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WIND TURBINE CONTROL FOR REDUCING TOWER OSCILLATIONS

Diploma Thesis

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ABSTRACT

This master thesis deals with the reduction of tower oscillations on the D8.2 wind turbine in Cuxhaven. First, basic terms needed in wind turbine control are clarified; a brief description of the D8.2 wind turbine in Cuxhaven is given, focusing on the main control plant and two controllers. Thesis is looking for the new design of a pitch controller, which reduces tower oscillations in a wind turbine, in first step through comparing existing methods to mitigate tower nodding. After comparison, a proper control strategy is chosen and the new pitch controller is tested on the current model of the wind plant. Finally, results are compared with those of the old pitch controller.

Keywords: wind turbine, damping of tower oscillation, wind turbine control.

SÚHRN

Diplomová práca sa zaoberá tlmením oscilácií veže veternej turbíny D8.2 v Cuxhavene. Približuje základné pojmy potrebné na orientáciu v danej tematike, zároveň opisuje časti veternej turbíny D8.2, s detailným opisom hlavného riadeného systému a dvoch regulátorov. V projekte sa hľadá návrh nového regulátora sklonu lopatiek veternej turbíny, ktorý by tlmil kmity veternej veže, najprv porovnávaním už existujúcich metód. Po ich porovnaní sa vybraná stratégia riadenia testuje na modeli danej veternej turbíny. V závere je porovnaná kvalita riadenia s použitím pôvodného a nového regulátora sklonu lopatiek.

Kľúčové slová: veterná turbína, tlmenie oscilácií veže, riadenie veterných turbín.

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CONTENTS

ABBREVIATIONS USED IN THE THESIS

A	ripple in the passband (Chebyshev filter)
a_T	tower acceleration in axial direction in m.s^{-2}
C_p	power coefficient
C_T	thrust coefficient
e_2	eigenvalue in the pitch control system
F	normalized passband edge frequency (Chebyshev filter)
F_T	thrust force in axial direction in N
H	guide vane position
k_1	gain for the P part in the cascaded pitch controller
k_2	gain in controlled system for blade adjustment
k_3	gain of wind speed in controlled system for blade adjustment
k_I	integral gain of the PI part of the cascaded pitch controller
k_p	proportional gain of the PI part of the cascaded pitch controller
k_R	gain for the PI part in the cascaded pitch controller
k_{Sp}	gain in controlled system for blade adjustment
M_A	aerodynamic torque in Nm
M_R	rotor torque in Nm
N	order of the filter (Chebyshev filter)
n_{An}	input rotor speed in rpm
n_{AnSoll}	input rotor speed setpoint in rpm
n_n	rotor speed setpoint in rpm
n_R	rotor speed in rpm
P_c	captured wind power
P_{Soll}	power setpoint
P_w	wind power
R	length of a blade in m
T_{Sp}	time constant in controlled system for blade adjustment
u_p	control signal of the pitch controller for blade adjustment
v_x	tower speed in axial direction in m.s^{-1}
w_∞	wind speed in m.s^{-1}

x_T	tower position in axial direction in m
β	pitch angle
λ	tip-speed-ratio
ρ	density of air
Ω_R	rotor speed in rad.s^{-1}

LIST OF FIGURES

1 INTRODUCTION

The mitigation of mechanical loads from tower's fore-aft mode and this way prolonging wind turbine's lifetime forces us to improve pitch control performance.

To become acquainted, some basic knowledge is needed in the field of wind turbine control. Brief descriptions of wind, its sources and properties are given in the second chapter, also objectives and strategies for controlling a wind turbine are presented. Several phenomena observable in the proximity of the wind turbine are introduced and different types of mechanical loads are listed.

The next chapter deals with the wind turbine plant D8.2 located in Cuxhaven. Currently used controllers are described, with a special attention to pitch control.

The goal of this work is to find a new pitch controller, which can reduce tower oscillation since tower acceleration is limited. First of all, a review of selected methods is given and being compared in the fourth chapter which serves as a base for improving the existing pitch controller. As the model of the whole wind plant is quite complicated and is a high order one, some simplifications have to be used to create a design model, which is going to be linearized. This acquired design model enables us to develop a pitch controller with better performance. Two approaches are applied, first one is based on retuning the existing controller with respects to tower oscillations, in the second one pitch controller is extended with the tower acceleration being used as a feedback signal.

At the end of the chapter, results are compared numerically and graphically, advantages and disadvantages of the new pitch controller are presented.

2 INTRODUCTION TO WIND TURBINES

2.1 Wind

Wind is the flow of air caused by pressure differences in the atmosphere caused by uneven solar heating. Wind at a given place is a combination of the geostrophic and local winds. Geostrophic winds are constituted when equatorial air, which is warmer and lighter, rises and moves towards the poles, while cooler air from the polar area replaces it. As the Earth rotates, Coriolis forces take affect on this flow. Local winds are formed when geostrophic winds are delayed by frictional forces and obstacles.

Most important characteristics of the wind are its direction and speed, which are, among other, affected by location, altitude, climate, surface, obstacles and presence of water. The wind speed can be measured with anemometers, in form of rotating cups or propellers.

We can divide wind speed into two components:

- mean wind speed
- and turbulence.

The mean wind speed is obtained as the average of the instantaneous speed over a time interval while turbulences include all wind speed fluctuations with frequencies over the spectral gap [1]. It is important to note that turbulences have great effect on loads and quality of power but almost negligible effect on the annual capture of energy.

Equation 1 shows how much power P_w is stored in wind in average:

$$P_w = \frac{1}{2}\rho A_w \int_0^T w_\infty^3 dt \tag{1}$$

where ρ is the density of air, A_w is the area through which wind is passing, w_∞ is the wind speed and T is the time period, usually one year.

2.2 Wind turbines

Wind turbines, according to [1], are mechanical devices specifically designed to convert a part of the kinetic energy of the wind into useful mechanical energy.

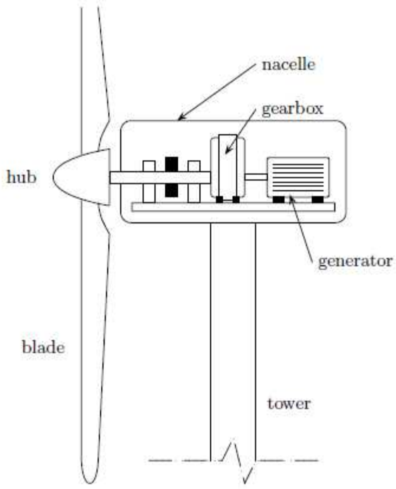

Figure 2.1 Example of a typical wind turbine [1]

A typical wind turbine as in Figure 2.1 has usually a horizontal-axis three-bladed rotor. Blades are connected to the hub that stands in front of the nacelle and contains the gearbox and the generator. The nacelle is on the top of the tower – they are joined together by a yaw mechanism that turns the nacelle and the rotor to face the wind.

An important characteristic of a wind turbine is its power coefficient C_p. Essentially, power coefficient C_p is a scaled static blade characteristic independent on the rotor speed. It is defined as the ratio of captured power to wind power:

$$C_p = \frac{P_c}{P_w} \tag{2}$$

In other words, it shows how much energy can be extracted from the wind. Of course, it is limited to a maximum achievable value of 0.593 known as the Betz limit. C_p is a function of the pitch angle β and the tip-speed-ratio λ. The pitch angle is an angle between the chord of the blade element and the rotor plane.

The tip-speed-ratio is defined as

$$\lambda = \frac{\Omega_R R}{w_\infty}, \tag{3}$$

where $\Omega_R R$ is the speed of the blade and w_∞ the speed of the wind.

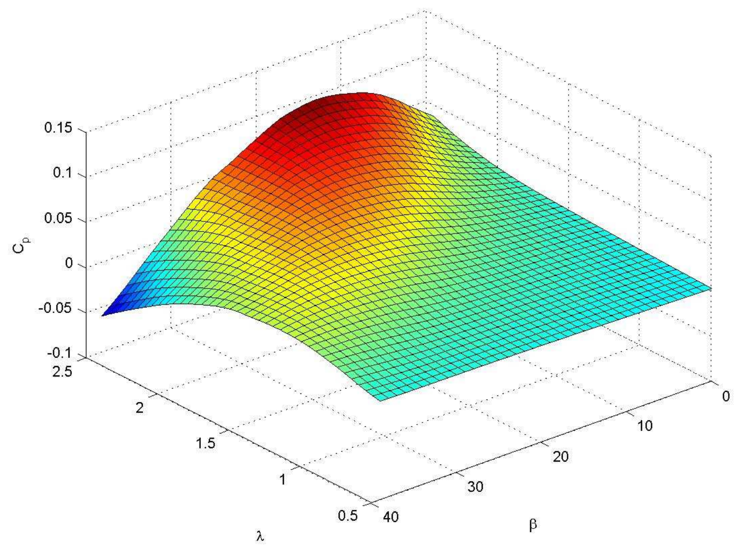

Figure 2.2 Variations of C_p for a wind turbine

On Figure 2.2 a typical dependency of the power coefficient C_p on the pitch angle β and the tip-speed-ratio λ can be seen.

In the proximity of the wind turbine two noticeable phenomena can be observed:

- wind shear
- and tower shadow.

Wind shear is the dependence of the wind speed on altitude. It means that with increasing height above ground the wind speed increases too because of the lack of terrain roughness. In case of the wind turbine, the tip of the blade in the uppermost position experiences higher speed than that blade in lowermost position.

Tower shadow is an effect caused by supporting tower acting like an obstacle that increases the wind speed in lateral direction and decreases in axial. This fluctuation has a greater effect on loads than wind shear.

As a flexible structure, a wind power plant exhibits several oscillatory movements as nodding – tower bending in for-aft direction, naying – tower bending in sideward direction, torsion, flap-wise and edgewise movements (Figure 2.3). From these entire oscillatory behaviours tower nodding has the largest influence on control. In general, it is caused by the fact that wind turbine towers are very high and they are just lightly damped.

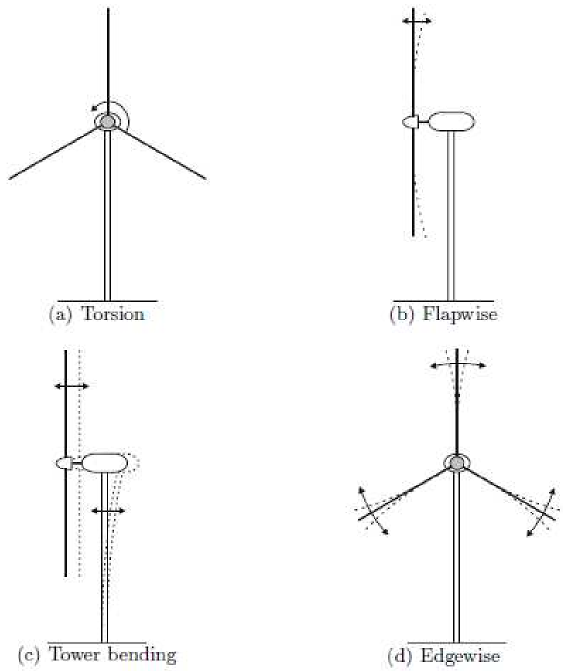

Figure 2.3 Oscillatory movements of the tower [1]

2.3 Control of wind turbines

The control objectives for a wind turbine can be formulated as following:

- Mitigation of mechanical loads
- Maximizing of captured energy
- Maintaining quality of power

Mitigation of mechanical loads – one cannot forget that the presence of permanent loads reduces life of wind turbines. Special attention during control design has to be paid to alleviate loads that can cause damage on parts of a wind turbine. Mitigation of loads lowers the cost of wind energy in longer periods.

Maximizing of captured energy – this objective is limited by economics. There exists a minimal value of wind speed, at which it is not worthy to run the turbine because of the fact that it consumes more energy than it produces. On the other hand, a maximum value of the wind speed must be defined to avoid dangerous mechanical loads at high wind speed. Between upper and lower limits exists a wind speed called rated wind speed. It is a compromise between captured energy and manufacturing costs. This speed divides the operational area into two parts: wind speeds below and above rated wind speed. Below the rated wind speed, power coefficient C_p must reach its maximum value to extract all available energy. However, above the rated wind speed value of power coefficient C_p has to be lowered to maintain rated power.

