

Active tower damping and pitch balancing - design, simulation and field test

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Abstract. The tower is one of the major components in wind turbines with a contribution to the cost of energy of 8 to 12% [1]. In this overview the load situation of the tower will be described in terms of sources of loads, load components and fatigue contribution. Then two load reduction control schemes are described along with simulation and field test results. Pitch Balancing is described as a method to reduce aerodynamic asymmetry and the resulting fatigue loads. Active Tower Damping is reducing the tower oscillations by applying appropriate pitch angle changes. A field test was conducted on an Areva M5000 wind turbine.

1. Introduction: Tower fatigue loads

This work is based on the load situation in the tower of a 5MW offshore wind turbine. In published works on load-reducing controls for the tower, the tower foot bending moment M_{TY} often is the only criterion for the effective load reduction. This section will clarify the fatigue share of other load components. In the subsequent evaluations, the tower loads will be evaluated at three tower sections (Bottom, Middle, Top) to account for the distribution of loads and the effectiveness of their reduction at different locations. The sources of different load components and their relative contribution to the overall fatigue loading are described below. The fatigue load reduction of each controller is later expressed as change of fatigue damage ΔD , where a negative value indicates decreasing damage. The tower coordinate system is defined as in Figure 1.

(1) roll / side-side bending moment M_{TX} : The mean moment is given by the drivetrain torque. Oscillations are related to the eigenmodes of the tower and the drivetrain and wind/turbulence excitation. The mean moment is constant along the tower. Periodic excitation spatially decays with increasing distance to the source. Tower eigenmode bending stresses are spatially distributed. Aerodynamic asymmetry causes 1p (one period per rotor revolution) periodic components of side-side bending.

(2) nod / axial / fore-aft bending Moment M_{TY} : The mean bending moment is mainly given by aerodynamic thrust force. The moment increases towards the tower foot. Oscillations are related to the tower eigenmode, turbulence excitation and periodic excitation caused by the tower shadow effect. Aerodynamic asymmetry causes 1p components in the fore-aft bending moment.

(3) yaw / torsional Moment M_{TZ} : torsional loads on the tower are caused by turbulence excitation, wind direction errors and yaw maneuvers of the turbine. Furthermore, aerodynamic



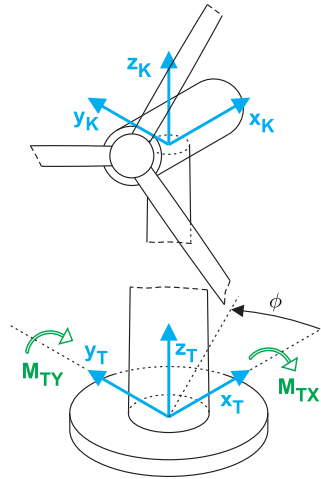


Figure 1. Tower Coordinate System

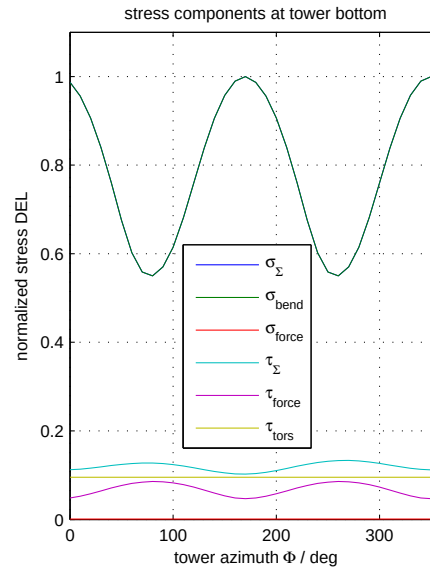


Figure 2. DEL distribution at tower bottom

asymmetry causes 1p components in the torisional moment. The side-side tower eigenmode also manifests to some extent in the torsional degree of freedom, i.e. a side-side oscillation also causes torsional oscillation and vice versa.

