison of *Tuning 1* and *Tuning 2* obtained with the fatigue-based method.

	$k_{P,0}$	$k_{I,0}$	$k_{P,0,\Omega}$	K_1	K_2	$K_{1,\Omega}$	$K_{2,\Omega}$
Ref.	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Tuning 1	1.140	0.894	0.800	0.934	0.937	1.032	1.119
Tuning 2	11.059	0.702	1.400	0.823	1.858	1.216	1.940

Both proportional gains are higher than the reference one. *Tuning 1* is uniformly higher at all wind speeds. At low wind seed, *Tuning 2* is similar to the reference value and it becomes higher for higher wind speeds. On the other hand, the integral gains are both lower than the reference value.

Figure 3.6 shows the tower base longitudinal bending moment damage equivalent load evaluated with nonlinear time domain simulations. The figure shows the actual values for six different turbulence seeds and their mean values.

Figure 3.7 shows the tower base longitudinal bending moment and rotor speed fatigue damage variation with respect to the reference solution. The loads are evaluated with nonlinear time domain simulations. The variations in the tower loads are small and not uniform. *Tuning 2* achieves a load reduction that on average is 1%, while *Tuning 1* almost does not affect the loads. On the other hand, the rotor speed variations are more significant. *Tuning 1* satisfies the constraint on the rotor speed in all the operational region, on the other hand *Tuning 2* has higher rotor speed variations in the first part of the region. These increases are not captured by the linear model used for the tuning. *Tuning 1* is faster (it has a lower damping ratio) compared to *Tuning 2* because it has a higher proportional gain, especially below $20\,\mathrm{m/s}$. On the other hand, both tunings, have lower integral gain that means lower frequency of the regulator mode and, therefore, less aggressive regulation. The obtained loads are the result of a balance between these behaviors.
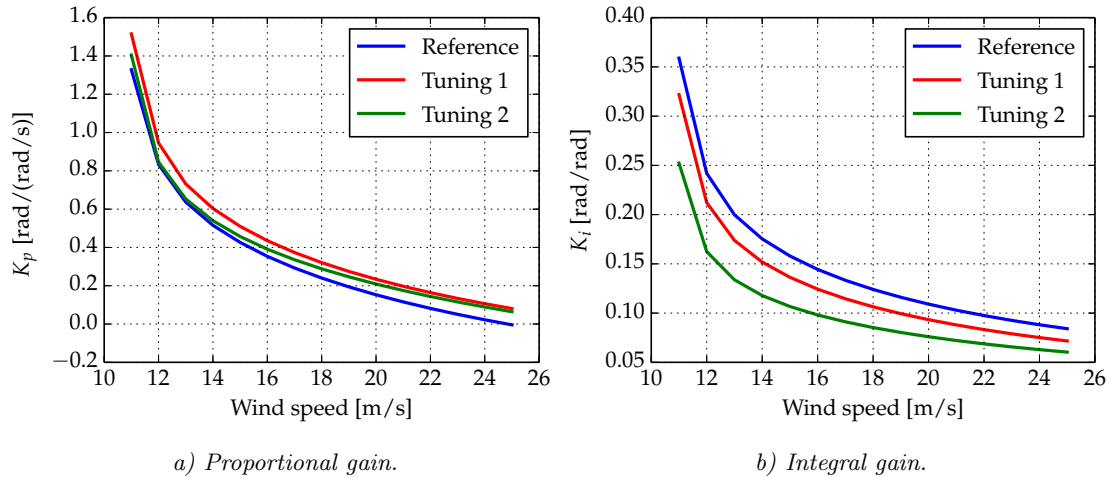

a) Proportional gain.   b) Integral gain.

Figure 3.5: Proportional and integral gains. *Reference*, *Tuning 1*, and *Tuning 2* obtained with the fatigue-based method.

This investigation should be repeated evaluating the loads also at higher wind speeds. The focus should be on understanding if the loads can be reduced above 20 m/s since the obtained tunings lead to lower rotor speed variations.
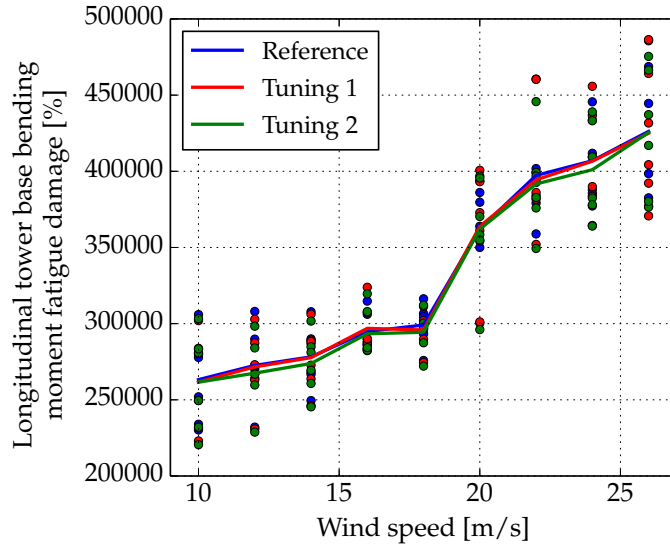