Maintaining quality of power – "power quality is mainly assessed by the stability of frequency and voltage at the point of connection to the grid and by the emission of flicker"[1]. Usually wind farms are considered as poor quality suppliers but with appropriate control design, the quality of power can be increased.

Wind turbines can be controlled by the rotational speed of the generator and the pitch angle. According to these types of control, four modes of operation can be used depending on the operational wind speed:

- Fixed-speed fixed-pitch – used in older wind turbines. It is very simple and low-cost but not optimal because of the lack of active control which could mitigate loads and improve power quality.
- Fixed-speed variable-pitch – belongs to control strategies used in the past. Conversion efficiency below rated wind speed is not optimal.

- Variable-speed fixed-pitch – used in commercial wind turbines, especially at low wind speeds.
- Variable-speed variable-pitch – conversion efficiency is optimal both in above and below rated wind speed. Wind turbine is operating as variable-speed fixed-pitch below rated wind speed and variable-speed variable-pitch above rated wind speed.

3 CURRENT SITUATION

The wind turbine plant D8.2 with the rated nominal power of 2 MW is located in Cuxhaven, Germany. It is the first wind turbine with an innovative hydrodynamic torque converter technology called WinDrive. WinDrive is a variable-speed gearbox for wind turbines that controls electric power. Its benefits lie in saving cost of the wind turbine, in reduction of down time, in enlarged range of application and in high power feed in quality.

To analyze the current situation a general description of the wind turbine system is needed. In Figure 3.1 the control structure can be seen.

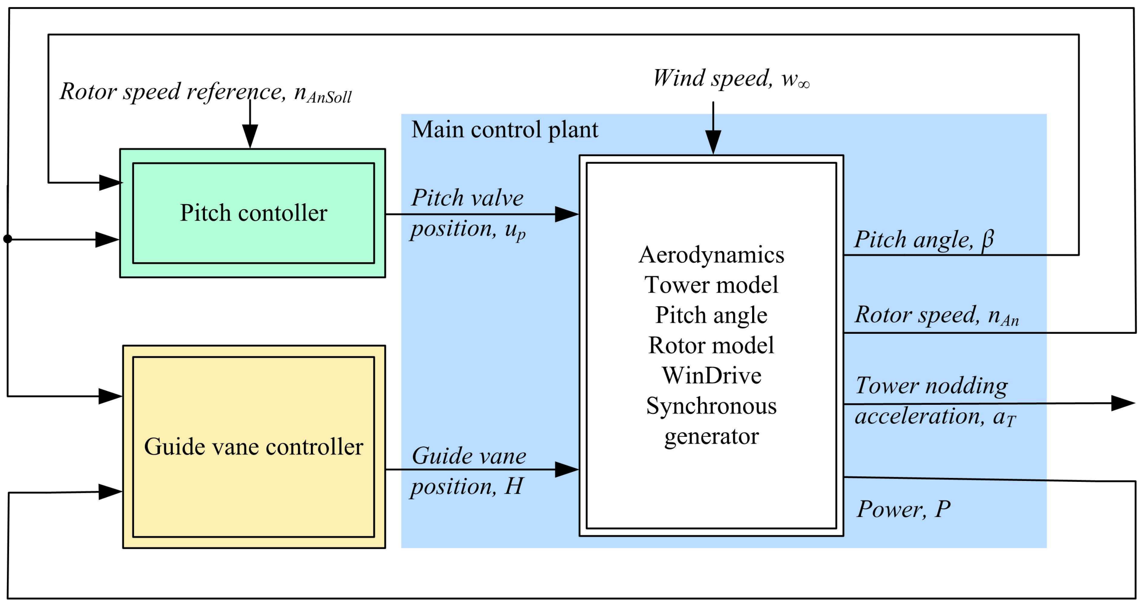

Figure 3.1 General control scheme

The dynamical properties of the controlled system comprises besides aerodynamics, tower oscillation model and pitch angle system, also the coupling of the outputs and inputs, a main actuator, torque converter and hydrodynamic actuators for blade and vane position. The vane position controller depending on the actual rotor speed adjusts the position of the vane in hydraulics to reach the power set point. The main function of the pitch controller is to maintain the rotor speed set point.

3.1 Pitch control system

For control design, a simplified control loop is used as seen on Figure 3.2.

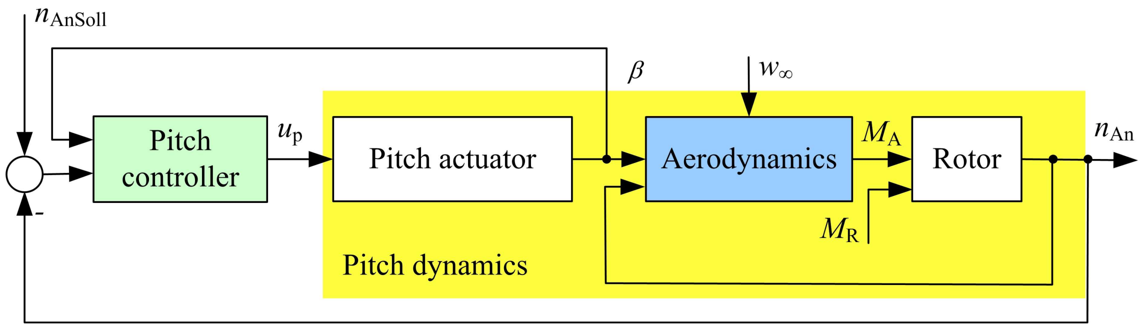

Figure 3.2 Pitch control loop

Based on Figure 3.2 a pitch control loop is designed as seen on Figure 3.3, linearized for different wind speeds, where the parameters k_{Sp} and T_{Sp} are given, parameters k_2, k_3 and e_2 depend on the wind speed w_∞. More information can be found in [2].

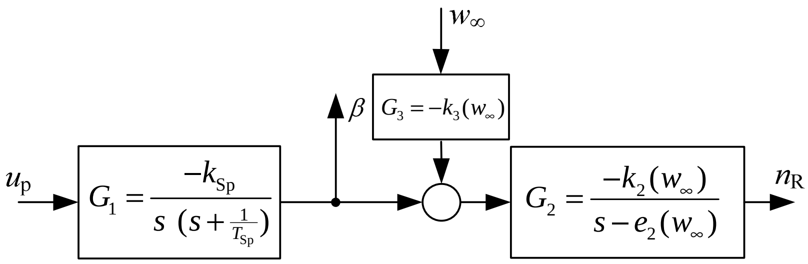

Figure 3.3 Linearized pitch plant

For this linearized pitch plant a P-PI cascade is designed as a controller, with a proportional gain k_1 and PI part in form of the transfer function

$$G_R = k_R \frac{s-e_2}{s}. \tag{4}$$

The realization of the cascade is shown in Figure 3.4.

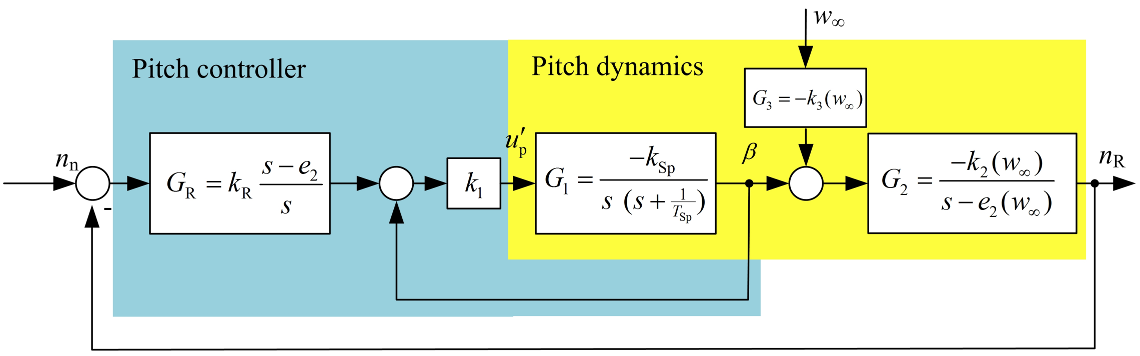

Figure 3.4 Pitch control using a P-PI cascade

Because parameter k_R is dependent on the wind speed, gain scheduling is used. As the controller includes an integrator, anti-windup is used to avoid windup effects (Figure 3.5).

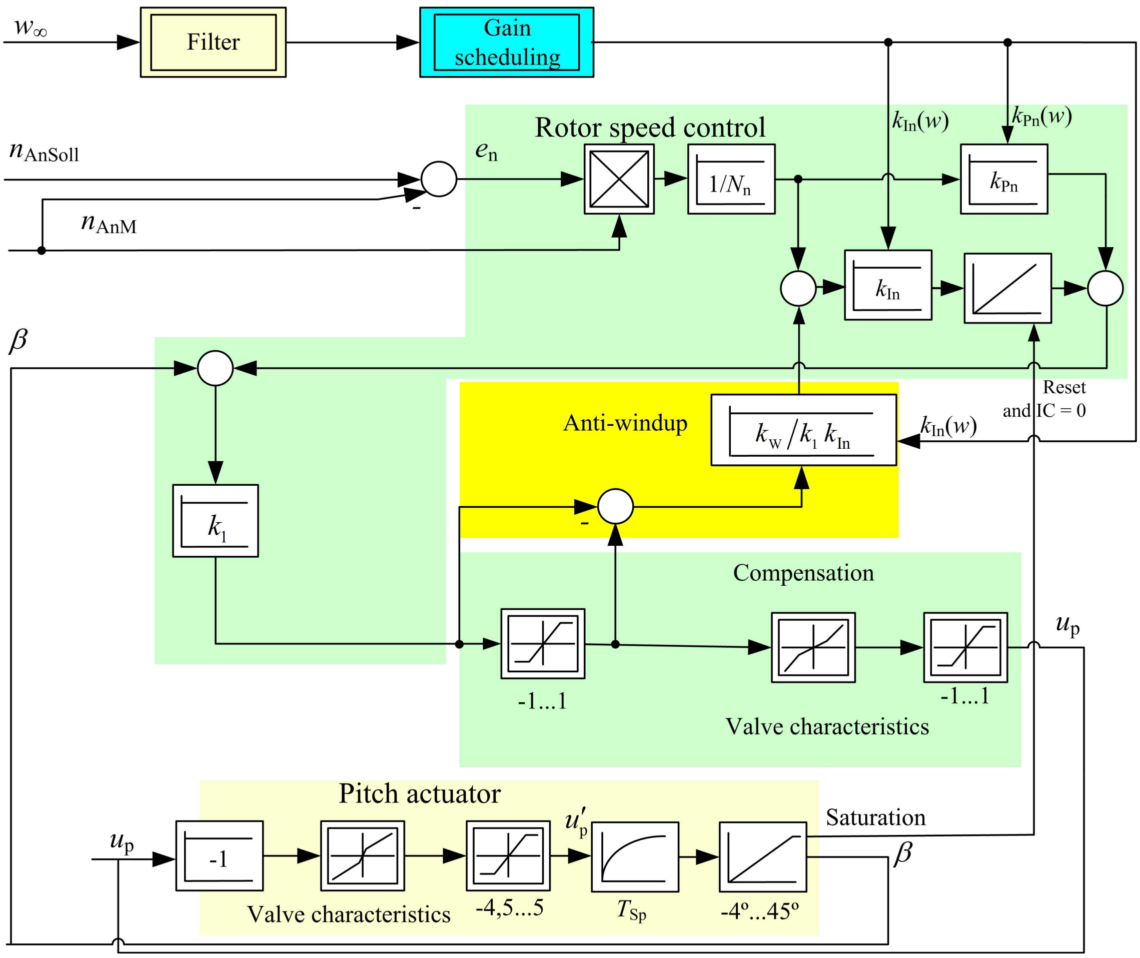

Figure 3.5 Realization of pitch control with gain scheduling and anti-windup

3.2 Power control system

For power control, a multivariable controller accompanied by an observer was chosen as depicted on Figure 3.6. The observer is needed as not every state can be measured and it is realized in form of Kalman filter. Together with the cascaded pitch controller, it ensures a higher dynamic range to settle rapid fluctuations in performance due to wind disturbances. Since both the measurement signals as well as the guide vane control include significant time delays, the design was carried out using a time-discrete model. The parameterization of the state feedback and the Kalman filter is done by weighting factors. The necessity of an integral component in the power controller was proved, as well as anti-windup and feed forward. More information can be found in [3].

