Technical University of Denmark

Design gridlines for integrated aeroelastic control of wind turbines - Task-12 report

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Design guidelines for integrated aeroelastic control of wind turbines – Task-12 Report

Edited by: T. Buhl, K. Thomsen & H. Markou (Risoe)

Contributions by:

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E.S. Politis (CRES)
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Final Report: December 20^{th} 2006

Risø National Laboratory
Roskilde
Denmark
December 2006

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Abstract (Max. 2000 char.)

The presented design guidelines for active aeroelastic control of PRVS wind turbines are derived by the partners of the project "Aeroelastic Stability and Control of Large Wind Turbines" (STABCON) partially funded by the European Commission (EC) under the contract NNK5-CT2002-00627. The objective of the active aeroelastic control is to investigate load alleviation potential, robustness and contradicting objectives for different controller concepts.
It is important to note that the conclusions and recommendations of the presented guidelines are derived partly on the experience obtained in the Work Package 5 and 6 of the STABCON project, and partly from the large amount of common knowledge and understanding on aeroelastic control that the partners have obtained in other previous projects. The partners gratefully acknowledge the support by the EC, which is vital for the continuation of this successful long term research cooperation.

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Contents

Preface

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The STABCON partners are:

- Risø National Laboratory (RISO)
- Energy Research Centre of the Netherlands (ECN)
- Centre for Renewable Energy Sources (CRES).
- National Technical University of Athens (NTUA)
- Technical University of Denmark (DTU)
- University of Stuttgart (USTUTT)
- Delft University of Technology (DELFT)
- Vestas Wind Systems A/S (VESTAS)

Presently, most of the STABCON partners are cooperating in the large UPWIND project under the EC framework programme VI.

It is important to note that the conclusions and recommendations of the presented guidelines are derived partly on the experience obtained in the Work Package 5 and 6 of the STABCON project, and partly from the large amount of common knowledge and understanding on aeroelastic control that the partners have obtained in other previous projects. The partners gratefully acknowledge the support by the EC, which is vital for the continuation of this successful long term research cooperation.

[1] The topic of passive instability suppression is discussed in the Risø-R-1575 report "Design guidelines for passive instability suppression – Task-11 report" [1]

1 Introduction

This report contains the design guidelines for active aeroelastic control of PRVS wind turbines. Different control concepts are investigated for load alleviation potential, robustness and contradicting objectives. The investigated control concepts are: drive train damping, tower damping, cyclic pitch and the controllers combined.

The objective of WP 6 ”Integrated Aeroelastic Control Design” is to built know-how and methods for aeroelastic control of wind turbines and design guidelines for integrated design towards active gust alleviation, instability suppression, and power enhancement by considering the conditions set by

- The site, e.g. wind conditions, onshore site, or offshore site.
- The turbine concept, e.g. sensitivity to gust, controllability, and lifetime costs.

This objective is achieved by designing different controller concepts and analyzing these in different aeroelastic codes, linear as well as nonlinear. First, four base cases where investigated with six different random seeds; 18 m/s with high turbulence, 14 m/s with high turbulence, extreme operating gust (mexican hat) and 18 m/s with low turbulence. Second, more site specific cases where investigated; low turbulence vs. high turbulence, normal shear, high shear and extreme shear.

1.1 State of the art

More and more focus is given nowadays to developing more advanced controllers that will limit costs on large scale wind turbines by potentially increasing energy capture and /or reducing loads. As the size of the turbines increases and they become lighter and more flexible, the control issues are also becoming more and more complex and with increased limitations due to issues such as increased blade inertia, actuator limitations, reduced structural frequencies. The majority of multi-megawatt turbines designed nowadays are pitch regulated variable speed turbines (PRVS), and this is focus of this report.

Important aspects for the realization of the controller concepts are the sensors, actuator and data processing equipment. The commonly available control signals (actuators) on a PRVS turbine are the blade pitch angle and the generator counter torque. Commonly available measurements for feedback control is the generator speed; The tower top motion in measured acceleration and blade root bending moments are becoming increasingly available on wind turbines as controllers for load reduction are implemented. More details on sensors, actuator and data processing equipment for wind turbine control can be found in the STABCON Task 7 report [2].

1.1.1 Control objectives

To define the controller concepts, it is necessary to understand what one is trying to achieve, in terms of the desired influence of the controller on the turbine behavior. The overall aim can be plainly stated as wanting to maximize energy capture at the lowest possible cost. The latter mostly translates into a reduction of loads, especially drivetrain, bottom tower and blade root loads. The cost for the reduction of these loads should also be considered, which is the actuation activity. For the PRVS turbine the controller objectives can more specifically be defined as:

- Maximum energy yield in partial load

- Rated power in full load under speed regulation
- Reduced flap, tower bottom and tilt and yaw moments
- Enhanced damping of tower and drivetrain modes
- Avoid excessive pitch activity
- Avoid decrease in modal damping by other loops

Some of these objectives may be conflicting. An optimisation/trade off is necessary, taking costs into account. The later depends on many factors such as the wind regime, but also electricity pricing etc.

1.1.2 Control design methods

From the control theory point of view it is well known that a control loop that is 'active' up to a certain frequency, the bandwidth, inevitably affects the overall system dynamics below that frequency. This makes an integrated approach to control, aerodynamics and structural dynamics necessary (aero-servo-elasticity).

For the actual design and testing of the closed-loop controller software, linear and nonlinear models are essential, before this is run on the actual wind turbines. The existing tools for time-domain simulation are able to satisfy the requirement on the integrated aero-servo-elastic approach. However, the tools for linear stability analysis do not. These tools, when control is included, enable efficient identification of potential causes for 'unexplained' phenomena. In addition, such a stability tool is very valuable during control design for damping enhancement and reduction of 'cyclic' loads on wind turbines (aeroelastic control).

The use of linear models provides a method to the design of feedback controller loops: PID control, classical control and almost all modern multivariable controller design techniques use linear models. Linear models for controller design used to be simple, usually incorporating the drivetrain, elementary tower dynamics, maybe blade flap mode, and a linearised wind speed model. The design of more advanced aeroelastic control concepts require more complex models that would also include the rotor dynamics and the combined bending and torsion of the tower. Such models did not exist before the STABCON project started. The availability of such models as aero-servo-elastic design tools is one of the outcomes of the STABCON project. An example of how the more complex tools are used for the design of load reduction controllers is included in section 5 on Cyclic Pitch Control.

1.1.3 Control concepts

Increasingly load reduction controllers are being implemented on industrial wind turbines to meet the above defined objectives. The following concepts for load reduction controllers have been investigated and in some cases implemented on turbines:

- Drive train load reduction: Adjustment of generator torque based on rotational speed to enhance the damping of the first drivetrain mode [3]
- Tower load reduction
  - Reduction of the sideward tower loads through adjustment of the generator torque based on tower acceleration measurement.
  - fore-aft tower load reduction by adjusting the collective pitch based on a tower acceleration signal [3], [4].

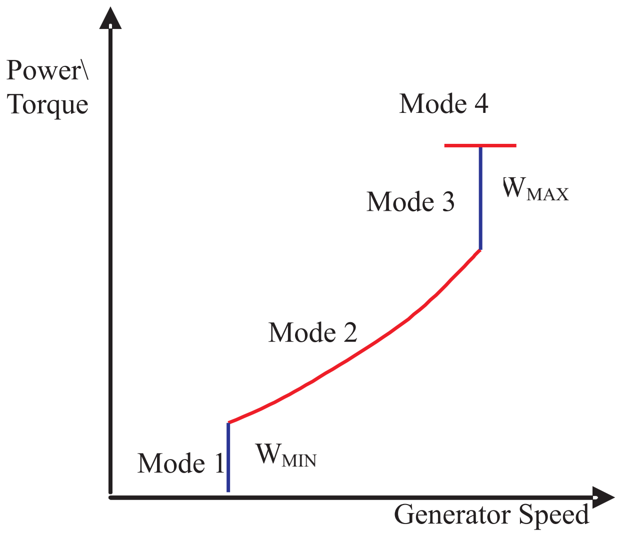


Figure 1. Power/speed regulation NM80 turbine

- Blade load and tilt and yaw moment reduction .
  - Cyclic pitch based on blade load measurements [2].
  - Individual pitch based on local blade flow measurements [5].

A base power/speed controller must of course always exist in order to guarantee continued operation, and any conflicts between the base power/speed controller and load reduction controller investigated.

1.2 Test Turbine

While the design guidelines for passive instability suppression [1] are for both ASR and PRVS turbines, the guidelines in this report are focused on PRVS turbines. PRVS turbines are exemplified by the NM80 turbine. The natural frequencies and damping of the NM80 are summarised in [1]. The operation of the controller of the test turbine is summarised here. From cut-in to cut-out wind speeds, the wind turbine operates in four modes (Figure 1): Low wind constant speed WMIN (Mode 1), variable speed (Mode 2), high wind constant speed WMAX (Mode 3) and high wind pitch control regulation (Mode 4). The main data for the NM80 turbine, with regards to controller operation is provided for reference in Table 1. In variable speed the Cp_{max} curve is tracked (Mode 2). Two separate PI controllers are implemented for the other modes: One for the constant speed tracking (Mode 1 and Mode 3), the controller input being the generator speed, the controller output the generator torque; One for constant torque full load control (Mode 4), the controller input being the generator speed, the controller output the collective pitch angle.