Figure 3.6: Tower base longitudinal bending moment damage equivalent load evaluated with HAWC2. Values and mean. Comparison between the *Reference* tuning, *Tuning 1*, and *Tuning 2*.
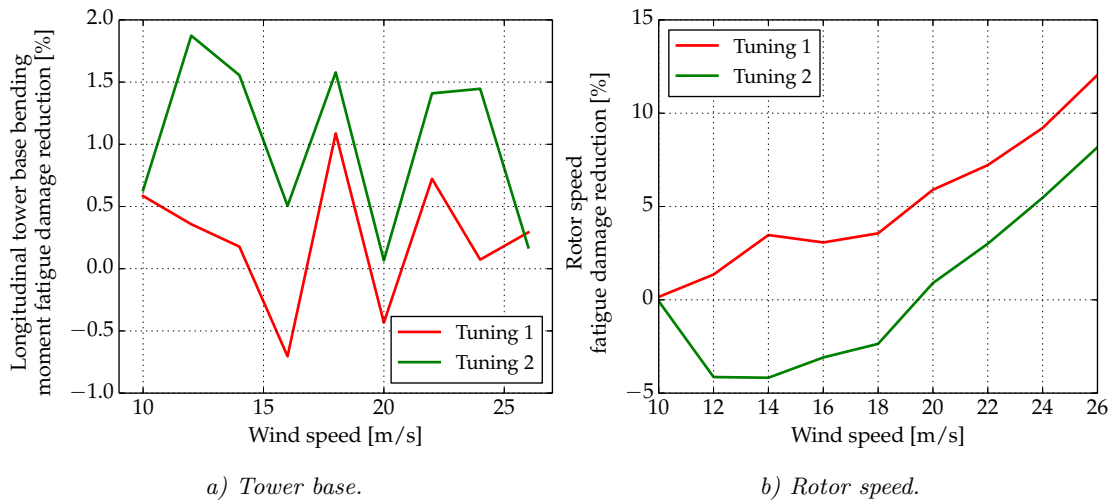

a) Tower base.

b) Rotor speed.

Figure 3.7: Tower base longitudinal bending moment and rotor speed damage equivalent load evaluated with HAWC2. Load variation of *Tuning 1* and *Tuning 2* with respect to the reference tuning.

4 Conclusion

This report has presented two methods to systematically tune the gains of the PI pitch controller of the Basic DTU Wind Energy Controller. The first method is based on pole-placement technique and the second on fatigue loads reduction. Both methods require linear models of a wind turbine that are here obtained with HAWCStab2. These techniques are solved with numerical optimization.

The frequency placement method shows improvements compared to the state-of-the-art method but only when the model complexity is low. Including the rotor speed low pass filter in the tuning model improves the placement of the mode increasing the damping. However, when the model order increases, no significant improvements are noticed. Further investigations are required to better understand the interaction between the pole associated with the regulator and those associated with the dynamic inflow. Improvements in the gain-scheduling, such as a higher order scheduling function, could allow for better placement of the mode.

The fatigue based method has the advantage that it does not require any parameter decided a priori, since it is load based, therefore, better trade-off between tower loads and rotor speed regulation should be achieved. The tunings obtained with this techniques leads to lower tower loads at the price of compromising the rotor speed regulation in the first part of the operational region. The performances are evaluated by nonlinear time domain aeroservoelastic simulations.

Further analysis with the fatigue based techniques should be performed to identify if the reduction of the rotor speed variations at high wind speed can be limited to further reduce the tower loads.

However, these methods might be too slow to be used extensively for tuning applications. Only the pole-placement technique with the model that includes also the rotor speed filter improves the placement of the pole and gives results within few seconds, therefore it can be employed as a new tuning reference without compromising computational time.

No considerations on the actual load level have been done for the pole-placement technique. New investigations should focus on identifying better strategies than having the regulator mode frequency at the same value throughout the operational region.

Future analysis should focus on the integration of these techniques in a wind turbine optimization design procedure to perform concurrent rotor and controller design.

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DTU Wind Energy

DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 230 staff members of which approximately 60 are PhD students. Research is conducted within 9 research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.