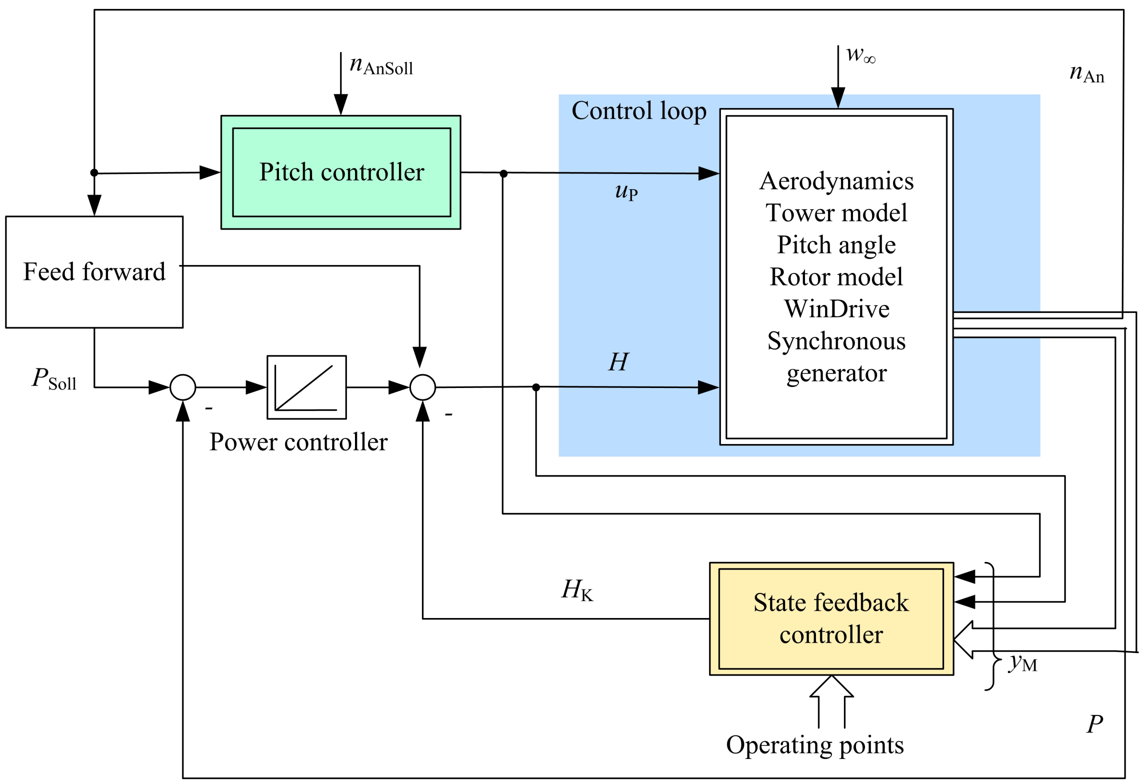

Figure 3.6 Control structure with detailed guide vane control

4 CRITICAL REVIEW

For an improved design for reduction of tower oscillation, a review of current literature has to be made, which compares and highlights advantages of different approaches.

The authors in [4] compare three pitch controllers to reduce tower oscillations. The first one is a standard PID controller without any effort made to improve tower damping. It handles keeping of the rotor speed at a chosen value well when the wind speed changes but tower oscillations are very pronounced.

A new PID controller is designed using an input-output pole-placement method where a desired behaviour of the closed-loop system is chosen through the pitch controller $G_R(s)$. The arranged model is shown in Figure 4.1, where $G_1(s)$ is the transfer function of the servo drive (actuator), $G_{2\beta}(s)$ and $G_{2w}(s)$ are transfer functions of the whole system linearized around the pitch angle and wind speed, respectively.

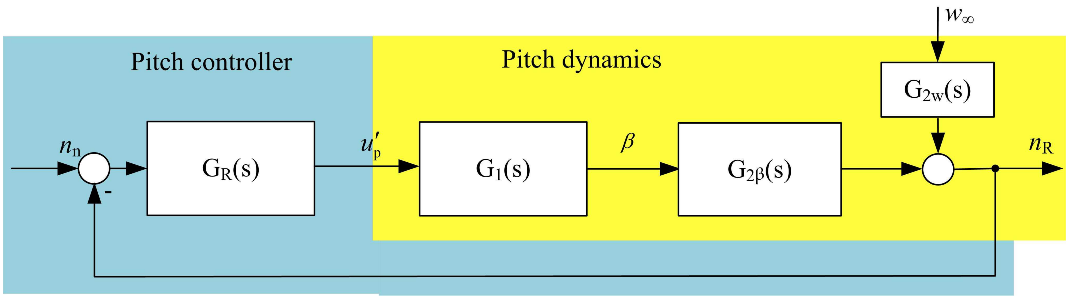

Figure 4.1 Principle scheme of the linearized wind turbine model [4]

The closed-loop transfer function can be derived with respect to the wind speed as in

$$G_{CL\_w}(s) = \frac{G_{2w}(s)}{1 + G_R(s)G_1(s)G_{2\beta}(s)}. \tag{5}$$

This closed-loop transfer function should be equal to the model transfer function G_m realized via the pitch controller G_R, which can be now expressed as

$$G_R(s) = \frac{1}{G_1(s)G_{2\beta}(s)} \frac{G_{2w}(s) - G_m(s)}{G_m(s)}. \tag{6}$$

The model transfer function is chosen in a form that reduces tower oscillations. This means that the tower modal damping has to be increased, naturally without changing tower's structural parameters but by means of pitch controller actions. A desired value of the tower damping coefficient is chosen forming a model with a new set of parameters. This model is linearized and transfer functions are calculated which are used for designing a new PID controller. Now it is possible to calculate a closed-loop transfer function as in Equation 5 that leads us to the desired model. The outcomes are better, the controller deals with rotor speed regulation as good as the previous PID controller and, furthermore, tower oscillations are more damped. However, choosing a larger damping coefficient results in a higher pitch activity that causes additional oscillations, i.e. ability of a controller for reducing tower oscillations is limited.

Finally, a full state-feedback controller is designed using the same method of input-output pole-placement. The process model is rewritten in the space-state form

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{7}$$

where the state variables are rotor speed, rotor acceleration, tower top speed and tower top acceleration and the input variables are wind speed, pitch angle and generator torque. The feedback gains for the selected states can be calculated using Ackermann's formula. The designed controller seems to be a good compromise between increased pitch activity and tower damping. It gives the best results for reducing tower oscillations based on the fact that it uses actual tower oscillations as a feedback signal.

An improved damping of tower oscillations in fore-afterward direction is presented in [5] with respects to external wave forces. The total tower damping comprises three components: structural damping, natural aerodynamic damping and finally active damping. The proposed structure as shown in Figure 4.2 consists of three parts: phase corrected band pass filtering (BPF), conditional feedback gain and non-linear scheduling.

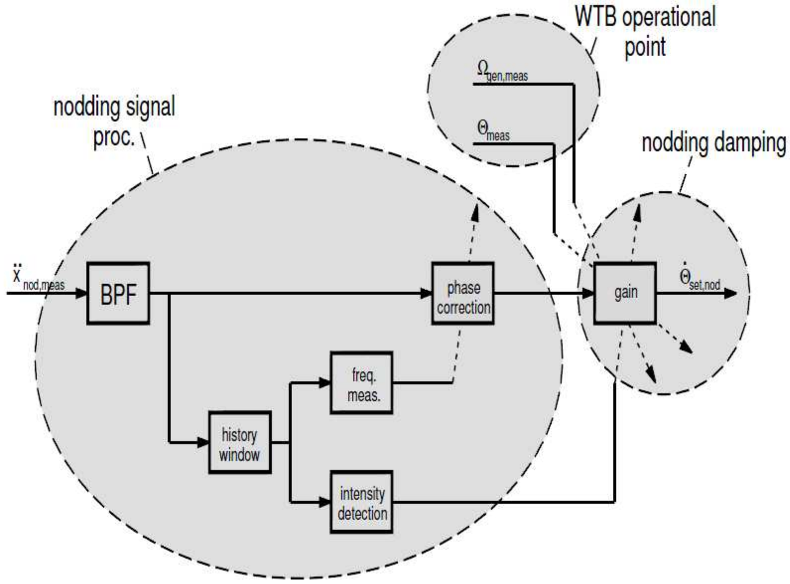

Figure 4.2 Control structure for improved damping of tower nodding [5]

For bandpass filtering a fourth-order Chebyshev filter with 40 dB reduction is used as the most suitable. The choice of this filter is based on the fact that it has a moderate phase slope and that outside this band reduction is guaranteed. The feedback gain factor depends on approaching the chosen tower acceleration limit. If the compared tower acceleration is close to this limit, the value of the feedback gain decreases to an acceptable one. There exists a lower limit too, when the gain factor equals zero to avoid a loss of power. For better results, nonlinear gain scheduling is used as aerodynamical gains depend on rotor speed, pitch angle and wind speed. By applying this design the fore-aft tower bending moment is decreased by 40 percent. However, more frequent pitch actuations lead to variations in rotor speed and power. These deviations are acceptable due to the fact that rated values are maintained.

The authors in [6] are emphasizing the interaction between different loads in blade flap-wise mode and in tower fore-aft mode. The objectives are, besides cancelling tower nodding, do it without reduction of the generator speed loop performance and without exciting other oscillation modes. For simulations a wind turbine aero-elastic package is used which provides results representative of a full 20 years lifetime of a wind turbine.

A tower feedback loop is designed which uses tower speed derived from the tower acceleration as a feedback and without redesigning an existing generator speed loop. It is possible because tower feedback loop and generator speed control loop do not interact with each other, as they are active over different frequency ranges. The proposed structure is depicted in Figure 4.3,

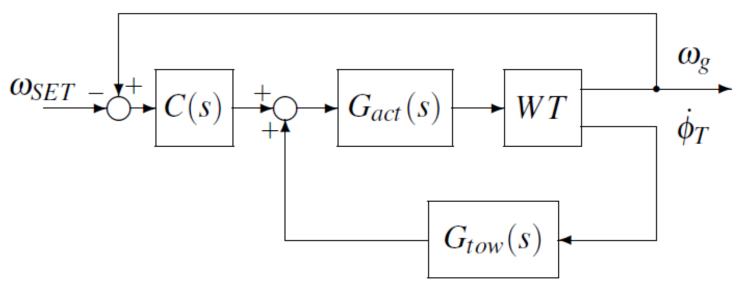

Figure 4.3 Inner loop for the cancelling of the tower fore-aft mode [6]

where ω_{SET} is the generator speed set point, ω_g represents the generator speed output, $\dot{\phi}_T$ is the tower speed output, *C(s)* is the generator speed loop controller, *WT* represents the dynamics of the wind turbine from pitch angle to the generator speed, $G_{act}(s)$ is the pitch actuator and $G_{tow}(s)$ is the tower feedback loop controller. As mentioned before, the tower feedback loop controller is added to an existing design, forming an inner loop but with respect to the fact that the generator speed feedback loop is already closed.

The inner loop has impacts on the outer loop, thus the dynamics of the outer generator speed feedback loop is modified as seen on Figure 4.4.