Control algorithm	Pitch regulated variable speed
Rated Power	2750 kW
Rated wind speed	14.4 m/s
Minimum generator speed (WMIN)	800rpm
Maximum generator speed (WMAX)	1140rpm
Minimum pitch angle in below rated	0.1 deg

Table 1. NM80 Operational Data

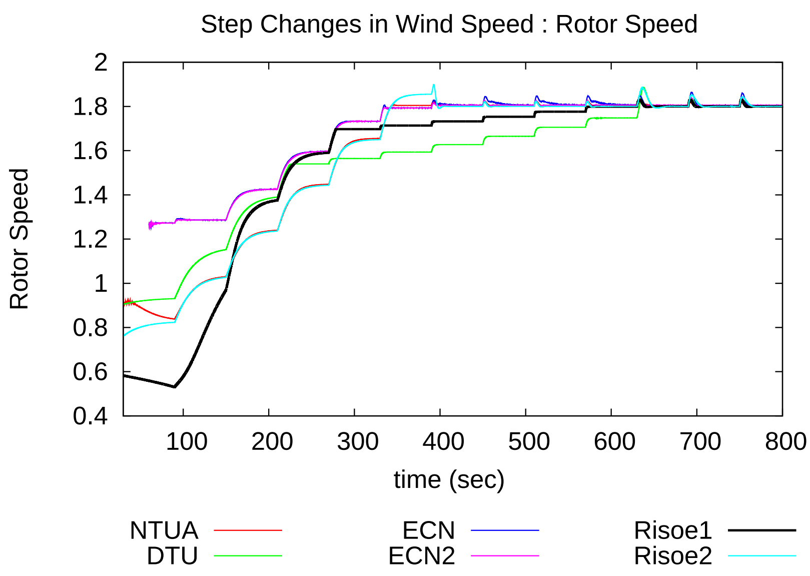


Figure 2. Rotor Speed: comparison of partners power/speed controllers

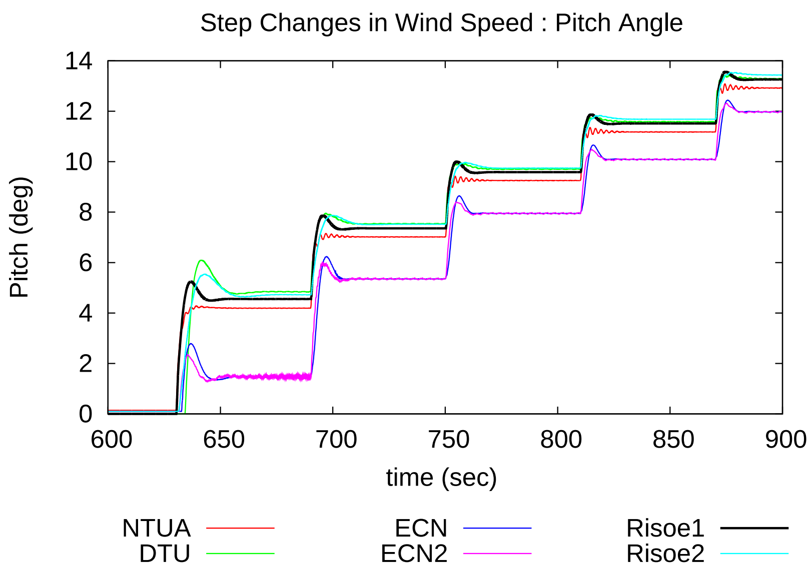


Figure 3. Pitch Angle: comparison of partners power/speed controllers

The following power and speed controllers were implemented in the partners nonlinear tools: NTUA's, ECN's, and Risoe's (Risoe2) power/speed controller is based on the description of the controller on the test turbine [1], DTU have implemented a LQ controller, and Risoe have also implemented a second base case controller (Risoe1), with a reference power/rotor speed table in partial load, and a collective pitch, constant power, PI controller to regulate generator speed in full load. A comparison of partners implementations of a base power/speed regulator in their nonlinear tools was done via the aero-servo-elastic behaviour during stepwise changes of the wind speed. Figures 2, 3 show the step responses of the rotor speed, and pitch angle. The differences are mainly in low wind speeds ($< 7m/sec$) and in the transient region between partial and full load. The behaviour in full load is similar for all partners implementation.

1.3 Outline for the guidelines

The guidelines for the present report are divided up into main topics. The list of topics were identified from the control concepts discussed in the state of the art section (1.1), and additionally the combination of the load reduction controllers.

1. Power speed controller issues
2. Drive train damping
3. Active tower damping
4. Cyclic pitch
5. Combined controllers

2 Power-speed regulation

For a PRVS turbine in above rated wind speeds the collective pitch limits the aerodynamic power to its rated value, whilst in below rated wind speeds the energy output is optimised. The selected power/speed strategy and implementation of this can have a major influence on the loads experienced by the wind turbine, and needs to be carefully designed.

Control strategies define a torque rotor speed trajectory, as in Figure 4.

In partial load the generator torque is usually adjusted to obtain maximum aerodynamic efficiency (optimal tip speed ratio) up to a maximum rotor speed (controller objective 1). This can be done simply by the definition of the demanded generator torque to equal $T := k_{opt} * omega^2$, where $k_{opt} = Cp_{max}\rho_{air}(\pi R^2)$ is the optimal torque co-efficient. Maintaining maximum Cp_{max} is more difficult for larger rotors: Firstly, due to the non-uniformity of the wind field across the rotor; Secondly, due to the high inertia of the rotor blades. For example, in high turbulence, the high rotor inertia prevents the rotor from changing speed fast enough. The design factors that will affect efficiency in below rated operation are thus the weight of the blade and whether the Cp-λ curve is sharp or not. Several ways to improve tracking in below rated operation and cause the rotor speed to change faster when required, by changing the demanded generator torque, have been proposed [6]. Speed exclusions zones may also be implemented in variable speed operation, to avoid rotational speeds that would excite resonances, for example the tower resonance [3].

Due to design constraints (noise, loading), the rotor speed is limited to a maximum value, which is then the limit to the variable speed operation in partial load. Thereafter the turbine will run at constant speed or a ramp up in speed is defined up to rated power. Converters with limited variable speed operation can be more cost efficient, so it is also quite common to run at constant speed at the very low wind speeds. A torque controller is operational in this region, PI-based or table based. Usually there is no pitch control in this mode, although in some cases the pitch controller is activated close to rated power, to reduce the chance of a speed overshoot in the case of a gust and to reduce the peaks in the thrust loading.

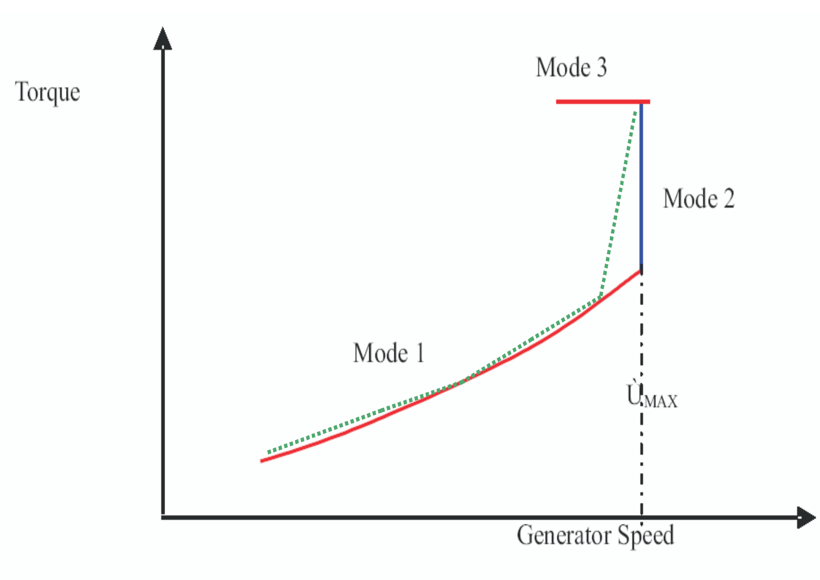


Figure 4. Power/speed regulation strategies for PRVS turbines

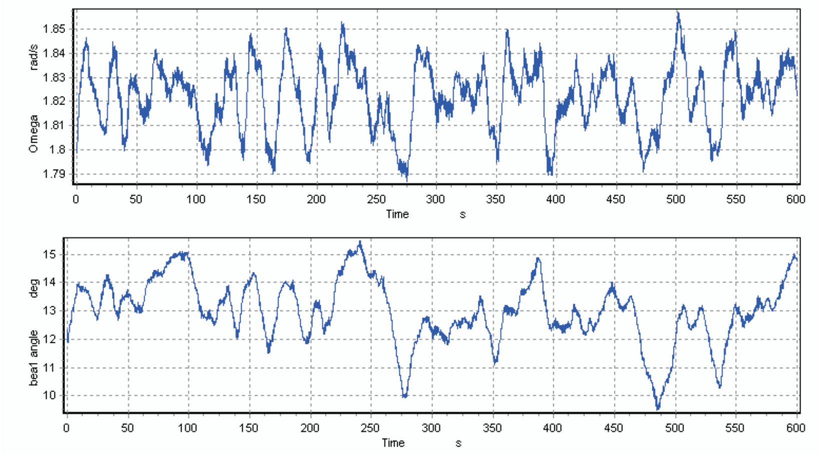


Figure 5. NM80 rotor speed and pitch activity at 18m/s with original PI gains

In full load operation collective pitching is activated for constant torque or constant power control. A PID controller is used to control the rotor and therefore the generator speed via the pitch actuator i.e. the collective pitch angle is based on a measurement of the generator speed. The most common input to the PID controller is the measured generator speed, although in some cases a measurement of wind speed has been used, but this is not very reliable. As the aerodynamic gains vary considerably with wind speed (the required change in pitch angle for a given change in torque is higher at around rated wind speeds than in higher wind speeds), a gain schedule is necessary in this mode. Filtering of the input signal, i.e. the error between reference and actual generator speed can be in many cases useful in reducing unnecessary pitch activity. The frequency where notch filters are best placed are for example at 3p (blade-passing frequencies) and at the drivetrain frequency. Pitch signal spectra can be used to identify these.