To determine the contribution of each load component to the overall fatigue loading, the total stress in the material has to be calculated. The calculation follows for a tubular steel tower section based on the timeseries of moments M_{TX} , M_{TY} , M_{TZ} and forces F_{TX} , F_{TY} , F_{TZ} . The local stress depends on the azimuth ϕ along the tower wall (see Figure 1). The longitudinal stress σ_Σ (aligned with z-axis) and shear stress τ_Σ (tangential to tower wall) are calculated from the load components according to

$$\sigma_\Sigma(\Phi) = \frac{M_{TX} \sin(\Phi) - M_{TY} \cos(\Phi)}{W_B} + \frac{F_{TZ}}{A} \text{ and} \quad (1)$$

$$\tau_\Sigma(\Phi) = \frac{F_{TX} \sin(\Phi) + F_{TY} \cos(\Phi)}{0.5A} + \frac{M_{TZ}}{W_T}. \quad (2)$$

In the above equations, A refers to the cross-sectional area of the tower section, W_B is the axial section modulus and W_T is the polar section modulus of the tower section (see [2]). As the tower is long compared to its diameter, the shear stress from bending is expected to be very small compared to the longitudinal stress. However, the trend of increasing rotor diameters may also cause an increase in torisional loads on the tower which are expected to result in more significant shear stress. For the tower bottom, a normalized example distribution is given in Figure 2 (constant wind direction). The longitudinal stress σ_Σ is dominated by the stress from bending σ_{bend} , while the component σ_{force} caused by the force F_{TZ} is almost zero. The resulting shear stress τ_Σ contains components of τ_{force} (caused by F_{TX} and F_{TY}) and τ_{tors} (caused by M_{TZ}). The resulting τ_Σ is not the sum of the components, because of the nonlinear damage accumulation. For this example, τ_Σ is less than 15% of σ_Σ . For the dimensioning of the tower, wind direction distribution has to be considered and a method to calculate the equivalent stress has to be chosen according to applicable standards[3]. For the above example, the resulting

contribution of τ_Σ to the tower bottom damage can be neglected.

The conclusion from above analysis is, that the bending moments M_{TX} and M_{TY} contribute more than 99% of the tower bottom fatigue damage. Now, a random wind direction distribution is assumed so that the resulting damage from bending is evenly distributed. Therefore the sum of the damage from M_{TX} and M_{TY} is the benchmark criterion for tower load reduction. For very large turbines, this approach should be re-verified as the torisonal tower loads are likely to increase.

The subsequent sections contain results from a field test which was carried out on an Areva M5000 turbine. Due to confidentiality reasons, the axes of figures have partly been removed or values may have been normalized. Most plots have markers for the tower frequency, 1p and 3p frequencies instead.

2. Pitch Balancing

Geometric asymmetries of the rotor may cause mass imbalances and aerodynamic imbalances. Mass imbalances can be removed by adding suitable weights to each blade. It is assumed, that mass imbalance has been dealt with before the aerodynamic asymmetry is taken care of. The aerodynamic asymmetries of the rotor include blade misalignment (pitch angle and azimuth angle) and geometrical errors of the aerodynamic profiles. These asymmetries lead to constant out of plane bending moment components at the main shaft. When the moment is transferred to the nacelle by the main bearing, periodic moments with a period of one rotor revolution $1p$ are observed. To reduce these periodic moments, the out of plane forces at the blades need to be modified. This is achieved by adding small quasi-constant offsets to the pitch angle of each blade. The method has been reported in Kanev [4] earlier. This work contributes a suitable setup of the sensors, a control algorithm, the results of a load calculation and the results of a field test. Although the out of plane or thrust forces are equalized by the pitch balancing controller, this is not necessarily true for in plane forces. In plane forces may be different between the blades, if the imbalance is caused by profile errors. The effect of aerodynamic asymmetries may depend on the operational point.

2.1. Sensors and Control Scheme

To equalize the thrust forces at the blades, the resulting bending moment at the blade roots could be measured and the differences between the blades would be used as the control variables. However, since bending moment measurements are normally not perfectly equal for all blades regarding zero and gain, measurement errors would cause a proportional thrust force offset, thus potentially worsening the imbalance. Placing the sensors at the rotating main shaft may also introduce measurement offsets and is therefore not suitable.

