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“Integrated Wind Turbine Design”

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Abstract: This report starts with a description of active tower damping control algorithms, their general advantages and disadvantages as well as their economical application potential. More specific simulation results of a MM92 with 100 m hub height are shown, followed by the presentation of measurement results of the field test to validate the functionality of the active tower damper.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	●		**R0**	General public	●		Private web site	
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1. Introduction

The potential of reducing tower and foundation fatigue loads by tower damper control algorithms in general is well known for a long time and has been verified in simulations, e. g. [1]-[3]. Though there have been implementations on series turbines [4], reports of tests and successful applications on series turbines are rare.

Within the UpWind project, WP5 “Advanced Control” REpower performed a half year field test to validate tower damper control algorithms. Prior to the UpWind project REpower developed a new method to damp side-side tower movements [5]. Unlike earlier concepts the side-side tower damper acts via individual blade regulation instead of torque modification. Side-side damping is of particular relevance for large offshore turbines operating in conditions of wind-wave misalignment. The field test includes a validation of this new side-side tower damper and a commonly known fore-aft damper, together referred to as “tower damper”. Two neighbouring MM92 with 100 m hub height have been chosen as prototype and some load measurement took place.

This report starts with a description of the control algorithms, their general advantages and disadvantages as well as their economical application potential. More specific the simulation results of a MM92 with 100 m hub height are shown, followed by the presentation of measurement results of the field test to validate the functionality of the tower damper.

2. Active tower damping algorithms

The considered active tower damper consists of two controller components that operate independently from each other:

- A collective pitch controller to reduce fore-aft movements of the tower (tfa damper)
- A cyclic pitch controller to reduce side-side movements of the tower (tss damper)

Both components are add-ons to the standard speed controller and can be switched on and off during operation. Figure 1 shows the control structure design and how the standard speed controller and the tower damper components are combined.

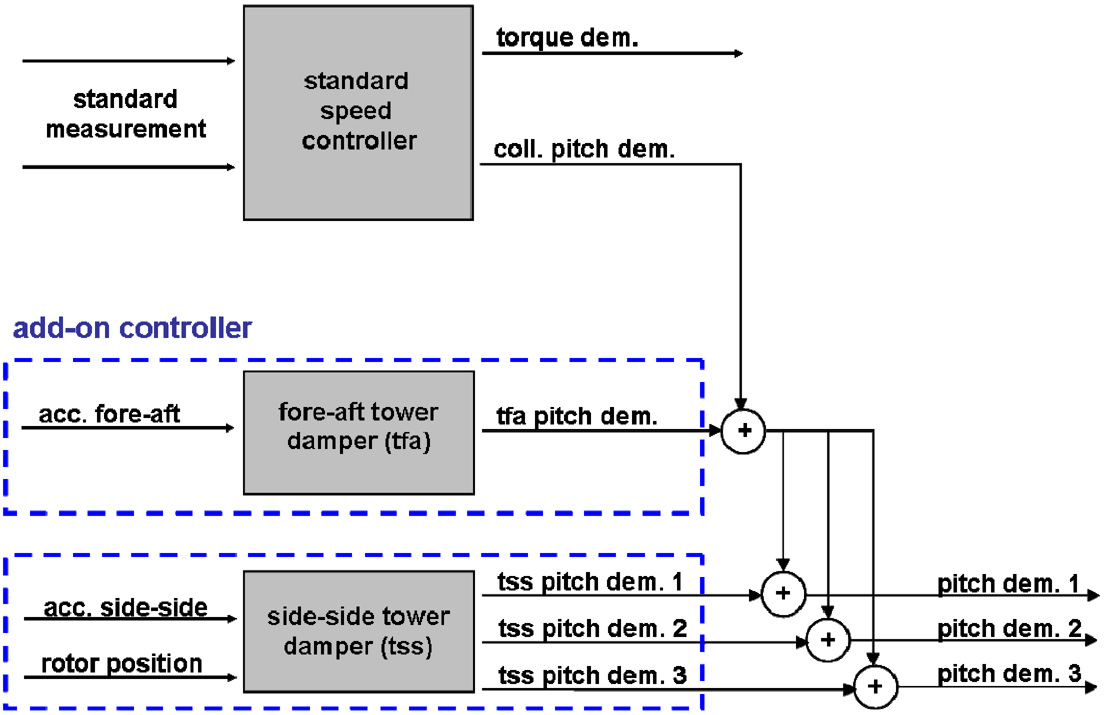

Figure 1: Control structure with standard speed controller, fore-aft tower damper and side-side tower damper

2.1 Fore-aft damper

To implement a fore-aft tower damper (tfa) an accelerometer is installed in the nacelle aligned to the fore-aft direction of the turbine. From the measured acceleration the algorithm calculates an additional collective pitch angle demand to regulate the thrust of the rotor. As a basic concept the blades are pitched in counter-phase with the tower displacement and thereby increase the aerodynamic damping of the tower.

Damping of movements at tower eigenfrequency is the prior intention of that controller. Thus, the fore-aft acceleration signal of the damper has to be treated in a way to minimise these movements without affecting higher modes of tower and blade negatively. Sometimes filtering the signal is necessary to suppress high frequency or distinctive components such as 1p and 3p harmonics.