2.1 Selected STABCON results

The power/speed controllers implemented by each partner, and a comparison via step responses of the wind speed is briefly presented in section 1.2. The feedback loops and dynamics involved with sensoring, actuation and data processing were included in the nonlinear implementation as:

- Finite bandwidth of pitch servo($\simeq 1Hz$)
- Negligible dynamics of generator torque setting
- 50 Hz data for execution of control cycles

The choice and tuning of the power speed controller has a significant impact on the loads experienced by the wind turbine. A significant difference was seen in the tower loading before any additional load reducing controller was implemented, with the change in the PI gain for the collective pitch controller. The standard deviation of the tower bottom fore-aft moment is increased by 10% when the gain is doubled. A higher gain results in a tighter tracking of the rotor speed, which results in the increased tower loads. The rotor speed and pitch angle with the original and with double the full load collective pitch controller gain are depicted in Figures 5 and 6. The pitch angle standard deviation is the same in both cases.

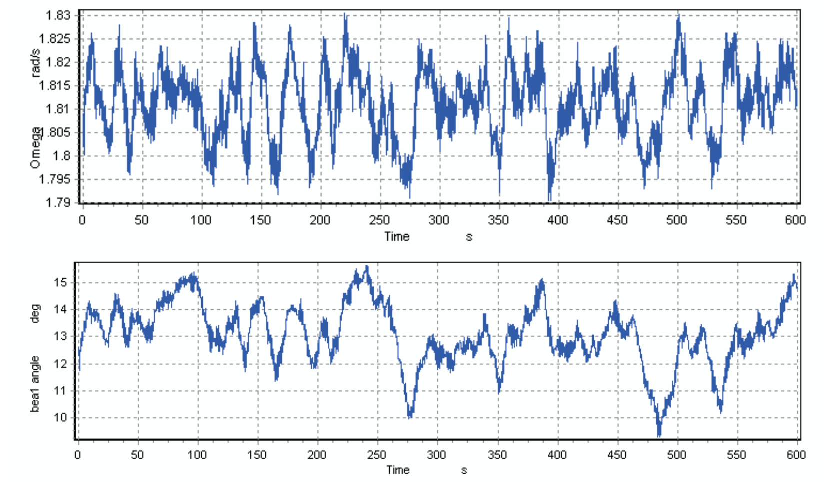


Figure 6. NM80 rotor speed and pitch activity at 18m/swith double the original PI gain

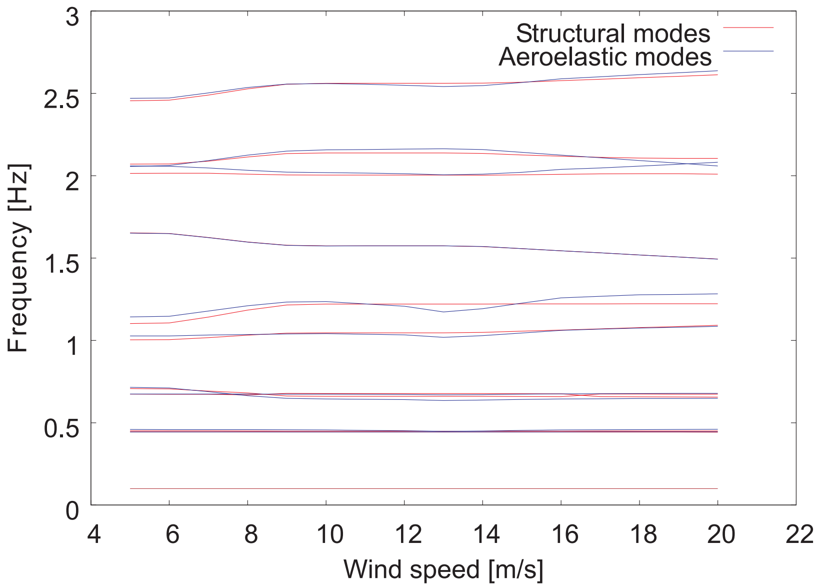


Figure 7. NM80 structural and aeroelastic natural frequencies. The tower frequencies are at 0.44 Hz. The controller natural frequency is 0.1 Hz

The effect of the interaction of the speed controller natural frequency with the aeroelastic frequencies was investigated. For conventional turbine designs, as the Vestas NM80 turbine, the structural and aeroelastic natural frequencies are significantly higher than the speed controller natural frequency of 0.1 Hz, see Figure 7, and no unexpected interference is observed between the controller and the response of the turbine, see Figure 8. This figure illustrate the response in a simulation at 18 m/s and the speed controller works well: The variations in rotational speed are small and the pitch angle variations tend to follow the wind speed smoothly. Furthermore, the tower top downwind deflection is limited.

The stiffness of the lower part of the tower of the Vestas NM80 turbine has been reduced to obtain a tower frequency of $0.1Hz$, identical to the frequency of the PI speed controller. The response is illustrated in Figure 9 and it should be compared to the response in Figure 8. For this case, a clear interference between the speed controller and the tower motion is observed. It should be noted that both the control loop itself and

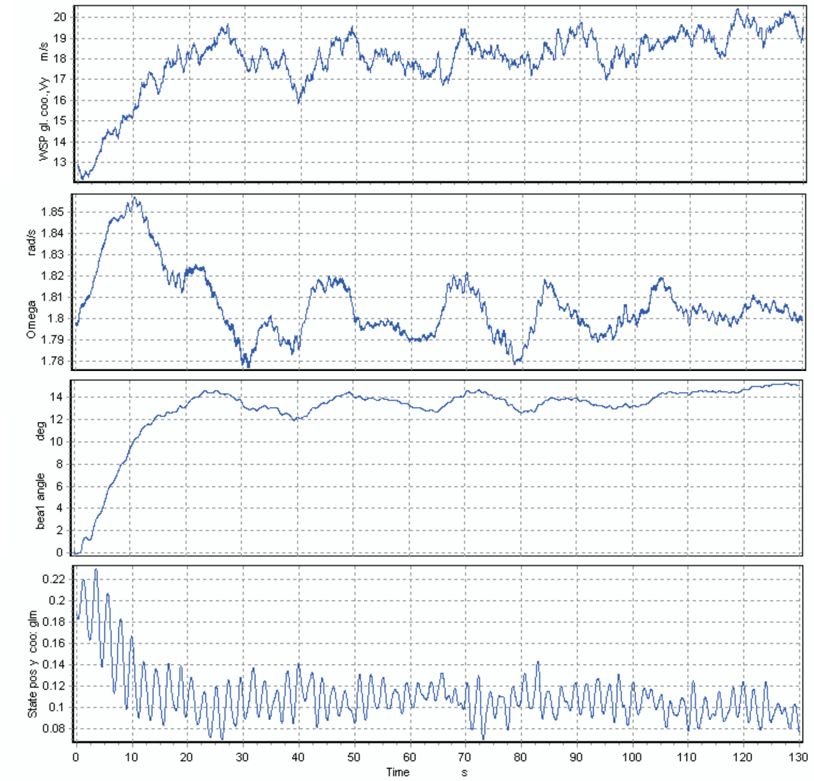


Figure 8. Response of the Vestas NM80 turbine at 18m/s. Tower natural frequency 0.44 Hz. From top: wind speed, rotational speed, pitch angle, tower top downwind deflection

the aeroelastic mode of the tower are positively damped, but the combined system has a negative damping. The interaction is obvious from Figure 9: When the tower moves forward, the aerodynamic load on the rotor increases and thus the rotational speed increases. The controller demands a pitch action to reduce the aerodynamic loading and track the nominal speed and at the time where this pitch action occurs, the tower has started to move backwards. This means, that the reason for the interference is the identical period time in the tower vibration (i.e. the frequency) and the period time of the controller (i.e. the controller frequency).

Transfer function analysis was performed by ECN. Figure 10 shows the sensitivity of the rotor speed and tower bottom fore-aft moment to wind speed variations with a collective and tilt-wise orientation. The dashed blue lines represent the open loop behaviour while the solid red lines appear when the basic controller is linked to the wind turbine.

It can be observed that the rotor speed variations from the turbulence are reduced by the controller in frequencies up to ca. 0.08 Hz. This also holds, in less sense, for the fore-aft moment. However, between ca 0.1 and 0.4 Hz the closed loop behaviour is slightly worse than the open loop behaviour. Since the 'energy' of the turbulence is largely concentrated in frequencies below 0.1 Hz, the overall behaviour is (of course) expected to be improved, especially as concerns the rotor speed behaviour.

Figure 11 shows the servo behaviour of the rotor speed. The amplitude ratio is larger than 0.7 up to ca 0.2 Hz. This can be characterised as the bandwidth of the rotor speed regulation loops. This is 'confirmed' by the system frequency of 0.19 Hz. This frequency is introduced by adding the basic controller to the wind turbine model with pitch actuation included.