Instead of using sensors at the blade roots or the main shaft, it is proposed that torsional moment and nodding moment are measured at the tower top. For these sensors, an aerodynamic imbalance results in $1p$ periodic load components. The static offset of these signals can be removed by applying a high pass filter with a cutoff frequency below $1p$. When the remaining high-frequency content of this signal is transformed to the rotor coordinate system, the static component of the imbalance moment is known.

$$\begin{bmatrix} M_{R,op,y} \\ M_{R,op,z} \end{bmatrix} = \begin{bmatrix} \cos(\Phi_{Rot}) & -\sin(\Phi_{Rot}) \\ \sin(\Phi_{Rot}) & \cos(\Phi_{Rot}) \end{bmatrix} \begin{bmatrix} M_{TT,y} \\ M_{TT,z} \end{bmatrix} \quad (3)$$

The moment imbalance in the rotor coordinate system $M_{R,op,y}$ and $M_{R,op,z}$ can be removed using a simple I-Controller with gain k_i . The actuating variables are the y and z components of the pitch angle offsets $\Delta\theta_y$ and $\Delta\theta_z$.

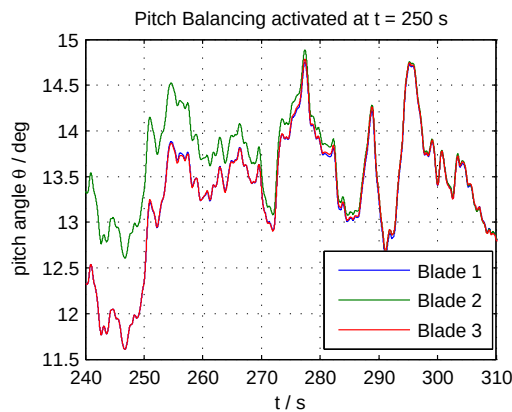


Figure 3. Pitch Balancing is activated at $t = 250s$, initial error of 1° at Blade 2 (Simulation)

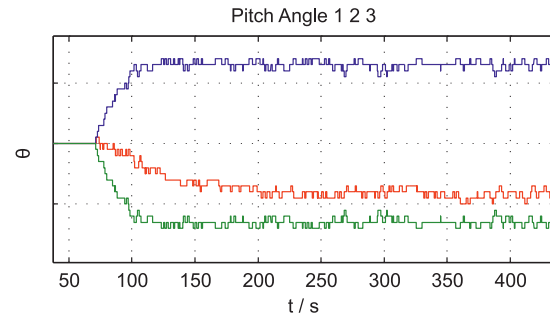


Figure 4. Pitch Angles during activation of Pitch Balancing Controller (Field Test)

$$\begin{bmatrix} \Delta\theta_y \\ \Delta\theta_z \end{bmatrix} = \begin{bmatrix} k_i \frac{1}{s} & k_i \frac{1}{s} \end{bmatrix} \begin{bmatrix} M_{R,op,y} \\ M_{R,op,z} \end{bmatrix} \quad (4)$$

The z and y component of pitch angles are then transformed to blade pitch angle offsets $\Delta\theta_1$, $\Delta\theta_2$ and $\Delta\theta_3$.

$$\begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \\ \Delta\theta_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\sin\left(\frac{30}{180}\pi\right) & \cos\left(\frac{30}{180}\pi\right) \\ -\sin\left(\frac{30}{180}\pi\right) & -\cos\left(\frac{30}{180}\pi\right) \end{bmatrix} \begin{bmatrix} \Delta\theta_c \\ \Delta\theta_s \end{bmatrix} \quad (5)$$

This control algorithm has been implemented as a DLL for load calculation and as ST code module on a real-time industrial PC for the field test. k_i was chosen so that a settling time of about 40 seconds was achieved. This low bandwidth eliminates interference with structural dynamics and reduces reactions to turbulent wind to a tolerable minimum, while the pitch offsets are still adjusted slowly when the imbalance depends on the wind speed or the pitch angle. Figure 3 demonstrates the basic functionality. The pitch offset of blade 2 initially is $\Delta\theta_{initial,2} = +1^\circ$ and decreases to zero after the activation of the pitch balancing controller at $t = 250s$.

2.2. Load calculation

The GL2010 standard [5] states in section 4.3.4.1:

aerodynamic asymmetries, which can arise through production or assembly tolerances of the rotor blades [... shall be taken into account]. A verified tolerance shall be observed. If this is not (or not yet) known, a deviation of the blade angle of attack of $\pm 0.3^\circ$ (i.e. for a three-bladed rotor: blade 1 at 0° , blade 2 at -0.3° , blade 3 at $+0.3^\circ$) shall be assumed.