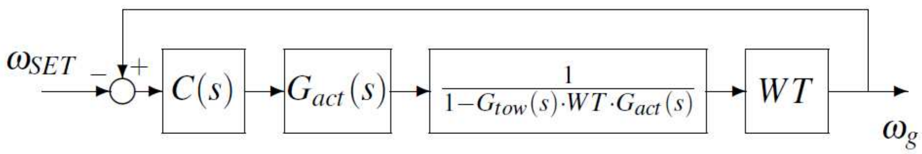

Figure 4.4 Modified control loop

A first approach is setting the tower feedback loop controller as a constant, i.e. proportional feedback. Despite using this gain decreased tower oscillations in fore-aft direction, it reduced stability margins or even led to instability. In addition, it had negative effects on the performance of the generator speed loop. In lifetime simulations instead of reducing the load this approach increased it by 4 percent. An alternative tower feedback loop controller was designed in form of a filter, consisting of a bump that enhances signal in tower nodding frequencies and a wash out filter providing phase advance in tower frequency and filtering out low frequencies. The controller succeeds in damping of tower oscillations without exciting the flap mode and it causes just a little reduction in performance of the generator speed feedback loop. In lifetime simulations this controller reduced tower fatigue loads by 8 percent.

Conclusions from the review for the design of a new controller:

- current pitch controller uses a P-PI cascade, so instead of building a state-feedback controller, current one should be tested whether there is a place for improvements or not,
- based on the fact that a simple proportional tower feedback can lead to instability, it would be much cleverer to build a tower feedback controller consisting of a filter and a gain,
- as on the wind turbine plant in Cuxhaven tower acceleration is measured, this signal should be used as a feedback signal for the controller. Moreover, the derived tower speed used in [6] usually generates some information losses.

5 CREATING A DESIGN MODEL

For creating the design model for the pitch controller that reduces tower oscillations, the existing one (Figure 3.2) should be extended. This extension includes primarily tower dynamics as can be seen on Figure 5.1. Tower dynamics gives us the signal of tower acceleration (a_T) on which we can observe tower oscillations. However, it needs the input signal of thrust force (F_T) which is not added as an output from the aerodynamics yet. First, let us see what is happening inside aerodynamics.

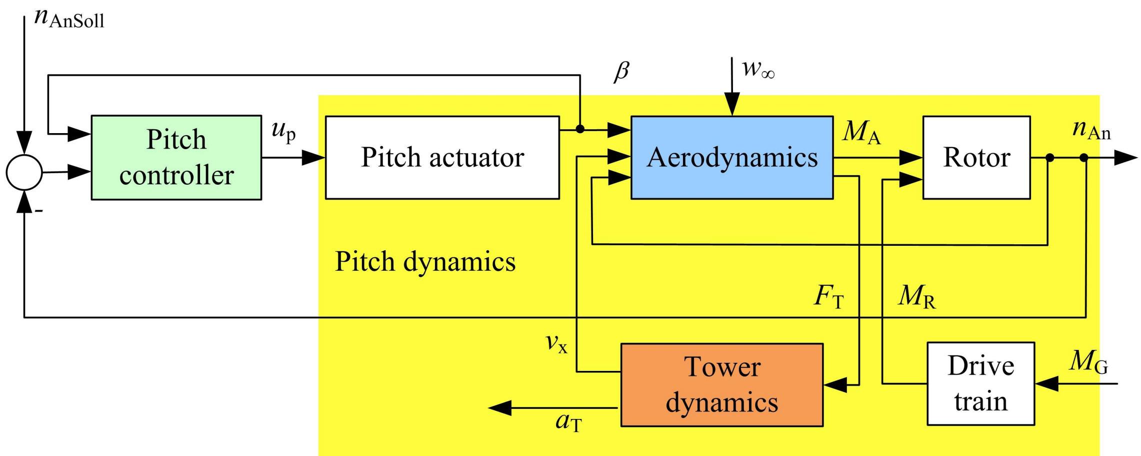

Figure 5.1 New design model extended with tower dynamics

Aerodynamics includes power coefficient C_p that transforms inputs as wind speed w_∞, pitch angle β and rotor speed n_{An}, into aerodynamical torque M_A. To see this in a form of an equation, firstly, captured power has to be expressed, as C_p is a power coefficient:

$$P_c = C_p(\beta, \lambda)P_w \tag{8}$$

Thus, according to [1] we can write:

$$P_c = \frac{1}{2}\rho\pi R^2 C_p(\beta, \lambda) w_\infty^3 \tag{9}$$

and

$$M_A = \frac{1}{2}\rho\pi R^3 \frac{C_p(\beta,\lambda)}{\lambda} w_\infty^2, \qquad (10)$$

where ρ is the density of air and R is the length of a blade.

For the new signal of thrust force, which makes the tower move in axial direction, there is a need to generate a new coefficient C_T similar to C_p that transforms all inputs into thrust force F_T.

5.1 C_T-table

The thrust force F_T can be expressed [1] using thrust coefficient C_T as

$$F_T = \frac{1}{2}\rho\pi R^2 C_T(\beta,\lambda) w_\infty^2. \qquad (11)$$

According to equation above, following simulation scheme (Figure 5.2) was used to obtain the C_T-table.

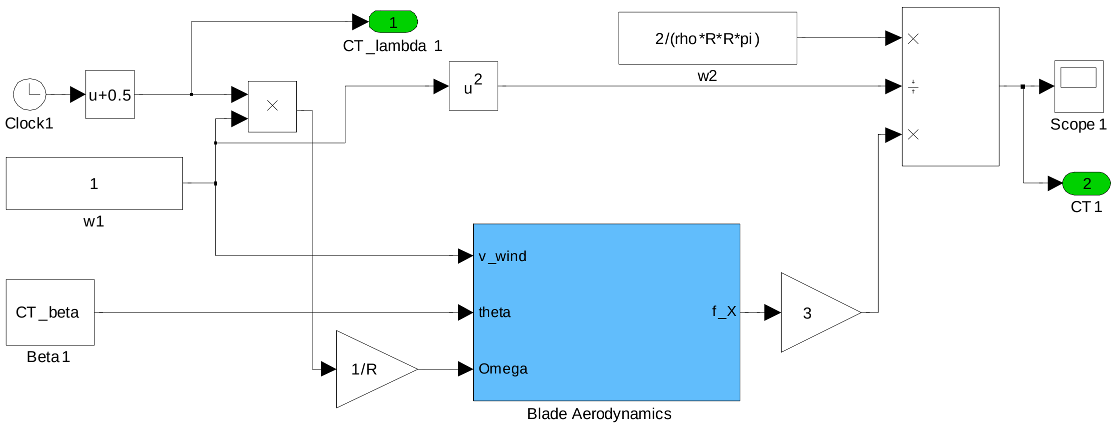

Figure 5.2 Simulink realization of the C_T-table generation

Blade Aerodynamics is a modelling block, which describes the behaviour of the blades, in this case just thrust force *f_X* (corresponding to F_T) was used as an output signal.

The dependence of C_T on the pitch angle β and tip-speed-ratio λ is depicted on Figure 5.3, detailed view in working area on Figure 5.4.

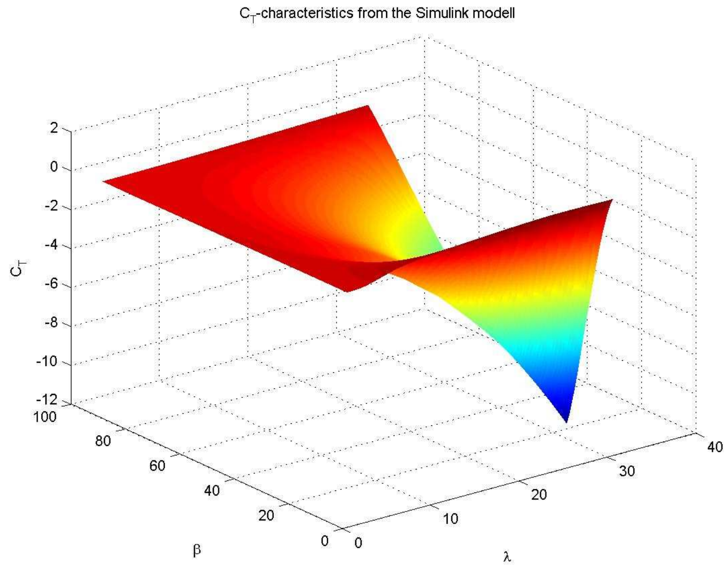

Figure 5.3 Generated C_T-table

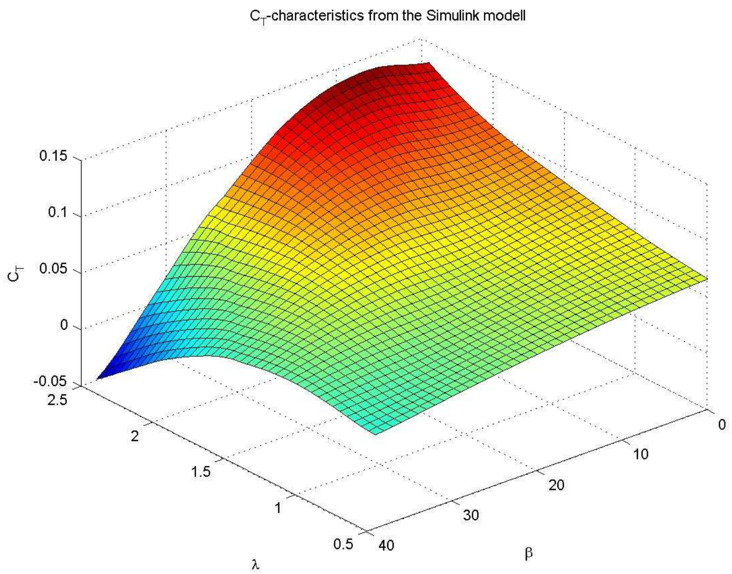

Figure 5.4 C_T-table in the working area

The C_T-table is ready to use, let us move on to the linearized design model.

5.2 Linearized design model

A design model should be linear, it makes easier to design a controller. A design model with three inputs – wind speed w_∞, pitch angle β and guide vane position H and three outputs – rotor speed n_{An}, power P and tower acceleration a_T, as seen on Figure 5.5, was linearized. Linearization of the whole design model was made by *linmod* command in MATLAB. You can find the simple input-output model on Figure 5.6.

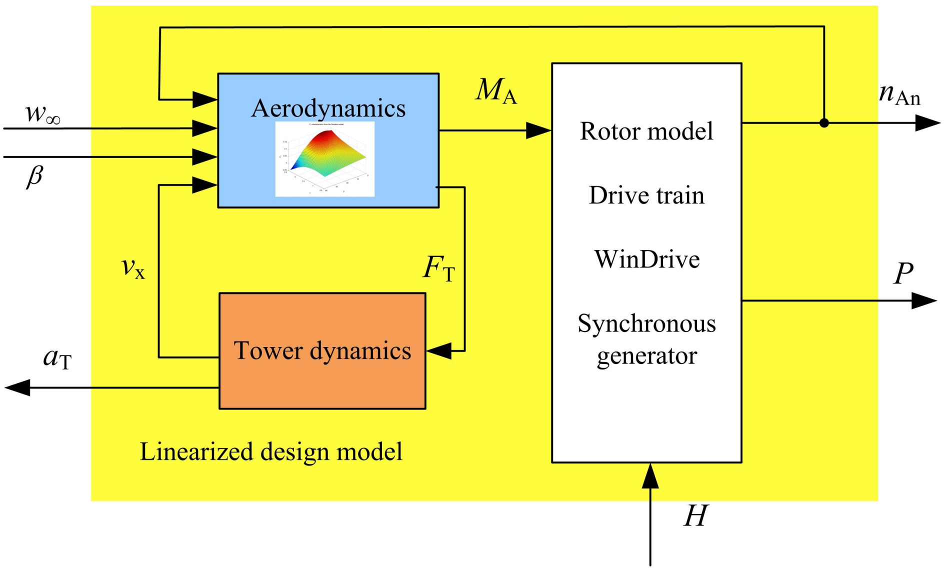

Figure 5.5 Linearized design model

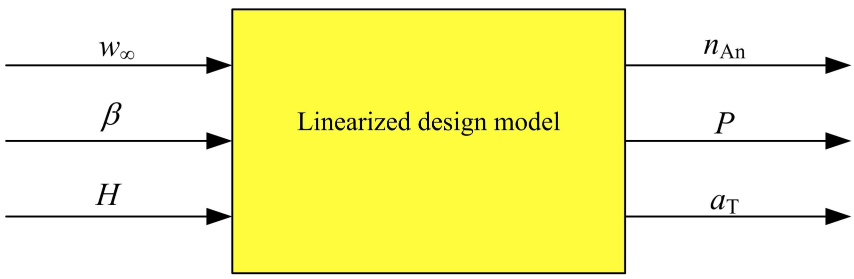

Figure 5.6 Simple structure of the linearized design model

In Figure 5.7 the correctness of the linearization is shown by a step response to a +20 % change made in input signals wind speed w_∞, pitch angle β and guide vane position H.