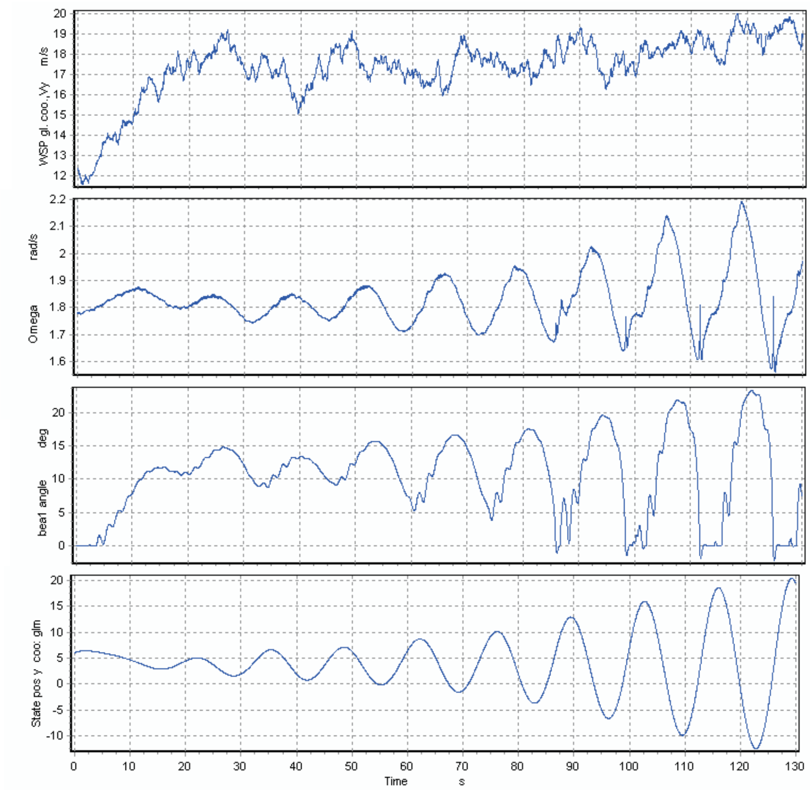


Figure 9. Response of the Vestas NM80 turbine at 18m/s with interference between the controller mode and the long. tower mode which has a reduced frequency of 0.1 Hz. From top: wind speed, rotational speed, pitch angle, tower top downwind deflection.

2.2 Conclusions and recommendations

In this section conclusions and recommendations for implementation and using the power/speed controllers are summarized. These conclusions and recommendations are based on this report and the Task 8, 9 and 10 report from the STABCON project and furthermore, the knowledge obtained by the STABCON partners in other projects.

Recommendations

- Use both linear and nonlinear tools.
- Include dynamics of sensors, actuation and data processing in the nonlinear and linear tools.
- The tuning of the power/speed regulator can have a major effect on the tower loads. This should be considered in any investigation of load reduction control.
- Filtering of the input signal in full load should be considered to reduce unnecessary pitch activity.
- Keep the speed controller frequency (-ies) apart from aeroelastic frequencies.

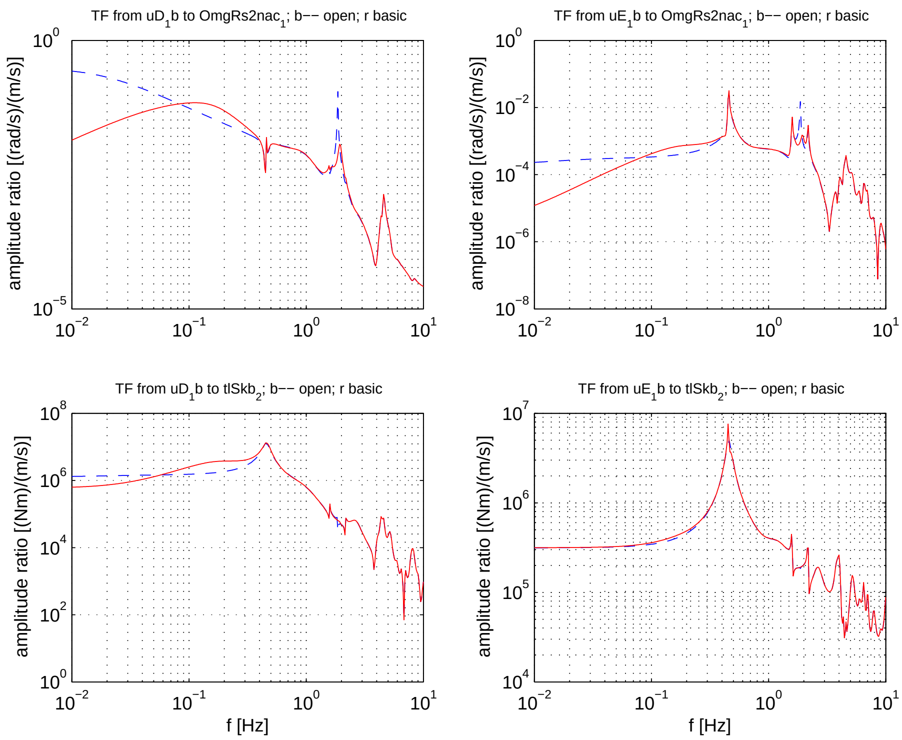


Figure 10. Sensitivity of rotor speed and tower bottom fore-aft moment to collective (left) and tilt-oriented (right) wind speed variations of the wind turbine without (blue dash) and with (red) basic control

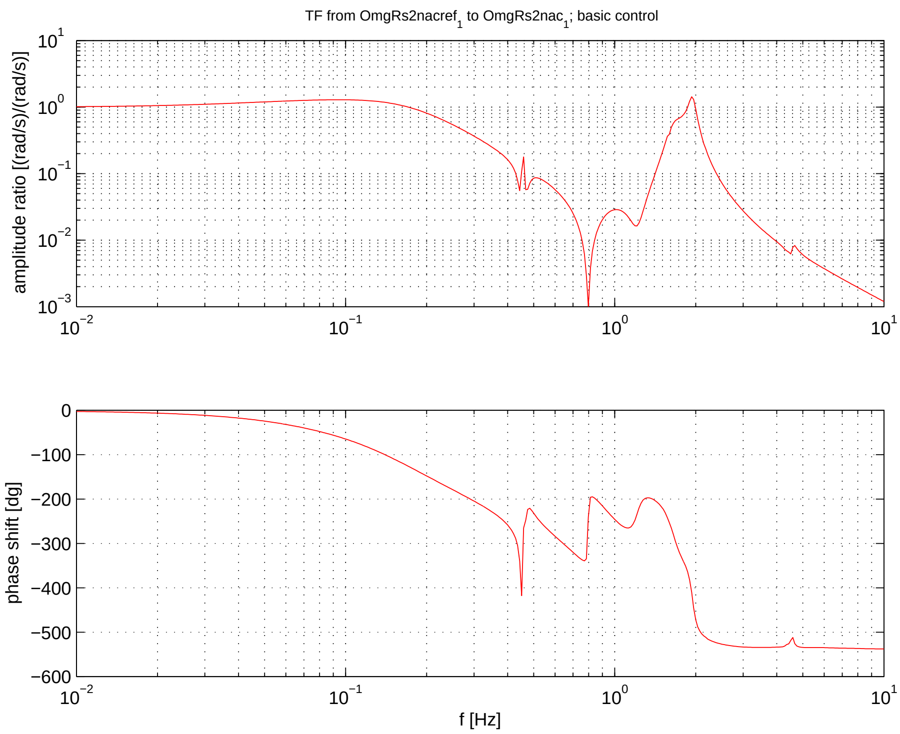


Figure 11. Servo behaviour for rotor speed regulation by collective pitch; amplitude ratio (upper) between ‘rotor speed model output value’ and ‘rotor speed reference value’; phase lead angle of rotor speed output relative to rotor speed reference (lower)

3 Drivetrain damper

A full load controller can be designed as a constant power or constant torque controller. The resulting drivetrain damping on a variable-speed turbine depends significantly on this, since the constant torque turbine will have zero damping and the constant power turbine will have negative damping in the drivetrain [1]. A constant power turbine needs some kind of active damping in the drivetrain in order to be stable in full load operation. A constant torque turbine also needs additional damping to avoid excessive oscillations which will increase gearbox loading.

In reference [7] the drivetrain damper (DTD) is a band-pass filter, acting on the measured generator speed, and centered at the first free-free mode frequency. Placed in the feedback loop, it increases the drivetrain damping: Essentially, instead of demanding a constant generator torque, a ripple is added to the torque demand. The drivetrain damper can be active in all the partial and full load, but will be mostly active in full loads.

3.1 Selected STABCON results

All partners have implemented a drivetrain damper as part of the base-case power/speed regulator. The drivetrain dampers have been implemented as described above. DTU have compared results with and without the damper as seen in Figure 12. The inclusion of the DTD results in a 18% and 21% reduction in the drivetrain loads at 18 m/s at 5% and 25% T.I. respectively. It has the additional benefit of reducing the standard deviation of the pitch speed and pitch acceleration. The cost of including the DTD is an increase in the standard deviation of the power and generator torque.