If smaller tolerances cannot be guaranteed, the above requirement of pitch angle offsets must be used for load calculation and causes additional loads. These additional loads can be removed

if pitch balancing is applied. The pitch balancing controller has been tested for a DLC 1.2 fatigue load calculation in bladed (66 timeseries of 10 minutes). The loads have been calculated for a 5MW offshore turbine model with wave excitation. A mass imbalance of the rotor was present in all calculations.

The results of DLC 1.2 have been analyzed by applying rainflow counting, the linear part of the Wöhler curve (S-N curve) and linear damage accumulation to the time series. For steel parts the S-N slope has been set to $m = 4$ and for the blades (fiber composite) an S-N slope of $m = 10$ was assumed. The next paragraphs will describe the expected change of loads and the actual load situation for each component.

Tower: The asymmetric axial force rotating with the rotor translates to periodic yaw and nod moments at the non-rotating nacelle and tower top. At the same time, the in-plane forces will also be balanced (as the aerodynamic error will fully be compensated in the simulation). Under unbalanced conditions, the in-plane force offset causes a roll moment at the tower, which increases along the tower axis from top to bottom. This leads to the expectation of reduced torsional M_{TZ} , reduced nod M_{TY} and roll / axial M_{TX} moments at the tower.

The actual values of reductions are given in Table 1. As expected, the damage is reduced for all moment directions. The relative share of side-side bending damage compared to fore-aft bending is small at the bottom but increases towards the tower top. Therefore, the sum of the damages of M_{TX} and M_{TY} is a good single measure for the load reduction. A damage reduction of -10.59% (-7.88%) is equivalent to a DEL reduction of -2.7% (-2.0%).

Table 1. Change of Tower Damage (Pitch Bal.)

Tower ΔD of	roll M_{TX}	nod M_{TY}	yaw M_{TZ}	nod+roll X and Y
Top	-14.95%	-7.63%	-0.87%	-10.59%
Middle	-14.77%	-10.67%	-2.76%	-10.71%
Bottom	-14.65%	-7.87%	-3.43%	-7.88%

Table 2. Change of Hub Damage (Pitch Bal.)

ΔD of	M_{HX}	M_{HY}	M_{HZ}
Rotating	-0.73%	+7.23%	+3.11%
Fixed	-0.73%	-5.12%	-14.57%

Hub: The actual loads the hub have to be evaluated in the rotating coordinate system. In this coordinate system, the aerodynamic imbalance causes a relatively constant bending moment offset. Looking at the hub loads in a fixed coordinate system is representing the load situation for the main bearing. These loads are closely related to the tower top loads. The damage components around the nod and yaw axis have been reduced strongly.

Blades: The balancing controller is expected to equalize the loads between the blades. In the unbalanced state, the pitch angle errors cause an inequality of the aerodynamic thrust and torque contribution between the blades. The blade with a pitch angle offset of -0.3° is expected to contribute a higher torque in above rated conditions, while the blade with $+0.3^\circ$ offset would contribute less, resulting in increased and reduced loads respectively. However, the actual numbers in Table 3 do not support this theory. The sum of the damages of the bending moments M_{BX} and M_{BY} has been analyzed. The table is divided into three main section. The upper section contains the relative change of damage between baseline case and pitch balancing. The first row of this section contains the values for the steel parts at the hub-blade interface (S-N slope $m = 4$, i.e. blade bolts). The next row contains the values for the fiber composite at the same location ($m = 10$). The next lines give the values for the radial location at one third and at two thirds of the rotor radius ($m = 10$). From this section of the table, it can be concluded that the damage changes slightly and with different signs at different locations. In the fiber composite, the maximum change of $\Delta D = 3.32\%$ translates to a change in DEL of $\Delta DEL = 0.33\%$ and in the steel section, the change of $\Delta D = 0.35\%$ corresponds with

$\Delta DEL = 0.09\%$. However, as these data do not consider the difference of loads between the blades, the next two sections of the table give the normalized absolute values of damage. For each row, the damage was normalized to the maximum damage in the baseline case. From the second section of the table, the distribution of damage in the unbalanced case can be calculated, e.g. at radius $r = 1/3$ the damage unbalance is 8.5%. Unlike expected, the damage imbalance does not decrease noticeably when the pitch balancing controller is applied. The remaining load imbalance might be related to the mass imbalance of the rotor.