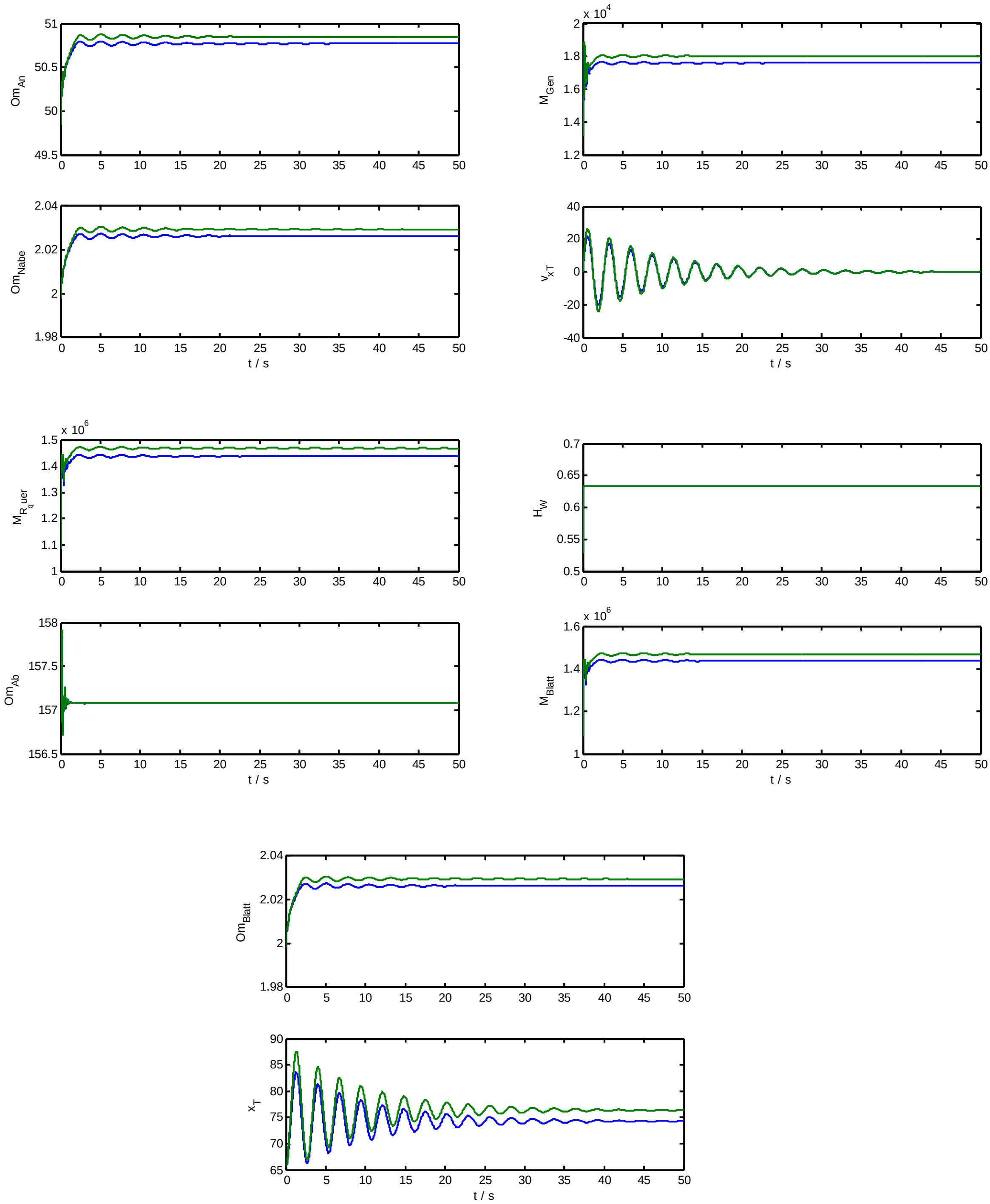

Figure 5.7 Comparison of nonlinear and linearized model's stationary states to a step response of a +20 % change made in input signals

With a correctly linearized model, it would be interesting now to inspect the system's behaviour characterized by frequency responses. On Figure 5.8, where the frequency response of the pitch angle to the tower acceleration is depicted, a remarkable positive peak can be seen at the tower's own frequency, 0.37 Hz. For damping tower oscillations this peak is quite important and should be lowered later.

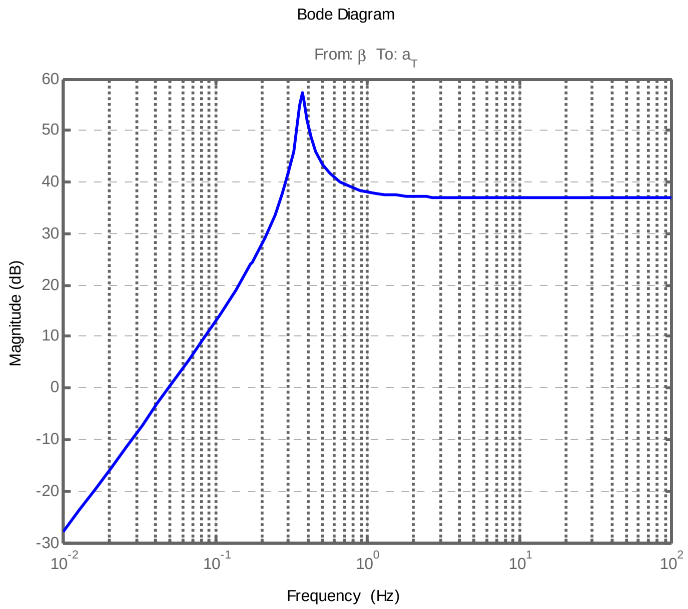

Figure 5.8 Frequency response of the pitch angle to the tower acceleration

It is also worthy to compare the design model with and without including tower dynamics as shown in Figure 5.9, Figure 5.10 and Figure 5.11. In the first two cases, the frequency response of the wind speed to the power and the frequency response of the pitch angle to the power, the only significant difference is again at the tower's own frequency in a form of a prominent negative peak. In third case, there is almost no difference between the new design model and the current one.

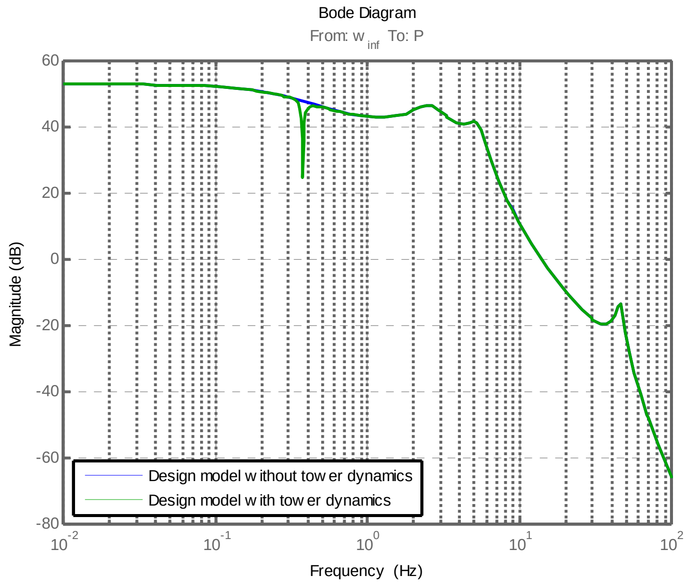

Figure 5.9 Frequency response of the wind speed to the power

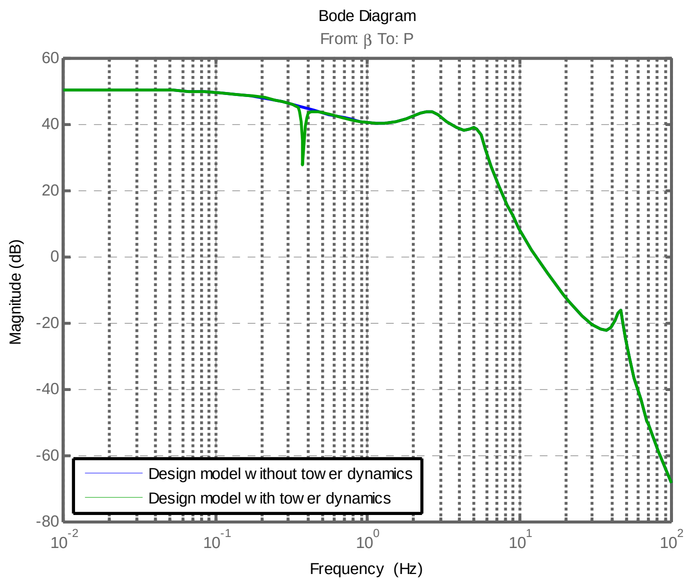

Figure 5.10 Frequency response of the pitch angle to the power

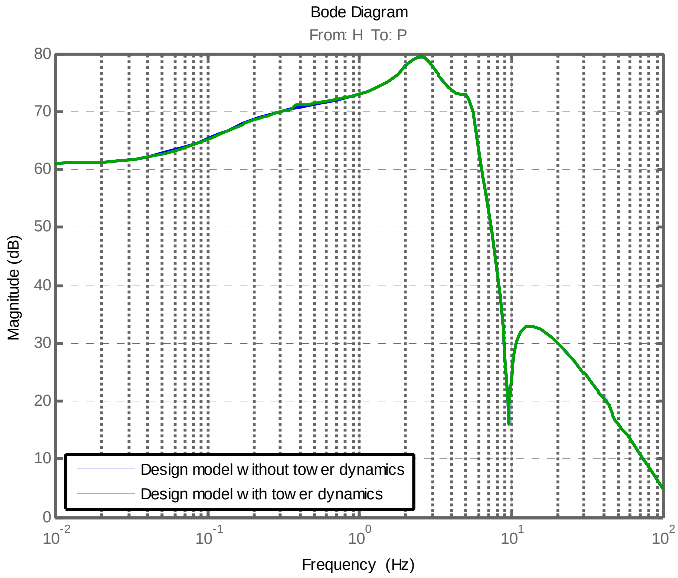

Figure 5.11 Frequency response of the guide vane position to the power

As one can see, the tower dynamics plays an important role in the behaviour of the design model. This extended linearized design model can be used in simulation based control design where the objective will be to smoothen the peak at the tower's eigenfrequency.

6 CONTROL DESIGN AND RESULTS

6.1 Retuning parameters of the P-PI cascade

The first step for damping the tower nodding can be made by retuning parameters of the P-PI cascade. Advantage of this approach is that the structure of the controller remains as it is, just the proportional and proportional-integrative parts are tuned. However, the question is if it is possible to improve the controller's performance just by doing this.

We also need to keep in mind that reduction of tower oscillations should be done with maintaining the preferred performance of the rotor speed. Therefore, two performance criteria are chosen: settling time of the rotor speed in a step response of the wind speed and maximum value (peak) of the tower acceleration in a frequency response of the wind speed.

The structure of the current cascaded pitch controller can be seen on Figure 6.1.