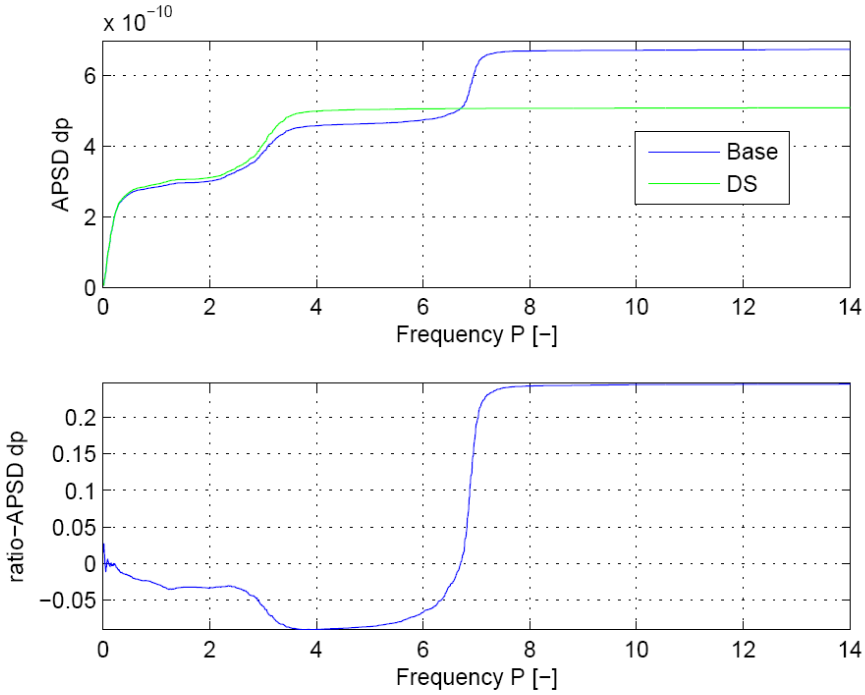


Figure 12. Accumulated power spectra the base line controller and the drivetrain damper at 18m/s with 17% turbulence intensity.

3.2 Conclusions and recommendations

In this section conclusions and recommendations for implementation and using drivetrain damper are summarized. These conclusions and recommendations are based on this report and the Task 8, 9 and 10 report from the STABCON project and furthermore, the knowledge obtained by the STABCON partners in other project.

Conclusions

- The drivetrain damper reduces drivetrain loads up to 10%.
- The drivetrain damper reduces the pitch activity
- The standard deviation of power/torque increases

Recommendations

- On a PRVS turbine it is advisable to use a drivetrain damper, as this mode is very lightly damped.
- The wider the filter, the bigger risk of affecting other frequencies in the neighborhood. It is thus recommended to make it as narrow as possible.

4 Active tower damping

The pitch action of the power/speed controller influences the effective damping of the tower modes shapes via the variations in the thrust force and the driving moment.

Above rated speed, the slope of the mean thrust curve will be negative. However, the effective slope for instantaneous wind speed variations will be positive, ensuring positive damping of the longitudinal tower mode shape — in case of no controller actions. Depending on the time constants in the speed controller, the combined system can be unstable as described in the section on power/speed controller issues.

The controller can, however, also add damping to the tower mode shapes. If a measure of the tower vibration level is used in a feedback loop to the collective pitch action, the level of tower vibration can be reduced. Basically, the concept is to pitch the blades collectively in counter-phase with the tower displacement and thereby enhance the damping of the first fore-aft vibrational mode of the tower.

Usually, it is convenient to use the tower top longitudinal acceleration as the feedback signal. Different approaches have been investigated for control input signal, e.g. tower top displacement, tower top velocity and tower top acceleration.

The primary objective of the active tower damping is to reduce the fore-aft vibrations at the tower natural frequency and thus reduce the fatigue loads. It is only relevant to use the active tower damping controller at the natural frequency of the tower—even though the tower load signal or the tower top acceleration contains energy at other frequencies. Low frequency accelerations can not be used in the active tower damping control loop, due to interference with the speed controller. High frequency accelerations typically originate from asymmetrical loading on the rotor which can not be reduced by collective pitching.

To ensure this effect of the active tower damping controller, it is necessary to use a series of filters on the input signal, usually a band-pass filter at the tower frequency and a phase-lag filter to obtain the proper phasing of the pitch action and the tower acceleration signal.

The concept of tower load reduction by active pitching is well-known and described several places [7],[4],[2],[6].

In the STABCON project, active tower damping controllers have been implemented for the Vestas NM80 turbine. Different partners have implemented controllers which differ only slightly. In all cases, the implementations were based on tower top acceleration input and controller action is the conventional collective pitching of the blades. Most partners implemented a traditional PI add-on controller, but also a more integrated approach was followed. In this latter approach, a simultaneous optimization of many control objectives were weighted — one of those being the reduction of tower vibration level.

Through the STABCON project, the potential of implementing an active tower damping controller has been investigated for different power/speed controller concepts, both constant power and constant torque controller concepts have been investigated.

The potential of adding an active tower damping controller depends significantly on the effective damping of the tower vibration mode. Usually, this effective damping will be dominated by the aerodynamic damping and for pitch-regulated/variable speed turbines the aerodynamic damping is often large. This is also the case for the turbine used in the STABCON project. The implication of large aerodynamic damping is that only a limited amount of energy is present at the tower frequency and therefore the effect of the active damping is relatively small.

4.1 Selected STABCON results

The active tower damper controller has been implemented by most of the STABCON partners. In this section few results showing the main results are presented.

In Figure 13 power spectra are shown for the tower bending moment for 18 m/s wind speed and 17% turbulence intensity. The tower frequency for the test turbine is at 1.5p and it is seen from the PSD that all the energy removed from the system is at the tower frequency. It can be seen that the peak at 1.5p is split up into two peaks on either side of the tower frequency as expected. In Figure 14, the power spectra for 18 m/s with 5% turbulence intensity are shown. As expected there is less energy in the tower bending moment which can be seen by comparing the scale of the plots. It is also noted that the reduction for the low turbulence case is higher. The equivalent load of the tower decreases by 9 % for the high turbulence case while the reduction is about 15 % for the low turbulence case. This is mainly due to the limitations on the pitch actuator accelerations and velocities which are more frequently reached for the high turbulence case compared to the low turbulence case. The blade loads are for these cases only slightly higher while the moments at the tower top are marginally lower.

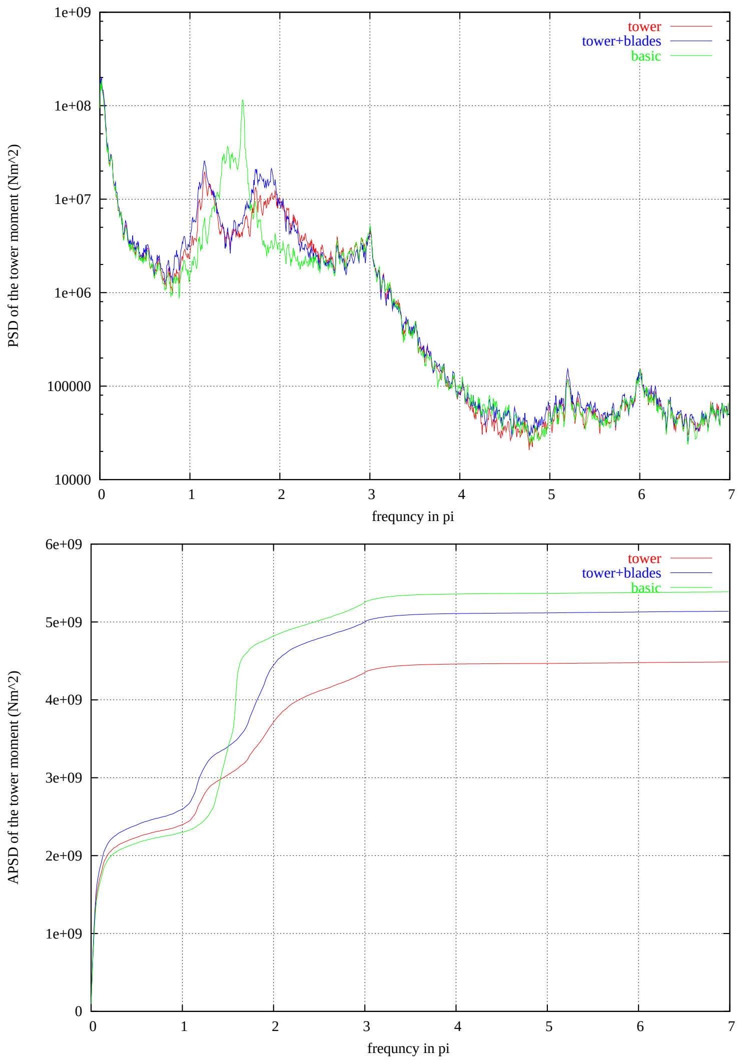
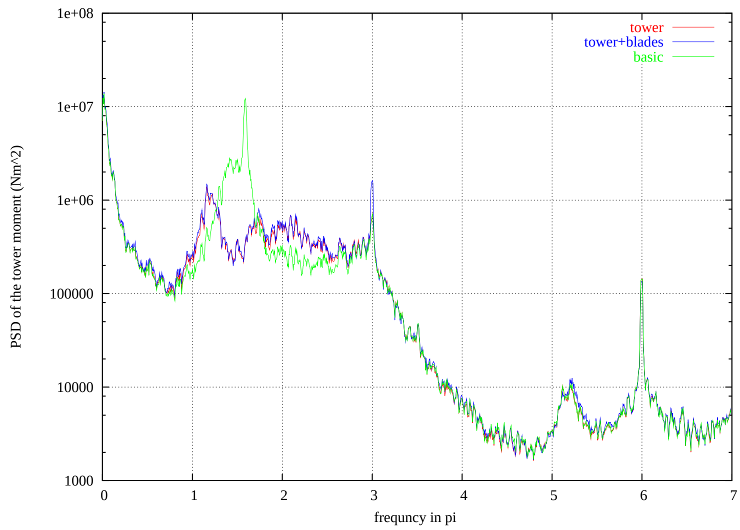


Figure 13. Power spectra for 18 m/s with 17% turbulence intensity. Top: PSD of the tower bending moment. Bottom: Accumulated PSD of the tower bending moment. Three controllers are considered: 'basic' power/speed controller; 'tower' with additional active for-aft tower damper; 'tower+blades' with additional cyclic pitch