To conclude, the tower DEL is reduced by 2% to 2.7% while the blade DEL increases by 0.3%.

Table 3. Change of Blade Damage (Pitch Bal.)

	Blade 1	Blade 2	Blade 3
Δ of ($Damage(M_X) + Damage(M_Y)$)			
flange hub	0.10%	0.03%	0.35%
flange blade	0.37%	-0.09%	0.86%
r = 1/3	3.32%	3.07%	3.03%
r = 2/3	-1.10%	2.89%	-2.02%
Baseline	$Damage(M_X) + Damage(M_Y)$		
flange hub	98.08%	100.00%	98.99%
flange blade	92.81%	100.00%	96.87%
r = 1/3	91.51%	98.49%	100.00%
r = 2/3	95.55%	88.30%	97.67%
Pitch Balancing	$Damage(M_X) + Damage(M_Y)$		
flange hub	98.18%	100.03%	99.34%
flange blade	93.16%	99.91%	97.70%
r = 1/3	94.55%	101.52%	103.03%
r = 2/3	94.50%	90.85%	102.02%

2.3. Field test

For the field test the controller has been implemented on a real time system which is equipped with strain gauges at the tower top. The pitch angle offset references are forwarded to the turbine main controller using a field bus interface. The timeseries of the activation of the pitch balancing controller are shown in Figure 4. After the controller was activated at $t = 70s$, the pitch angles began to reduce the aerodynamic asymmetry immediately and the steady state was reached within about 60s. The turbine was operated in partial load operation. The PSD of the tower top bending moments are depicted in Figure 5. Two traces with enabled pitch balancing have been analyzed and compared to the baseline situation. The $1p$ peak is fully suppressed in the pitch balancing spectra. Furthermore, the tower oscillation and $3p$ components are reduced. Long-term experience is not yet available but would allow additional insight, especially concerning the dependency of the pitch offset on the operational point. The ability of the pitch balancing controller to reduce tower loads has been demonstrated in this field test.

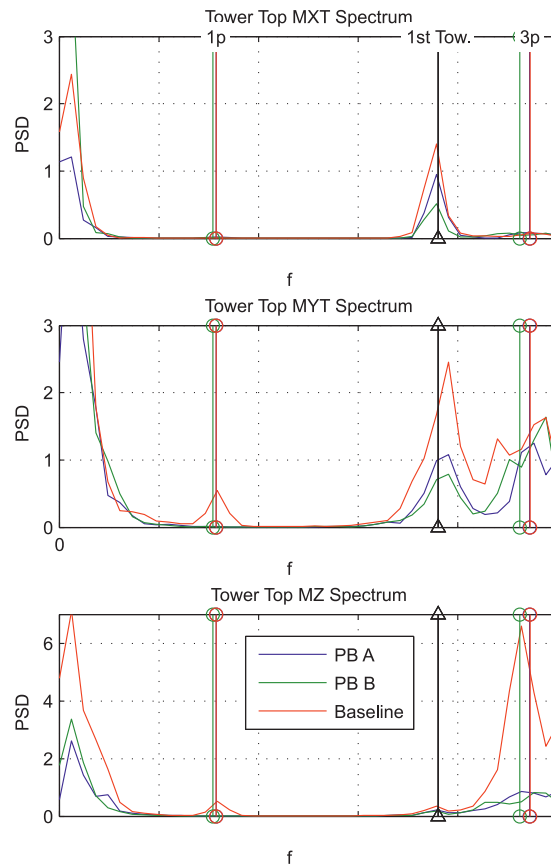


Figure 5. Pitch Balancing Field Test - Spectra of measured tower top moments

3. Tower Damping

The tower damping controller shall reduce the tower oscillation at the first tower bending eigenfrequency. As the loads from fore-aft bending are large compared to side-side bending, the damping of the side-side oscillation is not further investigated here. In [6], the authors have presented a side-side tower damping scheme which can be used to reduce extreme tower oscillations, but is not suitable for fatigue load reduction. In this contribution the focus is on fore-aft tower damping. The acceleration at the tower top is measured and fed back to the collective pitch angle so that the thrust force acting on the nacelle is counteracting the tower oscillation velocity. This controller type can be implemented on most wind turbines without hardware modifications as acceleration sensors and collective pitch actuators are already there.