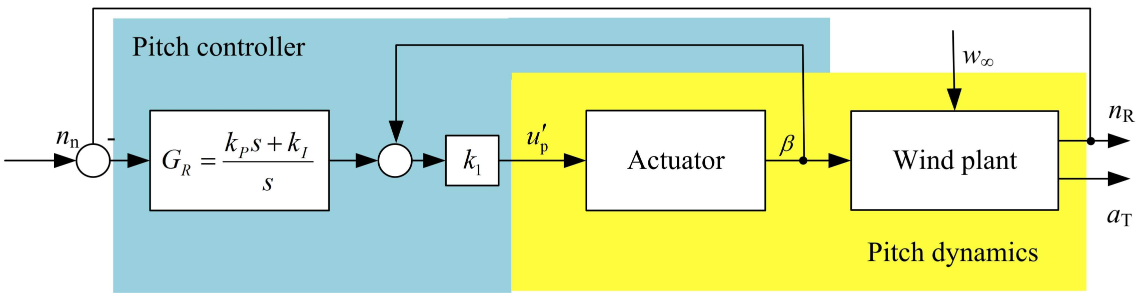

Figure 6.1 Pitch control using a P-PI cascade

During the first sets of simulations, it became clear that integrative part of the PI controller has just a negligible effect on decreasing of tower oscillations. Thus, instead of three parameters, just two proportional ones were tuned (k_1 and k_p, both in interval (0.01,5) with a 0.01 step).

Numerous cases have been simulated on the linearized design model; results are depicted on Figure 6.2. Cross formed by lines represents performance of the pitch controller with old parameters.

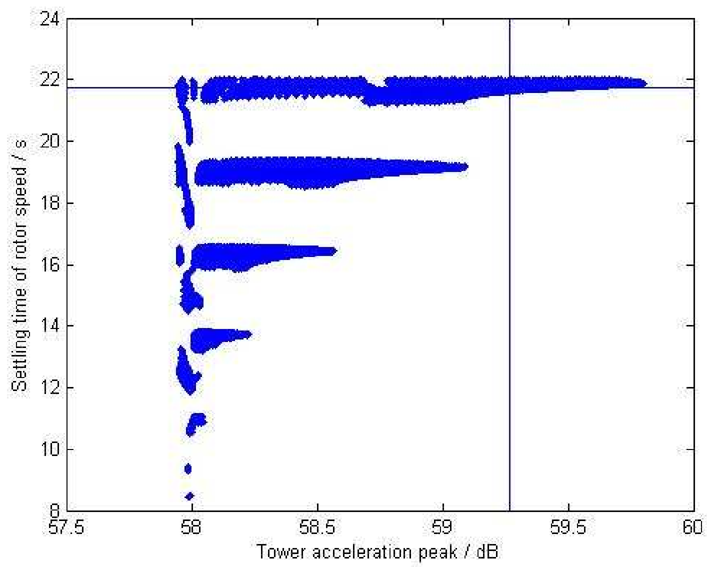

Figure 6.2 Performance depending on cascade parameters

As can be seen, actual structure of the pitch controller has its limits and seems to be fractional, i.e. ability of the controller for reducing tower oscillations is limited. However, there is a small improvement in lowering the peak of the tower acceleration (around 1 dB).

Best pair of k_1 and k_p is chosen (k_1 = 0.39, k_p = 0.09, k_I = 1.0201) and the step response and frequency response from wind speed is shown in Figure 6.3 and Figure 6.4. New parameters cause a bigger overshoot in step response of the rotor speed but the settling time is shorter. The step response of the tower acceleration shows that using the actual structure of the pitch controller cannot damp oscillations more than in the system without controller.

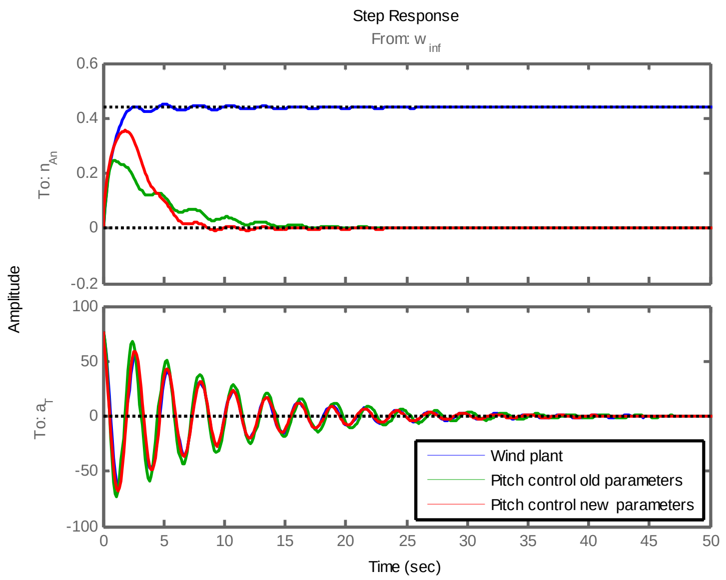

Figure 6.3 Step responses from the wind speed to the rotor speed and the tower acceleration

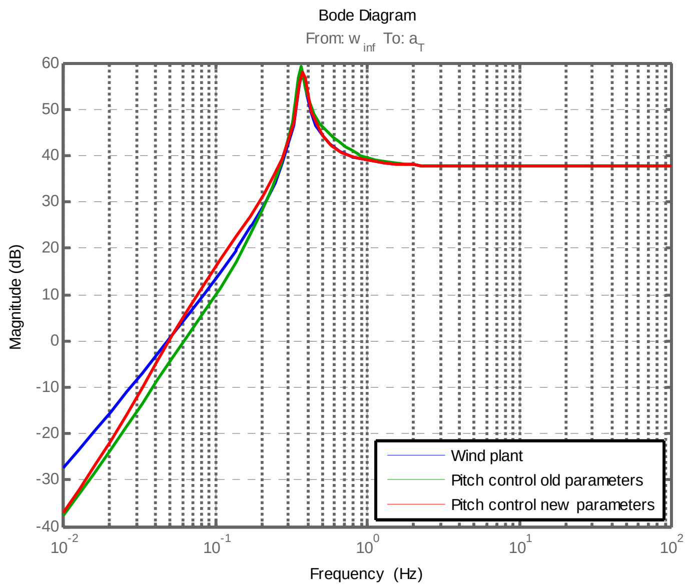

Figure 6.4 Frequency response from the wind speed to the tower acceleration

Although it seems to be a small improvement on the figure because of the logarithmic scale, tower acceleration peak is damped by 13.72 percents compared to pitch controller with the old parameters.

6.2 Filter approach

On the basis of [5] and [6] a feedback signal is led from the tower acceleration to the pitch controller. It goes through a filter first and is multiplied by a tower feedback gain K_{tow} (Figure 6.5). The filter is designed as a Chebyshev low pass filter.

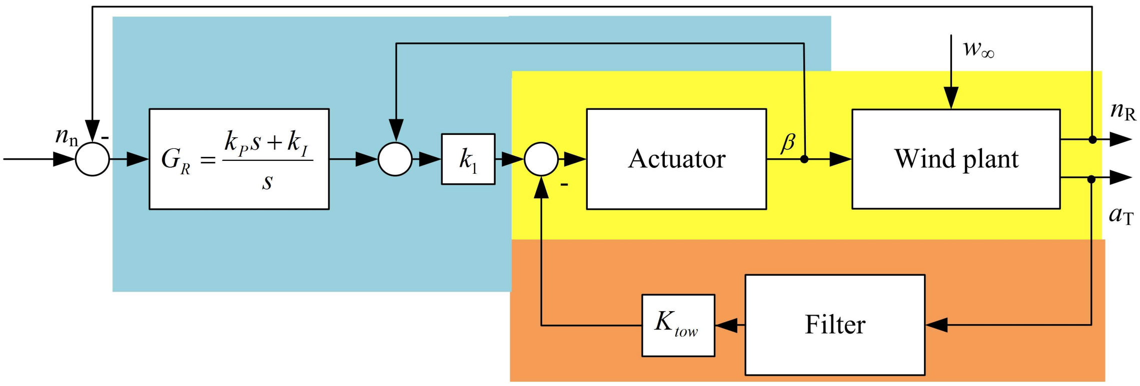

Figure 6.5 New pitch controller extended with acceleration feedback

Chebyshev filters are steeper at the cut-off frequency than other common filters but they generate more passband ripples (Figure 6.6).

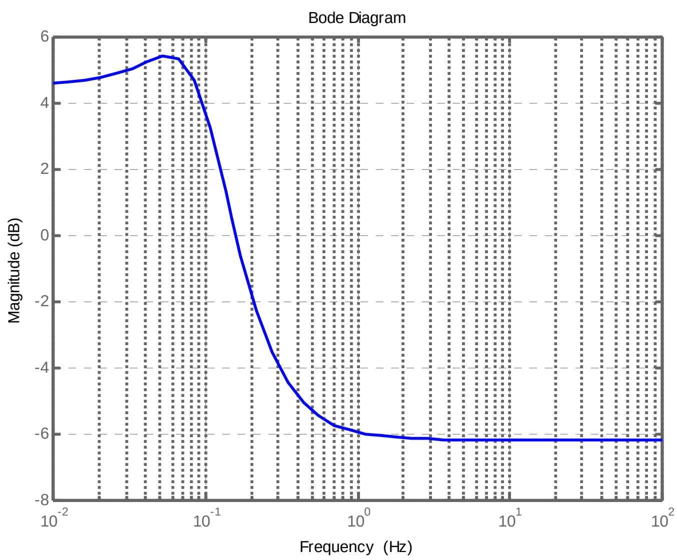

Figure 6.6 Second order Chebyshev filter with a 0.5 dB ripple

The MATLAB command *cheby1(N,A,F)* uses three parameters:

- *N*: order of the filter,
- *A*: peak-to-peak ripple in the passband,
- *F*: normalized passband edge frequency – it is a number between 0 and 1 and it is the ratio between the cut-off frequency to the half of the frequency window.

Different combinations of these three parameters are used in simulations to achieve the best performance of the pitch controller with the old cascade parameters. Results are depicted on Figure 6.7, parameters varied in following intervals: the peak-to-peak ripple *A* from 0.1 to 20 with a 0.05 step, the edge frequency *F* from 0.01 to 0.99 with a 0.01 step and the order of the filter *N* from 1 to 5. Tower filter feedback gain K_{tow} is set to a constant value of 0.01.

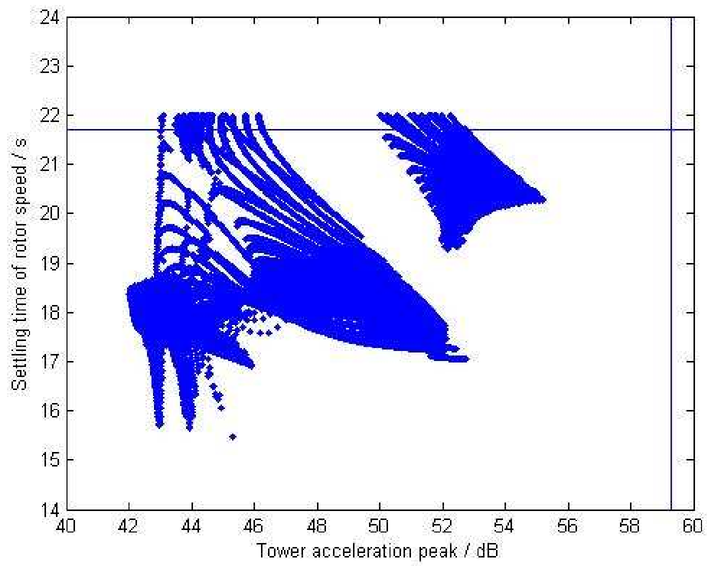

Figure 6.7 Performance depending on filter parameters with old cascade parameters

Comparing to Figure 6.2, current results show a great improvement in the damping of tower oscillations. However, improvements in settling time of the rotor speed are not that significant. We should have a closer look by choosing a set of filter parameters from the result set.

In Figure 6.8 step responses of the system are shown from the wind speed to the rotor speed and the tower acceleration, using a second order Chebyshev filter with a 2.1 dB peak-to-peak ripple at normalized passband edge frequency 0.58.