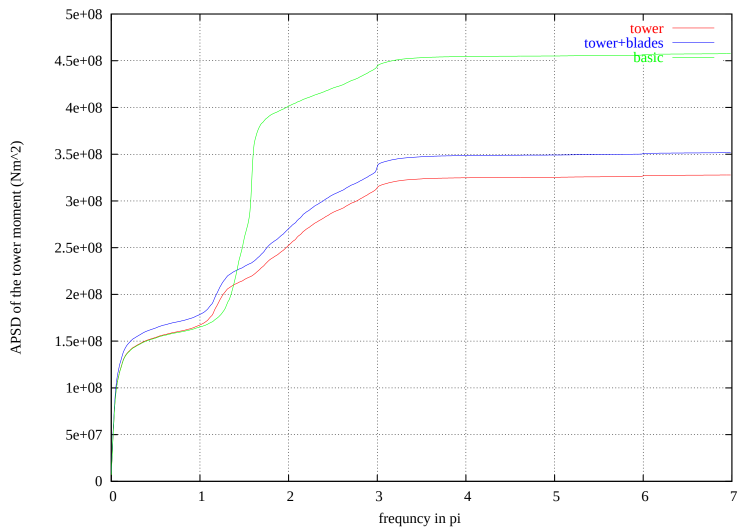


Figure 14. Power spectra for 18 m/s with 5% turbulence intensity. Top: PSD of the tower bending moment. Bottom: Accumulated PSD of the tower bending moment. Three controllers are considered: 'basic' power/speed controller; 'tower' with additional active for-aft tower damper; 'tower+blades' with additional cyclic pitch

4.2 Conclusions and recommendations

In this section conclusions and recommendations for implementation and using tower damper controllers are summarized. These conclusions and recommendations are based on this report and the Task 8, 9 and 10 report from the STABCON project and furthermore, the knowledge obtained by the STABCON partners in other project.

Conclusions

- The tower bending moments can be reduced with the use of a tower damper controller. The level of reduction potential depends on the damping properties of the given turbine.
- The potential of using a tower damper controller for active damping of the longitudinal tower mode is higher compared to the lateral mode since the longitudinal mode has a higher load level. Furthermore, the active pitching of the blades is directly linked to the thrust variations and thus the tower longitudinal loads.

- Blade loads are increased marginally.

Recommendations

- Since the contribution from the longitudinal tower mode usually is larger than the lateral tower mode, it is most beneficial to implement at longitudinal tower mode damper.
- Investigate the damping level of the tower modes using an aeroelastic stability tool, as those developed in STABCON, before implementing an active tower damper.

5 Cyclic pitch

The main purpose of the cyclic pitch controller is to alleviate the mean rotor moments and hereby reduce the 1P blade load contributions.

One aspect of a wind turbines behavior concerns the cyclic load variations due to rotational sampling of the wind field and the passage of the tower by the rotor blades. Mean wind shear and tower shadow give rise to periodic bending moment variations in the rotor blades at rotor speed angular frequency and integer multiples of it, generally referred to as nP, n = 1, 2, 3, ... Rotational sampling of atmospheric turbulence gives rise to stochastic blade load variations that have a broad frequency content with peaks centered around nP. The driving torque and thrust of a B-bladed rotor only experience the mBP (B = 3, m = 1, 2, 3, . . .) harmonic content of these (pseudo) periodic load variations.

This excitation spectrum also applies to the tilt and yaw moments on the nacelle while it should be noted that the loads exhibit a 1P frequency shift when transmitted from the rotating frame of reference to the fixed frame of reference, i.e. from the blades to the nacelle. The resulting rotor moments will be the sum of the three blade moments and, for an asymmetric 1P loading on each blade, the 1P and higher harmonics experienced at each blade will transform into a rotor moment of 3P and higher harmonics, while 1P, 2P, 4P etc will tend to cancel out. The mean (0P) value of the rotor moments will be offset from zero, too. Removing this mean value from the rotor moment will in turn reduce the 1P variations on each blade. Non-simultaneous, (pseudo) cyclic blade pitching is likely to be a suitable means to reduce these loads, see e.g. Bossanyi [7] and Larsen et al [5].

Often, the cyclic pitch load reduction controller is implemented as an additional pitch angle contribution to the collective pitch angle (from the speed controller), and the controller loop can be treated separately. In the following section, the focus will be only on the implementation of the cyclic pitch controller.

As mentioned, the objective is to remove the mean tilt and yaw moments. Some easily measurable quantities are needed that can be transformed into yaw and tilt moments. The measurable blade flap and edge moments can be transformed into the rotor coordinate system using the pitch angles of the individual blades. Using an inverse multi-blade (or Coleman) transformation will give the tilt and yaw moments. With these moments a PID controller can be used to find the resulting pitch angles that will counteract and thus remove the mean tilt and yaw moments. However, a number of steps are necessary from having the tilt and yaw moments to getting the resulting pitch angles. These step can be implemented in many ways and in different chronology.

There will exist a phase shift between an applied pitch variation and the resulting rotor moment. This phase shift comes mainly from the inertia of the rotor through gyroscopic coupling. This phase shift must be identified and taken into account in the design of the controller. The phase shift will vary with the rotational speed, however, using the phase shift at rated rpm will result in only a small error in below rated operation. The phase shift angle can be found by doing an aeroelastic calculation in idealized conditions (no turbulence, gravity, wind shear, yaw error etc.) and prescribing a sinusoidal pitch variation with maximum and minimum at the top and bottom blade position or by computing the transfer function from a cyclic pitch signal to the tilt or yaw degrees of freedom using a linear aeroelastic model. By tuning the phase shift angle until the mean yaw moment becomes zero, the angle can be determined for the specific turbine. For the given test turbine this phase shift angle were found to about 40 degrees, i.e. rotor moments lag pitch actions by 40 degrees. In Figure 15, a time series of the yaw moment with a prescribed sinusoidal pitch variation is showed, as the phase shift angle changes. At t=180 s the phase shift angle is 40 degrees, resulting in a zero mean yaw moment.

Another issue for the cyclic pitch controller is the filtering of the inputs to the PID controller. Turbulence will cause a 3P variation in the rotor moments. Due to the stochastic variation across the rotor disk the azimuthal position with peak rotor moment changes constantly and it is not possible to remove the complete 3P part of the loading with cyclic pitch. Thus, it is removed from the controller input signals with a notch filter (or a band stop filter).

Tuning the gains for the cyclic pitch controller, the standard Ziegler-Nichols method can be used. In this method, the proportional gain is increased until the system becomes unstable (see figure 16). Then the critical gain is used to find the proportional constant by multiplying with 0.45 and the integral constant is half of the proportional constant.

5.1 Selected STABCON results

In this section selected results from the STABCON project will be given and discussed. These results are given to illustrate the main issues with the cyclic pitch controller.

The cyclic pitch controller removes energy at mainly low frequency (0P) and some energy at 3P for the tilt and yaw and at 1p for the flap moments (1P is at 0.286 Hz for the test turbine). The reduction at 0P comes from removing the mean tilt and yaw moments while the 3P reduction arises from the nonlinear load distribution on the rotor. By removing the mean of these and thus reducing the 1P on the blades, the 3P is reduced from the rotor loads. The top spectrum in Figure 17 shows the tilt moment. It is seen that the main reduction is at low frequencies and a minor part is removed at 3p. The lower spectrum in Figure 17 shows the flap moments. Here most of the energy is removed at 1P as expected.

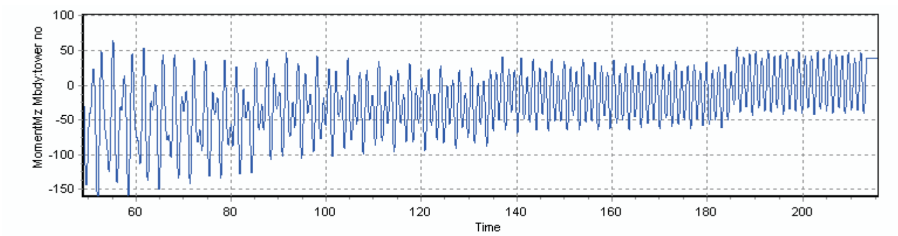


Figure 15. Time series of the yaw moment with a forced pitch angle varying from +5 to -5 degrees during one rotation with maximum and minimum at top and bottom. In the time series the phase angle is changed such that the average yaw moment is zero. From t=180 to 220 the phase angle is 40 degrees

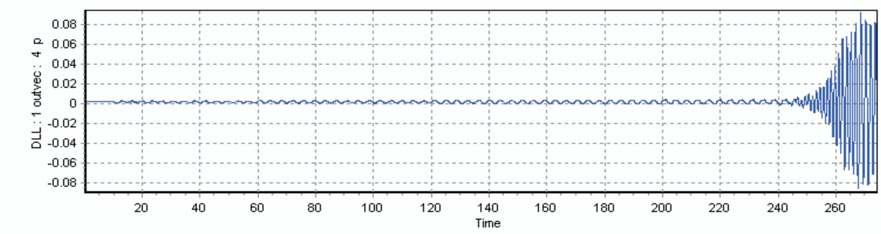
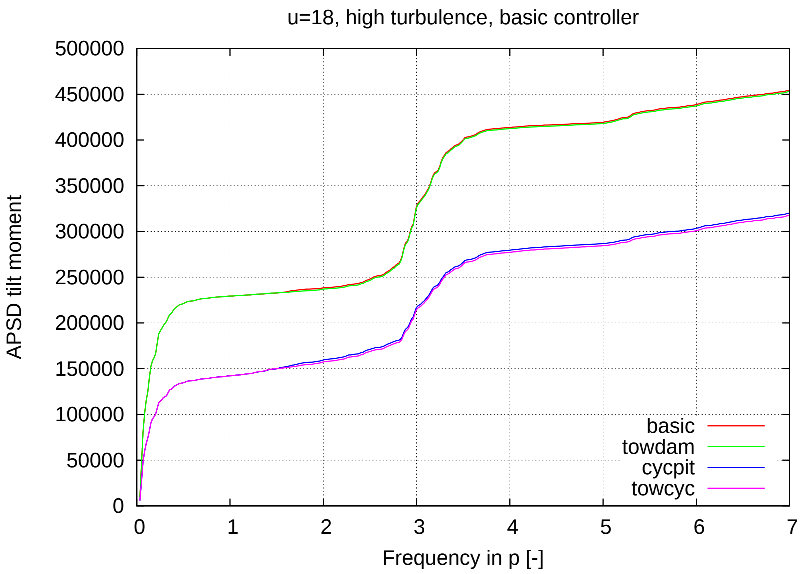


Figure 16. Tuning of the controller. The proportional constant is gradually increased from 100e-7 deg/sec. At t=240s the proportional constant is increased to 300e-7 deg/sec and the controller becomes unstable.