3.1. Control

The controller has been designed around a linear wind turbine model (IWES WTsim linear) which includes structural dynamics, aerodynamics, pitch actuators and the generator and pitch speed control loop. For the control design multiple criteria must be considered. The primary control target is to increase the damping of the first tower eigenfrequency. Secondly, the sensitivity to wind turbulence (disturbance) shall not be increased. And a third criterion is the pitch actuator activity, which should be kept within allowable limits.

To handle the interaction between rotor speed control and active tower damping, a multivariable control design approach would be possible, see e.g. [7]. However the turbine main controller cannot be changed easily and an additional control loop had to be designed

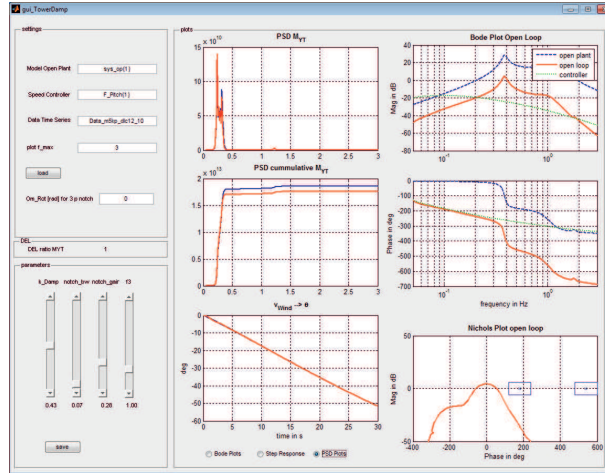


Figure 6. User interface for tower damping control design

around the main controller to be able to do the field test. To achieve a highly transparent design process, a simple transfer function has been parameterized for each operational point. A control design GUI was developed to define the control parameters and evaluate the system performance in various ways: bode and nichols diagrams, PSD of moments and accelerations resulting from wind turbulence spectra, cumulative spectra for load estimation.

A PT3-D-Notch transfer function $F_C(s)$ has been chosen for the controller. Two real poles form a low pass below the tower frequency ($\omega_1 < \omega_{Tower}$) and another pole above the tower frequency ($\omega_3 > \omega_{Tower}$) is further reducing high frequency noise. The differentiation of the signal is shifting the phase by 90° . A notch filter is used to block $3p$ components as these result from asymmetric effects (e.g. tower shadow effect only influences one blade at a time) and should not be reduced with a symmetric pitch signal here. The resulting transfer function is

$$F_C(s) = K_C \cdot F_{3p}(s) \cdot \frac{s}{\left(\frac{1}{\omega_1}s + 1\right)^2 \cdot \left(\frac{1}{\omega_3}s + 1\right)}, \text{ with} \quad (6)$$

$$F_{3p} = \frac{T_f^2 s^2 + T_f^2 k_{bw} k_{gain} s + 1}{T_f^2 s^2 + T_f^2 k_{bw} s + 1}. \quad (7)$$

The parameters have been adjusted manually in the GUI (Figure 6), with the target to minimize the cumulative PSD of the tower bottom bending moment, achieve good damping of the tower eigenmode and not to increase sensitivity to turbulence and periodic disturbances. Also, the gain and phase margin were required to be above $6dB$ and 60° . The parameterization was repeated for every operational point ($v_w = 4 - 25 \frac{m}{s}$). For the load calculation and real-time implementation, the notch filter time constant T_f and the controller gain K_C were scheduled according to the operational point. With the graphical evaluation in the GUI, the manual control design is an understandable and transparent procedure even though it is partly based on abstract criteria.

3.2. Load Calculation

The control design procedure allows some prediction of the fatigue loads, but for an accurate estimation of the effect of tower damping, the load calculation for the design load case 1.2 (fatigue) has been performed (also see Section 2.2). The change of damage is determined with

respect to the baseline scenario. In Table 4 the tower load reduction is given. The most relevant component is the nod-bending damage followed by roll bending damage. The DEL of the sum of the damages for nod and roll bending is reduced by 2.1% at the tower bottom ($\Delta D = -8.23\%$). Hub loads are also given in Table 4. There is a very slight increase in torsional

Table 4. Change of Damage (Tow. Damping)