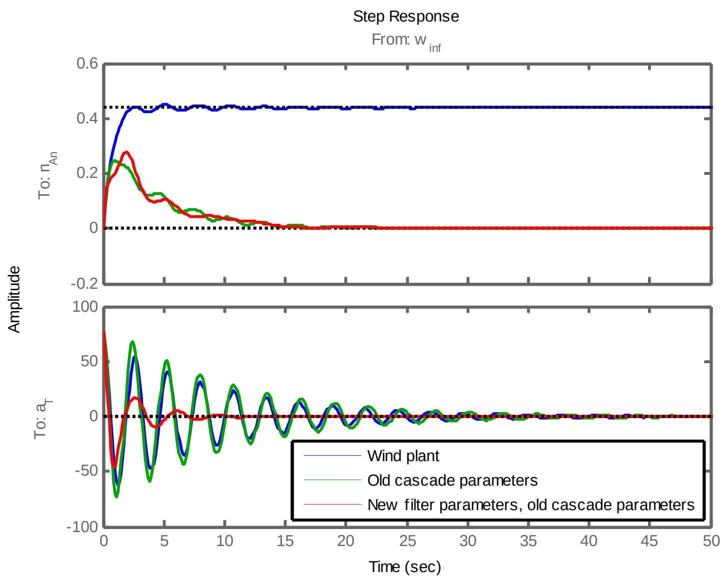

Figure 6.8 Step responses from the wind speed to the rotor speed and the tower acceleration

Improvements can be clearly seen on Figure 6.8, especially in damping of the tower nodding, furthermore, oscillations are not more pronounced as it was in case of the pitch controller with old parameters and they are reduced compared to the system without controller. The settling time of the rotor speed remains almost on the same value as before nevertheless it is not worse.

The frequency responses on the Figure 6.9 also confirm the rate of improvement where the peak of tower acceleration for the new controller is completely cut off and instead of it, two smaller peaks appear with lower amplitudes. The tower nodding is alleviated in this case by 84.67 % in frequency domain (by 74.91 % in time domain).

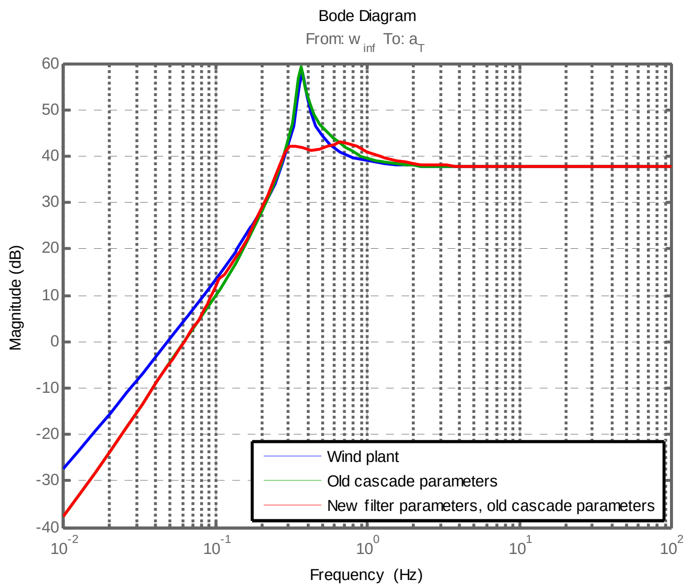

Figure 6.9 Frequency responses from the wind speed to the tower acceleration

Nevertheless, do not forget that this new structure has not been tested yet on the nonlinear wind plant. Let us see if the proposed structure can handle nonlinearities.

A simplified nonlinear controller-plant system was built in Simulink to test the new structure of the controller. Same filter and cascade parameters were used. The step responses can be seen on Figure 6.10.

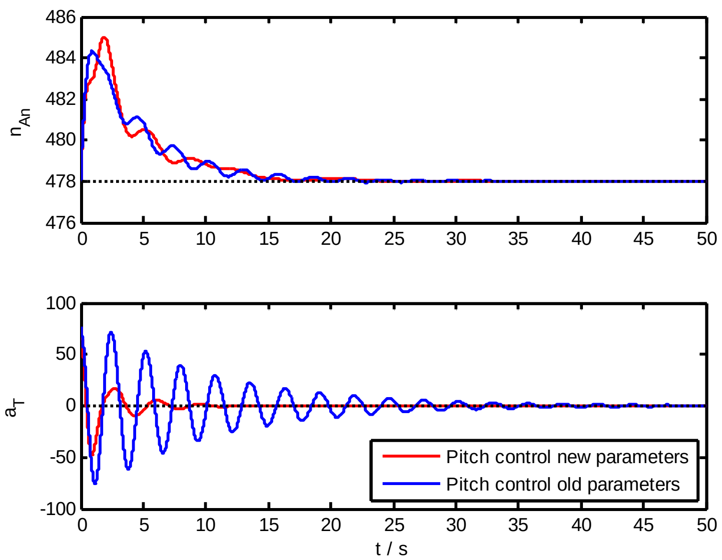

Figure 6.10 Step responses from the wind speed to the rotor speed and the tower acceleration, nonlinear system

Fortunately, nothing unexpected happened: settling times are almost equal but progress in the damping of tower oscillations is still significant. Tower movements in fore-aft direction are reduced by 76.47 % in time domain.

As one can see on the previous achievements, retuning of the cascade parameters resulted in better settling times of the rotor speed whilst the feedback of tower acceleration caused a considerable damping of tower oscillations. Combining of these two approaches could bring a fruitful outcome. Let us run a new set of simulations with the new (optimized) cascade parameters to find new filter parameters for the Chebyshev filter.

Figure 6.11 shows new simulation results tested in the following limits: the peak-to-peak ripple *A* from 0.1 to 20 with a 0.05 step, the edge frequency *F* from 0.01 to 0.99 with a 0.01 step and the order of the filter *N* from 1 to 5. As you could notice, there are two crosses on the figure: blue one stands for the P-PI cascade with old parameters, red slashed one represents the P-PI cascade with new parameters, acceleration feedback is used in none of them. Improvements in the damping of the tower acceleration remain near the level as on Figure 6.7, on the other hand, the settling time of the rotor speed is decreased extensively.

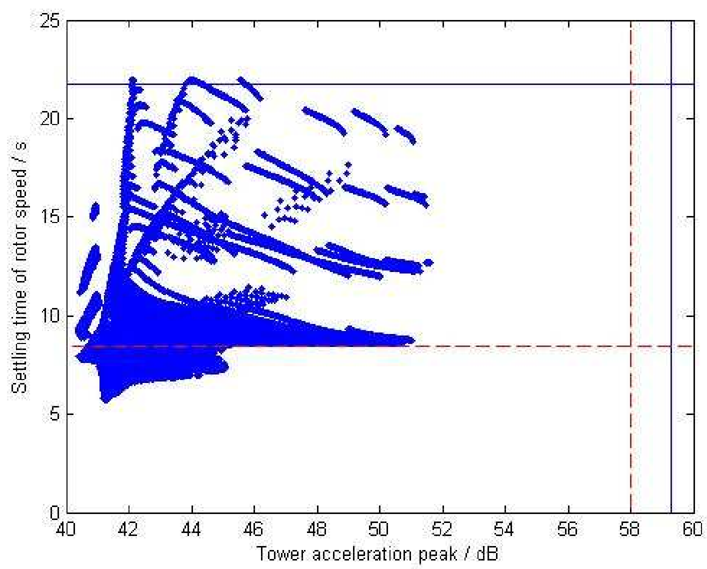

Figure 6.11 Performance depending on filter parameters with optimized cascade parameters

One of the best sets of filter parameters is selected to illustrate system's behaviour in a form of a second order Chebyshev filter with 0.1 dB peak-to-peak ripple at normalized passband edge frequency 0.62 (Figure 6.12).

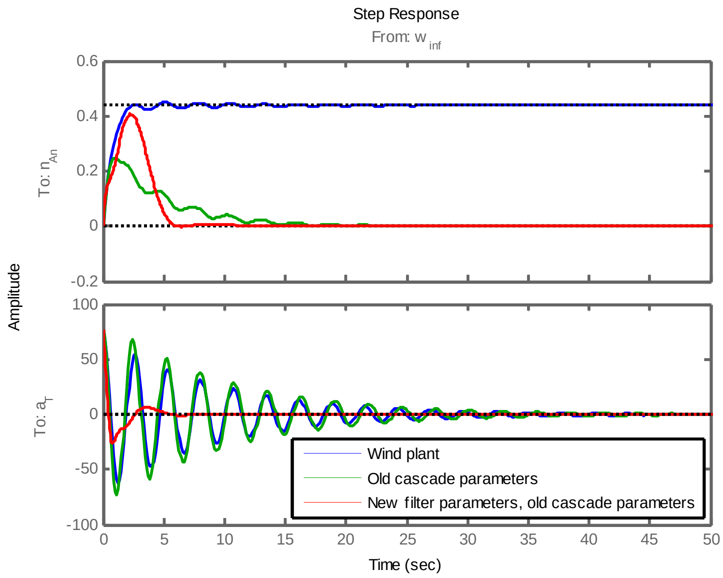

Figure 6.12 Step responses from the wind speed to the rotor speed and the tower acceleration

Enhancements in settling time are definitely recognizable on Figure 6.12, moreover oscillations seems to disappear after 6 seconds. Rate of the reduction of tower oscillations in numbers are 90.68 % in time domain and 87.45 % in frequency domain (Figure 6.13). On Figure 6.13, some changes can be observed compared to Figure 6.9. Besides cutting off the large peak, magnitude of the first of the remaining two peaks is lowered.

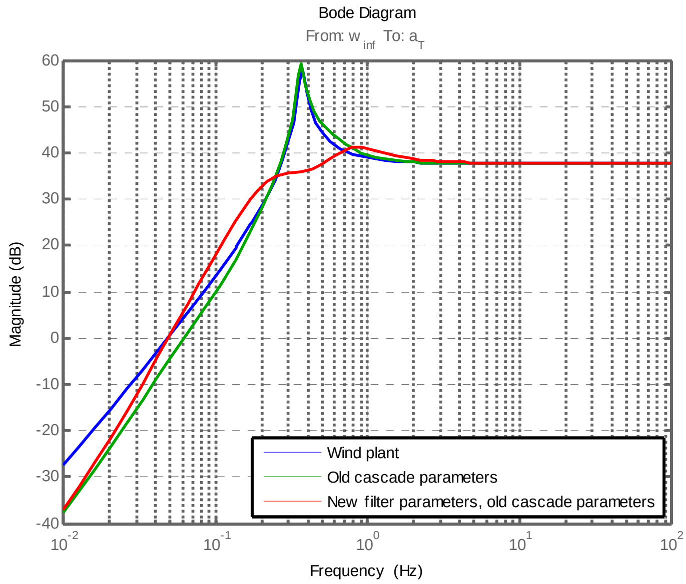

Figure 6.13 Frequency responses from the wind speed to the tower acceleration

The same set of the Chebyshev filter's parameters are tested on the nonlinear system. Unfortunately, improvements in the rotor speed performance do not appear in the nonlinear system (Figure 6.14) and the settling time is higher than in the standard case. However, this loss of performance is in acceptable limits and adjustments in damping control overtop it. Talking in numbers, oscillations are damped by 80.77 % in time domain.

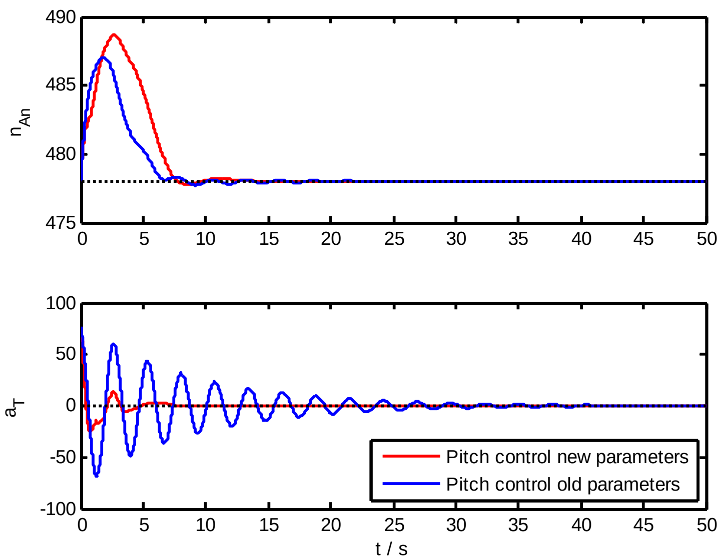

Figure 6.14 Step responses from the wind speed to the rotor speed and the tower acceleration, nonlinear system

Finally, let summarize the results in form of a table (Table 1). There are two so called “standard” situations, both referring to the pitch control without using tower acceleration as a feedback signal. Standard 1 is the pitch controller with old cascade parameters; Standard 2 is the pitch controller with new cascade parameters. *N*, *A* and *F* are filter parameters for the Chebyshev filter, *Acc. peak* refers to the maximum value of the tower acceleration in frequency domain and *Acc. step* stands for the time domain. *ST* is an abbreviation for the settling time of the rotor speed.