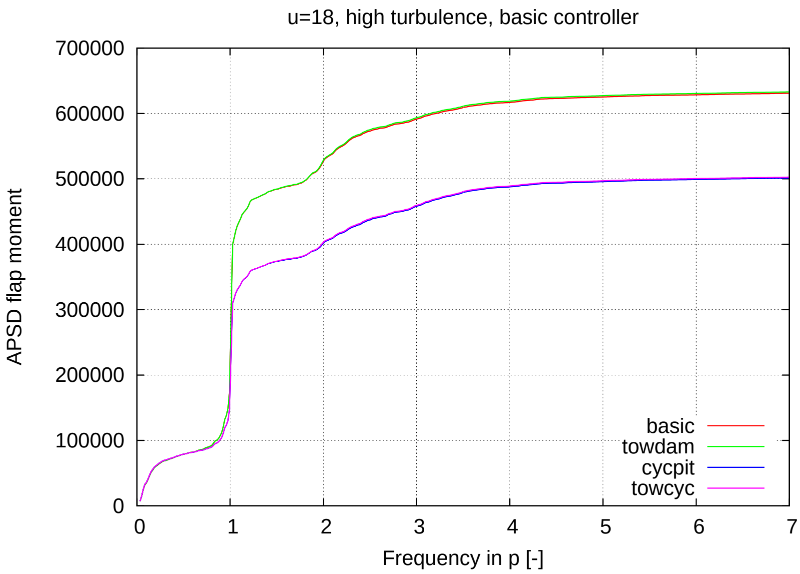


Figure 17. Basic controller with active load reduction: Tilt and flap moments at 18m/s 17% T.I. Different controllers are illustrated: basic: only speed controller. towdam: active tower damper. cycpit: cyclic pitch. towcyc: active tower damper and cyclic pitch combined.

As shown in the previous example, the nonlinear code is a power full tool to illustrate at which frequencies the energy is highest for the system for the given sensor. However, for fast stability mapping it is more illustrative to use linear tools. In Figure 18, a plot of the logarithmic decrement of the two tower modes (red and green marks) is shown for varying gains. It can be seen that the longitudinal tower mode becomes negatively damped for increasing gain. We know that by increasing the gain the system becomes unstable at some value, this is how the controller is tuned, however, the linear tool can show us which modes are affected by the gain.

Figure 19 shows the sensitivity as function of the frequency of the tilt- and yaw-moment to wind speed variations that cause tilt- and yaw-oriented rotor loads (tilt left, yaw right). The blue lines represent the transfer functions without cyclic pitch control (CPC) while the red lines reflect the behaviour with CPC included. Control gains were applied that correspond with a well damped fore-aft tower mode.

It is clear that with CPC included, in low frequencies below ca. 0.08 Hz, the influence of wind speed variations on the tilt- and yaw-moments is reduced. Between 0.1 and 0.3 Hz (1P= 0.286 Hz) a slightly worse rejection behaviour can be observed than without CPC ('overshoot' in figure 19). However, the tilt- and yaw-excitation in the very low frequencies and in frequencies around 3P is dominant. Thus, the net effect of the CPC can be expected to be positive. At higher feedback gains this 'overshoot' increases and the peak shifts to ca 0.3 Hz; it finally represents the tilt and yaw transfer function behaviour associated with the very poor to negatively damped fore-aft tower mode in figure 18 for '50% gain and higher'.

Figure 19 also shows that the CPC leaves the regressive and progressive first leadwise modes unchanged; equal open and closed loop behaviour at 1.6 and 2.1 Hz.

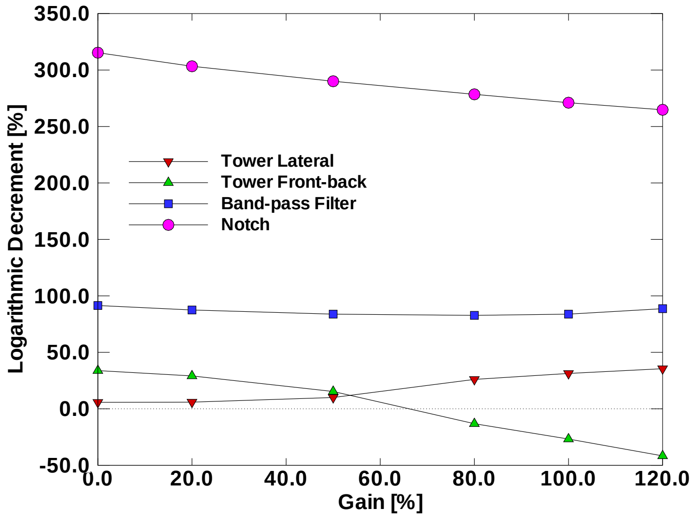


Figure 18. Damping in logarithmic decrement for different mode for variable gains.

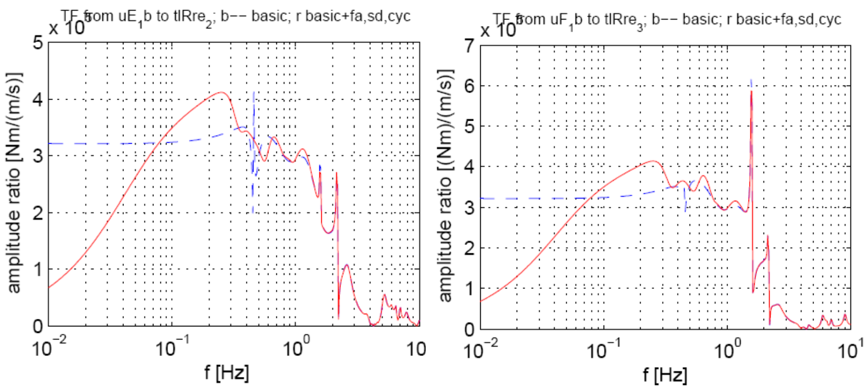


Figure 19. Disturbance rejection assessment via the frequency-dependent sensitivity of the tilt- and yaw moment loads to tilt- (left) and yaw-oriented (right) wind speed variations; blue lines: no cyclic pitch; red lines: cyclic pitch included

The same example can be run in the nonlinear tools and can be illustrated as shown in Figures 20 to 22. In Figure 20, the pitch angle (top graph) and the tower top displacement in longitudinal direction (bottom graph) are shown for the gain found by the Ziegler-Nichols method. The turbine is stable and running smoothly. In Figure 21, the gains are increased by a factor of 2.3 such that the turbine becomes unstable. This is clearly seen in the pitch angles (top graph) which is given in the same scale as in Figure 20. Also the tower top displacement in the longitudinal direction increases to large values and becomes unstable. In Figure 22 three shaft-end traces are shown and it is clearly seen that the whirl flutter mode is unstable. With these increased gain factors, the turbine vibrates in a rotor - whirl/tower mode shape, which does not exist for the reduced gain case. In the Task 11 report[1], on the passive instability suppression, it was shown that if the tilt and yaw stiffness are very low this can lead to whirl flutter. With cyclic pitch the effective tilt and yaw stiffness reduces for increasing gain such that similar instabilities can be seen.

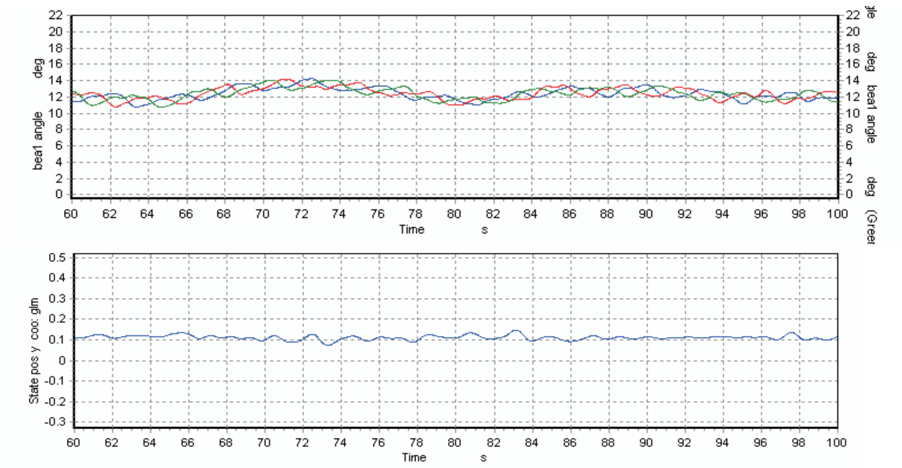


Figure 20. The top time series show the pitch actions for a stable situation where the gains are tuned by the mentioned method. The lower graph shows the same time series for the tower top position.