Tower ΔD of	roll M_{TX}	nod M_{TY}	yaw M_{TZ}	nod+roll X and Y
Top	-0.09%	-2.59%	-0.19%	-2.58%
Middle	-0.77%	-8.57%	-0.20%	-8.01%
Bottom	-0.71%	-8.94%	-0.19%	-8.23%
Hub ΔD of	tors. M_X	bend. Y M_Y	bend. Z M_Z	bend. sum Y and Z
Rotating	0.11%	0.17%	-0.3%	-0.07%
Fixed	0.11%	-0.69%	-0.13%	-0.43%

loads acting on the drivetrain, while the sum of bending is reduced. The blade loads change inconclusively with a maximum increase of the blade root DEL of M_{BLY} (out-of-plane bending) of $DEL_{op,max} = 1.26\%$ (not presented in detail here).

The achievable DEL reduction for the tower is 2.1% at the tower bottom with increased blade DEL (1.26%).

3.3. Field Test

The tower damping controller has been tested on the turbine in partial load conditions. The resulting spectra of accelerations (fig. 7) and bending moments (fig. 8) are compared to baseline measurements. In the baseline scenario (green), the acceleration exhibits spectral components around the tower eigenfrequency and 3p for both directions. With tower damping control, the acceleration is fully suppressed in the range of the tower frequency, while 3p components prevail. The same effect is observable in the tower bending PSDs especially for the fore-aft bending.

4. Comparison of Tower Damping against Pitch Balancing

Two different ways of reducing tower fatigue loads by means of control have been presented. Both approaches have exhibited load reductions for the tower in the same order of magnitude. The advantages and drawbacks shall now be compared.

First, the signals from the sensors are interpreted. In the tower damping field test results, the spectra of bending moments at the tower top and tower bottom (Figure 8) also reflect the behaviour of the tower: excitation around the tower eigenfrequency is passed from top to bottom, while periodic excitation at frequencies distinct from the tower eigenfrequency (here: 1p) is strongly present at the tower top but obviously not at the bottom. This is not surprising, as the tower is a dynamic system with a transmission peak around the eigenfrequencies. Now, when looking at the PSD of the accelerations at the tower top (Figure 7), the shape resembles the PSD of tower bottom bending, but the 1p components are not distinctively visible. This means that the tower top is not significantly accelerated by spectral components of excitation moments which are distinct from the tower eigenfrequencies. But, although there is little acceleration, the loads are contributing to fatigue at the tower top.

From this observation we can conclude that a load reducing controller which is solely based on acceleration measurements will only be able to reduce load components in the frequency range