Table 1 Improvements in reducing tower oscillations

				Linear			Nonlinear	
	N	A dB	F	Acc. peak dB	Acc. step $m.s^{-1}$	ST s	Acc. step $m.s^{-1}$	ST s
Standard 1	$k_1 = 0.50$	$k_p = 2.1577$	$k_I = 1.0201$	59.266	68.202	21.722	72.021	15.934
1.	2	0.20	0.62	42.022	17.088	18.371	17.638	17.258
2.	2	2.10	0.58	42.977	17.111	15.704	16.930	13.668
3.	4	3.25	0.77	43.942	19.554	15.648	18.957	13.806
Standard 2	k1 = 0.39	kp = 0.0900	kI = 1.0201	57.985	59.473	8.431	59.714	8.992
1.	2	0.10	0.62	41.241	6.3598	5.721	13.851	7.090
2.	2	4.65	0.96	40.406	14.329	7.962	17.916	9.348

I would like to highlight one of the few tendencies from this chart for the linear case: with increasing the performance in the tower oscillation damping, the settling time of the rotor speed always rises.

7 CONCLUSION

The main goal of this thesis was to design a pitch controller, which, besides maintaining the power quality, can damp tower oscillations. Two approaches were used, the first one retuning of the existing pitch controller and the second one using a tower acceleration feedback extension of the current controller.

The retuning of the cascaded controller resulted in a noticeable progress in lowering of the settling time of the rotor speed and in a small improvement in reduction of tower oscillations. The new pitch controller, with a tower acceleration feedback added, brought a prominent outcome in the damping of tower oscillations, however, enhancements in rotor speed were not that significant. Combination of both approaches ended in a fruitful cooperation and improvements in both performance criteria are in this manner remarkable.

Still, there are some open questions and further research areas left. Tower filter feedback gain K_{tow} is not optimized despite the fact that some effort was made to do so but with a small success. Further, deeper simulations should be done, as currently a new starting point exists to run them. Consequently, it would be less time consuming to find new parameters that are more precise. Another problem is that the linearized model and the nonlinear one show some differences in the behaviour of the system. Thus, developing a better design model, which describes the system’s behaviour in a more precise way, should eliminate this difficulty. Finally, new pitch controller should be tested on the real wind plant. However, we cannot forget that every improvement will be a compromise between increased pitch activity and tower damping.

8 RESUMÉ

Úvod do riadenia veterných turbín

Vietor je prúd vzduchu spôsobený tlakovými rozdielmi v atmosfére, ktoré vznikajú v dôsledku nerovnomerného slnečného žiarenia. Vietor je v konkrétnom mieste kombináciou geostrofických a lokálnych vetrov. Geostrofické vetry vznikajú, keď sa teplejší a ľahší vzduch na rovníku dvíha a prúdi k pólom a tým nahrádza chladnejší polárny vzduch, ktorý tak klesá k rovníku. Lokálne vetry sa formujú z geostrofických vetrov spomalených trecou silou zeme a rôznymi prekážkami.

Najdôležitejšími charakteristikami vetra sú jeho smer a rýchlosť, ktoré sú ovplyvnené geografickou polohou, nadmorskou výškou, podnebím, povrchom Zeme, prekážkami a vodnými plochami. Rýchlosť vetra môžeme deliť na dve zložky: na priemernú rýchlosť vetra a na turbulencie. Z hľadiska veterných turbín je dôležité poznamenať, že turbulencie majú takmer zanedbateľný dopad na ročný výnos energie, avšak značný vplyv na záťaž lopatiek a kvalitu energie.

Veterné turbíny sú mechanické zariadenia špecificky navrhnuté na premenu kinetickej energie vetra na užitočnú mechanickú prácu. Na obr. 2.1 je znázornená typická veterná turbína s trojlopatkovým rotorom. Významnou charakteristikou veterných turbín je koeficient C_p. Je definovaný ako podiel zachytenej energie a veternej energie. Je funkciou uhlu sklonu lopatiek β a podielového koeficientu λ (podiel rýchlosti lopatiek veternej turbíny a rýchlosti vetra).

Veterné veže sú flexibilné a vysoké, preto na nich môžeme pozorovať kmitavé pohyby a to v rôznych smeroch (obr. 2.3). Z týchto oscilačných pohybov má najväčší vplyv na riadenie veterných turbín pohyb v axiálnom smere.

Ciele riadenia by sme mohli formulovať nasledovne:

- Odstránenie mechanických záťaží na veternú turbínu
- Maximalizácie zachytenej energie
- Udržanie kvality energie

Opis súčasných riadiacich systémov

Skúmaná veterná turbína D8.2 s nominálnym výkonom 2 MW je lokalizovaná v Cuxhavene, SRN. Všeobecná riadiaca schéma systému je zobrazená na obr. 3.1, kde sa systém riadi pomocou dvoch regulátorov. Regulátor inovatívneho hydrodynamického konvertora WinDrive reguluje elektrickú energiu na základe aktuálnej rýchlosti rotora, kým hlavnou úlohou regulátora sklonu lopatiek veternej turbíny je udržať rýchlosť rotora na žiadanej hodnote.

Na základe zjednodušeného regulačného obvodu (obr. 3.2) bol navrhnutý regulátor sklonu lopatiek vo forme P-PI kaskády (obr. 3.4), ktorý bol neskôr doplnený prvkami ako gain scheduling a anti-windup.

Na účely regulovania elektrickej energie sa používa regulátor so stavovou spätnou väzbou doplnený pozorovačom stavu vo forme Kalmanovho filtra.

Zjednodušený model veternej turbíny pre návrh regulátora

Pre návrh nového regulátora sklonu lopatiek, ktorý by tlmil kmity veternej veže, je potrebné zjednodušiť model riadeného systému tak, ako to bolo v prípade predošlého návrhu (obr. 3.2). Avšak tento model musí byť rozšírený o dynamiku veternej veže, s ktorou sa doposiaľ pri návrhu regulátora nerátalo (obr. 5.1). Výstupným signálom dynamiky veternej veže je zrýchlenie veže (a_T), no vstupný signál F_T (nárazová sila) nie je k dispozícii v aktuálnom modeli systému. Vo vnútri aerodynamického bloku by bol potrebný koeficient, ktorý by transformoval vstupné signály na nárazovú silu F_T, podobne ako výkonový koeficient C_p transformuje vstupy rýchlosť vetra w_∞, uhol sklonu β a rýchlosť rotora n_{An} na aerodynamický moment sily M_A. Nárazový koeficient C_T sa dá vyjadriť z rovnice (11), pomocou ktorej bola na základe simulácií vytvorená tzv. C_T tabuľka (získané závislosti sú zobrazené na obr. 5.3 a 5.4).

Takto sa už dá opísať model, ktorý berie do úvahy aj kmity veternej veže. Model bol následne linearizovaný (obr. 5.5) a boli porovnané frekvenčné charakteristiky linearizovaného modelu bez dynamiky veže a modelu, ktorý s dynamikou veže ráta (obr. 5.9 až 5.11). Jediný signifikantný rozdiel modelov je pri vlastnej frekvencii veže 0,37 Hz vo forme záporného píku. Tento vrchol sa musí odstrániť, aby sa predišlo osciláciám veže.

Návrh regulátora a výsledky riadenia

Pri návrhu regulátora sa využili tri prístupy: prestavenie parametrov existujúcej P-PI kaskády, rozšírenie regulátora o spätnú väzbu filtrovaného zrýchlenia veže a kombinácia predošlých dvoch prístupov. Kvalita riadenia sa porovnáva dvoma veličinami: dobou regulácie pri skokovej odozve rýchlosti rotora na zmenu rýchlosti vetra a maximálnou hodnotou zrýchlenia veže pri frekvenčnej odozve na zmenu rýchlosti vetra.

Pri prestavení parametrov P-PI kaskády sa nanovo nastavovali len proporcionálne zložky, keďže integračná časť nemá vplyv na priebeh riadenia. Boli odsimulované priebehy riadenia s rôznymi kombináciami parametrov regulátora (integračná časť ostáva konštantná pri simuláciách), príslušné ukazovatele kvality riadenia sú zobrazené na obr. 6.2 (kríž reprezentuje regulátor so starými parametrami). Z množiny výsledkov je zvolená najlepšia dvojica proporcionálnych parametrov a takto nastavený regulátor je použitý na odsimulovanie priebehu riadenia. Priebehy sú porovnané v časovej (obr. 6.3) aj frekvenčnej oblasti (obr. 6.4). Nové parametre regulátora spôsobujú väčšie preregulovanie pri rýchlosti rotora, avšak doba regulácie je kratšia. Obr. 6.4 poukazuje tiež na skutočnosť, že použitím danej štruktúry regulátora nie je možné dosiahnuť lepšie tlmenie kmitov veže v porovnaní so systémom bez regulácie. Miera zlepšenia tlmenia kmitov je v tomto prípade 13,72 percent.

Na základe [5] a [6] je regulátor sklonu lopatiek rozšírený o spätnú väzbu od zrýchlenia veže. Tento signál prechádza filtrom realizovaným vo forme dolnopriepustného Čebyševovho filtra a následne je vynásobený zosilnením K_{tow} (obr 6.5). Filter v prostredí MATLAB má nasledovnú syntax: *cheby1(N,A,F)*, kde N je rád filtra, A je šum v pásme priepustnosti a F je normalizovaná rohová frekvencia. Rozličné kombinácie týchto troch parametrov sú použité v simuláciách na dosiahnutie najlepšej kvality riadenia, pričom je zosilnenie K_{tow} nastavené na konštantnú hodnotu. Výsledky sú zobrazené na obr. 6.7. V porovnaní s obr. 6.2, je tu vidno obrovský pokrok v tlmení kmitov veže, a to pri udržaní doby regulácie na podobnej úrovni ako v predchádzajúcom prípade. Miera zlepšenia tlmenia kmitov je 74,91 percent. Avšak tieto vylepšenia sa testovali len na lineárnom modeli, preto bol vytvorený zjednodušený nelineárny model v Simulinku. Výsledky ukazujú mieru zlepšenia tlmenia oscilácií o 76,47 percent oproti pôvodnému regulátoru.

Výhody obidvoch prístupov boli skombinované do jedného regulátora, kde parametre P-PI kaskády sa nastavili na zistenú najlepšiu voľbu a následne sa zisťovali parametre Čebyševovho filtra. Na obr. 6.11 môžeme vidieť zlepšenie nielen v tlmení kmitov veternej veže, ale aj v rýchlosti regulácie. Musíme si ale uvedomiť, že zlepšenie jedného ukazovateľa kvality obvykle vyústi do mierneho zhoršenia toho druhého. Zlepšenie tlmenia kmitov sa dá vyjadriť číselne ako 90,68 percent v prípade lineárneho modelu a v prípade nelineárneho modelu ako 80,77 percent.

Záver

V rámci projektu ešte stále existuje niekoľko nevyriešených problémov. Zosilnenie K_{tow} pri použití Čebyševovho filtra nie je optimalizované, napriek počiatočnému úsiliu tak učiniť (túto snahu však sprevádzal len malý úspech). Ďalším problémom sú rozdiely v správaní sa lineárneho a nelineárneho modelu. Preto by návrhový model pre regulátor mal byť viac komplexnejší a zjednodušenia by mali byť použité iba s dostatočnou opatrnosťou. Nakoniec by sa mal navrhnutý regulátor otestovať na samotnom systéme, t.j. na reálnej veternej turbíne.

9 REFERENCES

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