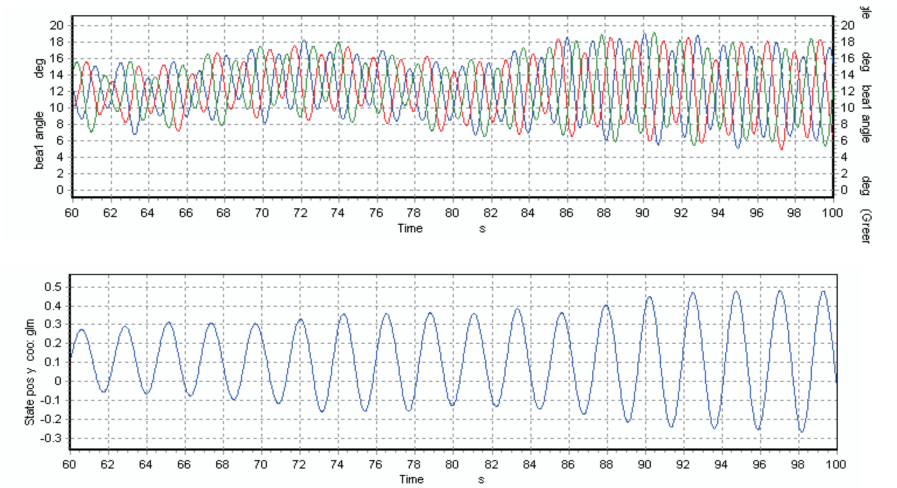


Figure 21. In this figure the gain are so high that the system becomes unstable and the turbine experiences whirl flutter. The top graph shows the pitch action in the same scale as the previous figure. The lower graph is the equivalent tower position.

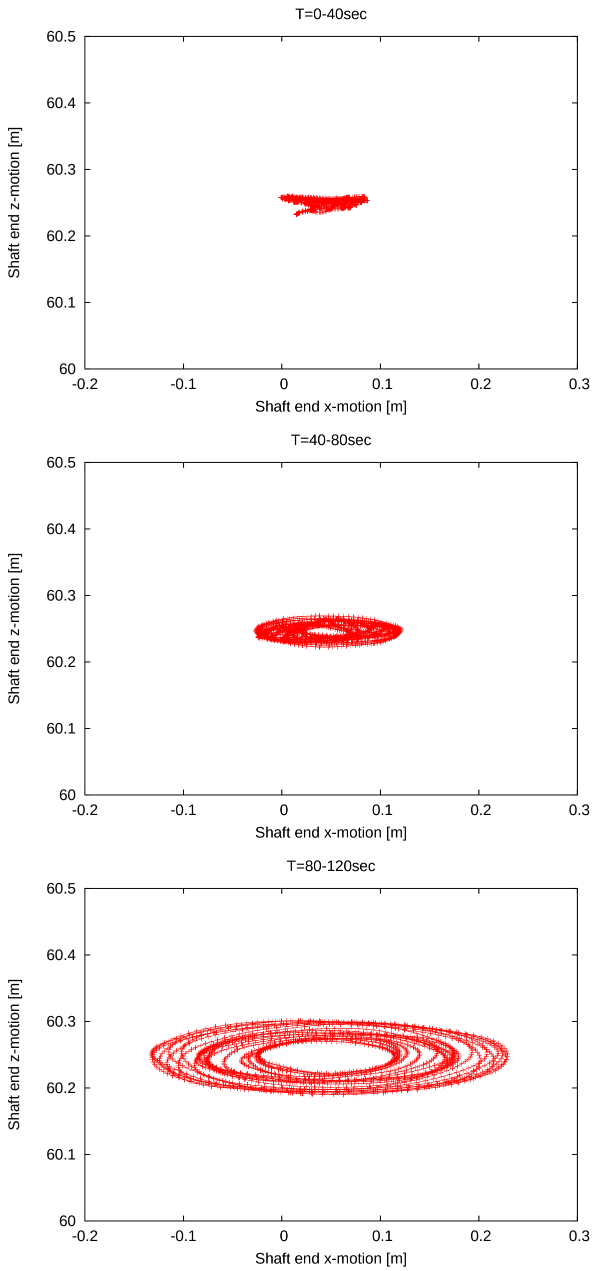


Figure 22. This figure illustrates the development in the whirl flutter mode caused by the high gain in the cyclic pitch controller. In the top figure the trace of the shaft end from 0 to 40 sec. is showed and is stable with small displacements. As time increases the displacement becomes larger and the turbine becomes unstable.

5.2 Conclusions and recommendations

In this section conclusions and recommendations for implementation and using cyclic pitch controllers are summarized. These conclusions and recommendations are based on this report and the Task 8, 9 and 10 report from the STABCON project and furthermore, the knowledge obtained by the STABCON partners in other project.

Conclusions

- A cyclic pitch controller can be used to alleviate the mean rotor moments and hereby reduce the 1P blade load contributions.

- The efficiency of a cyclic pitch controller depends on the ratio between the deterministic and the stochastic wind contributions. The more deterministic the wind conditions gets the more effective the cyclic pitch gets.
- In general, on both this test turbine and from previous experience, cyclic pitch can reduce the flapwise blade root fatigue moment with up to about 20%.
- Reductions in tilt- and yaw loads of up to 10% can be expected by implementing the cyclic pitch controller.
- Too large gain factors in the cyclic pitch controller can lead to negatively damped aero-servo-elastic mode shapes.

Recommendations

- It is recommendable to use both nonlinear and linear aero-servo-elastic design tool when designing a cyclic pitch controller.
- The linear tools gives a good overview when tuning the controller of which modes are affected by the controllers and how much.
- The controller should not be too aggressively tuned since this can have an effect on the stability characteristics.

6 Combined controllers

The controller concepts for power enhancement, instability suppression and gust alleviation have previously been discussed and evaluated independently. The rise of unstable interactions or loss in performance due to conflicting objectives of an integrated control design, i.e. where all previously discussed control concepts are implemented as one, is investigated within the STABCON project. The influence of external factors on the design of the control system, such as turbulence intensity and wind shear, that will effect the weighting of the controller objectives is also investigated.

The main issue with the combined controllers is to establish whether combining the two load reduction controllers; tower damper and cyclic pitch, will result in conflicts making the end results worse than the individual results.

6.1 Selected STABCON results

In this section selected results from the STABCON project will be given and discussed. All results by the partners indicate that there are no conflicts between the tower damper and cyclic pitch controller. Actually, an increased load reduction is seen when combining the two controllers in some of the cases. In Figure 23, an accumulated power spectrum of the longitudinal tower bottom moment is shown. It can be seen that at frequencies above 3P the tower damper controller reduces the accumulated energy more than that of the cyclic pitch controller, as expected. However, the combination of the two, results in a further reduction. Furthermore, it is seen that the tower damper controller removes the energy only on the tower frequency while the cyclic pitch controller removes energy on both the tower frequency and the 3p as concluded earlier. This difference in frequency band for the two controller concepts is believed to be the main reason for the non-interfering behavior. Interaction of the controllers should be expected and investigated in case of combining controllers where the action frequency bands are closer.

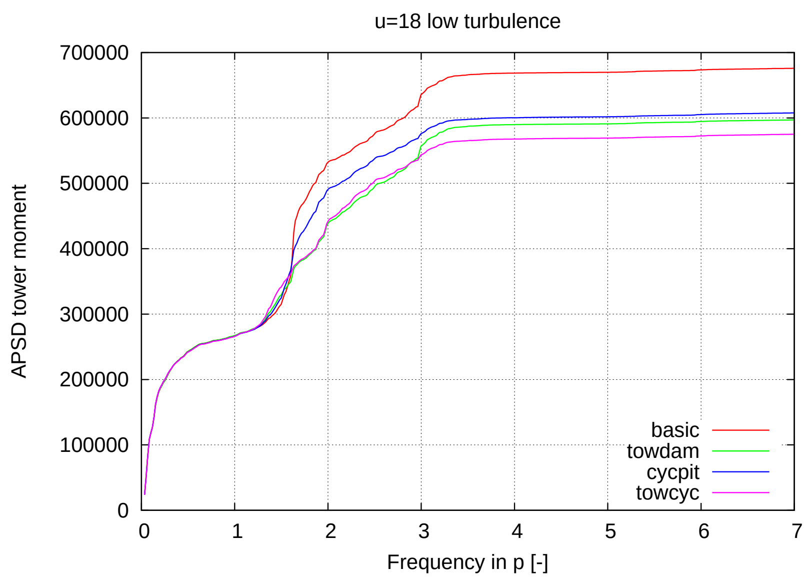


Figure 23. Accumulated power spectrum for the tower bottom moment at 18m/s 5% T.I. for the basic-, cyclic pitch(cycpit)-, tower damper (towdam)- and combined(towcyc) controllers.

6.2 Conclusions and recommendations

In this section conclusions and recommendations for the combined controllers are summarized. These conclusions and recommendations are based on this report and the Task 8, 9 and 10 report from the STABCON project and furthermore, the knowledge obtained by the STABCON partners in other project.

Conclusions

- There are no conflicts between the power/speed-, cyclic pitch- and tower damper controllers when they are combined.
- In specific cases an increase in reduction potential can be seen when combining the cyclic pitch and the tower damper controllers.

Recommendations

- Interaction of the controllers should be expected and investigated in case of combining controllers where the action frequency bands are closer.

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