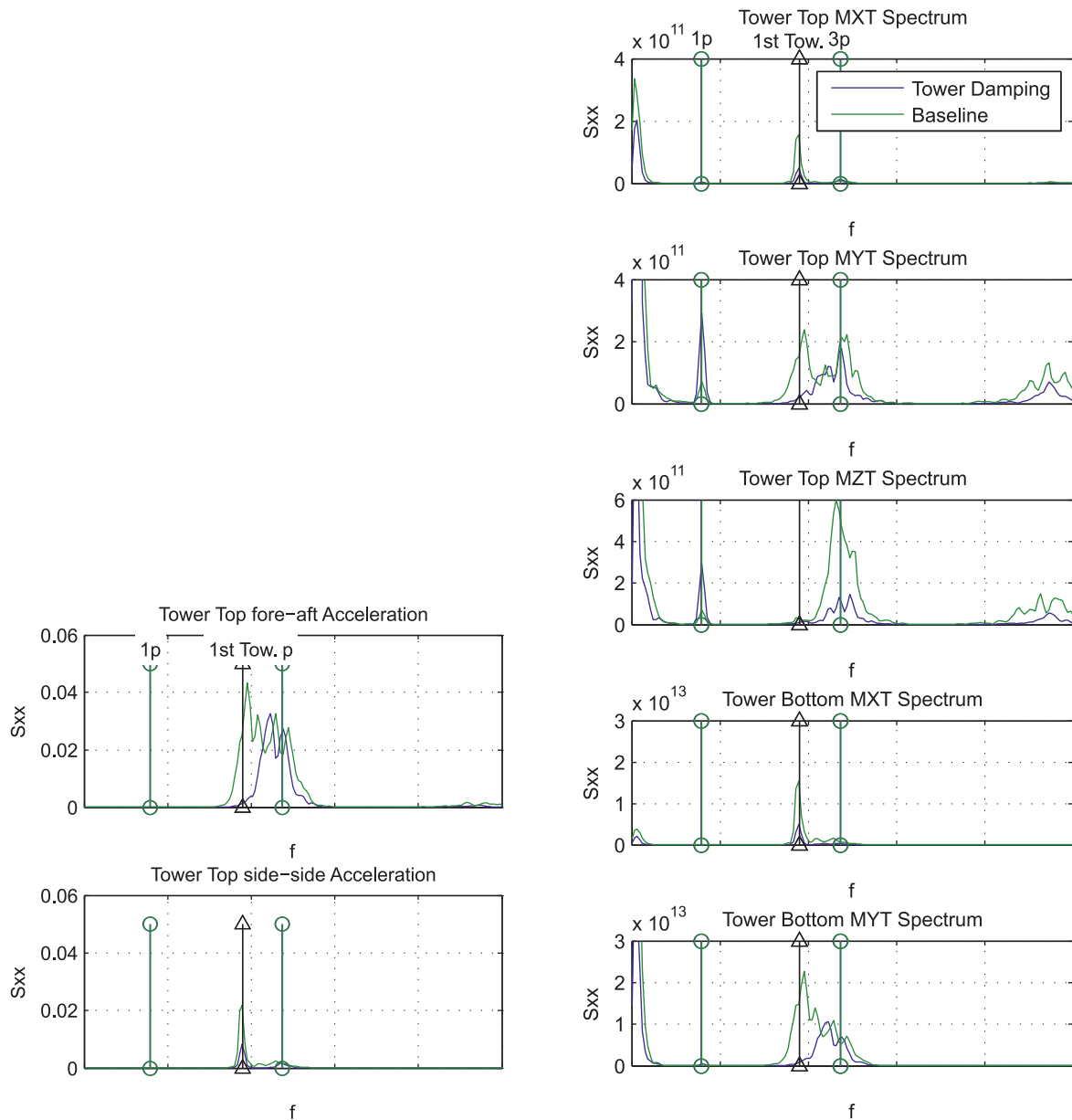


Figure 7. Tower Damping Field Test - PSD of Tower Top Acceleration. Base-line(green) vs. Tower Damping (blue)

Figure 8. Tower Damping Field Test - PSD of Moments

of the eigenfrequencies of the tower. However, the periodic loads and turbulent excitation from wind and wave forces causes fatigue in frequency ranges distinct from eigenfrequencies. Now, to reduce these loads, it is crucial to include measurements of actual loads (strain, bending moment) independent of the amplification of deformation around the eigenfrequencies of the structure. Due to this behaviour of the structure, the pitch balancing controller would likely not be functional if only accelerations were measured. This should be considered when trying to further reduce structural loads. In general, the main fatigue source in wind turbines is bending moments. Therefore reducing fatigue should in the most straightforward approach be based on

bending measurements and not necessarily straight-line accelerations.

Secondly, the actuation signals. Although the actuation was not considered so far, it is obvious that pitch balancing causes individual constant offsets, while tower damping is modulating the pitch angle with the tower eigenfrequency with amplitudes usually below 0.5° . When tower damping is applied continuously, it has to be considered in the pitch system design.

Finally it should be mentioned that the combined application of pitch balancing and tower damping results in an overall DEL reduction of 4.45% for the fore-aft bending component at the tower bottom.

5. Conclusion

In this work, two approaches for the reduction of tower loads have been presented. While the pitch balancing approach requires a slightly more complex sensor setup, it does not have any demanding requirements for the pitch system. With pitch balancing, the source of periodic 1p-loads is completely removed. The tower damping controller in the contrary works with sensors which are already present in most turbines, but it causes pitch system wear which has to be considered. Instead of removing load sources, tower damping control is a reaction to structural oscillations which are excited by external disturbances. The load reductions of both approaches are comparable, while the pitch balancing controller is most effective at the tower top and the tower damping controller shows the highest reductions at the tower bottom. When both controllers are combined, the load reductions superimpose, as both controllers work in distinct frequency ranges. To quantify the reduction in COE, the achievable cost-reduction of the tower will have to be determined and weighed against the cost of the enhanced control system and cost related to the pitch system.

Acknowledgments

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