The fore-aft damper is designed as an addition to the existing standard speed controller in the form of a fast inner controller. The collective pitch angle demand of the tfa damper superposes the demand of the speed controller. In general there is some interaction between the loops, but they can be treated as partially decoupled in most cases: Typically the frequencies of pitch operation due to speed control are significantly below tower eigenfrequency and the frequency range of the two controllers does not overlap. Furthermore only small pitch movements are necessary to damp the turbine as thrust is very sensitive towards pitch angle movements.

Pitch loads are slightly increased by the tfa damper, which needs to be taken into account when designing the damper e.g. for a turbine with already designed pitch system. The tfa damper is configured to be active only close to and above rated wind. Thus, additional loads for the pitch device are moderate and it avoids negative effects on the energy production due to variation of pitch angle on either side of the optimum value at partial load operation. This restriction has only small impact on the tower damage load reduction, as most damage occurs above rated wind when the aerodynamic damping of the fore-aft vibration is lowered by pitch interaction of the speed controller.

2.2 Side-side damper

Conform to the tfa damper an accelerometer is installed in the nacelle aligned to the side-side direction of the turbine. Supplementarily the rotor position is detected. From these signals the side-side tower damper algorithm (tss) calculates additional cyclic, individual pitch demands for each blade. The asymmetrical blade position results in a sidewise force at rotor hub that counteracts the side-side movements of the tower.

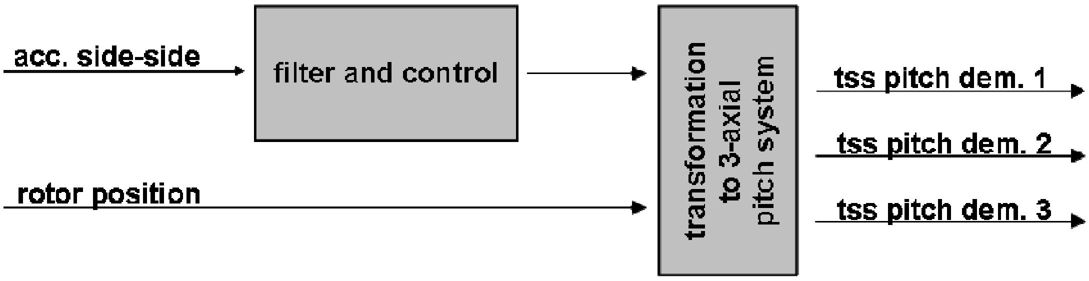

Figure 2: Control structure of side-side tower damper

Just like the tfa damper the focus of the tss damper is on damping oscillations close to tower eigenfrequency. To minimize negative influences on higher frequency and distinctive components, the acceleration signal is multiply filtered e.g. by a band-pass filter at tower eigenfrequency and by notch filter. The design of the side-side tower damper is independent from the speed controller, since collective and cyclic pitch is decoupled, such as shown in [3].

There is only a light natural damping of side-side tower movements and already small rotor asymmetry of few tenth of a degree cause significant damping. It is advisable to prevent excessive side-side damping as it might slightly increase main shaft and blade root loads as well as fore-aft tower loads. Pitch drive loads increase too.

The side-side damping is switched off below rated wind, so additional pitch drive loads are minimised and there is no negative influence on the energy yield.

2.3 Changes in the supervisory control and safety concept

It is necessary to adjust the supervisory control and safety concept to avoid that e.g. at sensor failure the damper loses its function or even causes damages. At worst a failure may cause strong tower oscillations. These are detected by the existing supervisory control. The standard vibration sensors monitor the oscillations. If the limits are exceeded, the turbine will be stopped.

The supervisory control is extended by the following functions:

- Continuous plausibility check of the rotor position
- Continuous plausibility check of tower damper algorithm outputs
- Continuous and temporary plausibility check of incoming accelerations
- Continuous check of sensor status of the internal sensor condition monitoring system

If a disturbance of the algorithm outputs or the incoming accelerations or a general defect of the sensors is detected, the tower damper will be deactivated.

2.4 Economic application potential

Side-side and fore-aft tower dampers are able to reduce tower and foundation fatigue loads without significant influence on other fatigue or extreme loads (see chapter 3). Considering these dampers for new turbines might help to reduce costs. Unfortunately, not all towers and foundations of various turbine types are fatigue load designed. In general designing these components for onshore and offshore turbines is different:

Onshore wind turbines are designed and certified for specific wind classes. The design load cases instruct an inflow from one direction over the whole live time cycle. Since fore-aft loads generally are higher than side-side loads under onshore conditions, only a reduction of fore-aft loads might help to reduce material or enable existing tower types to apply in higher wind classes. Onshore foundations usually are dimensioned by extreme loads, some towers or sections are fatigue load designed.

Unlike onshore turbines, costly parts of the offshore turbine as tower and foundation are designed and certified for individual sites, taking into account the direction of inflow. Hence both, fore-aft and side-side loads are considered for the design. Especially the side-side damper is very promising to reduce material: At offshore conditions side-side loads sometimes exceed fore-aft loads due to strong wind-wave misalignments. In difference to onshore foundations some offshore foundation structures such as monopile and jackets are typically designed by fatigue loads, towers need to be considered individually.

3. Simulation

There have been made several simulations for different turbine types and tower heights to quantify the load reduction by using active tower damping. In principle the reduction grows with increasing tower height and decreasing tower eigenfrequency. The well-established REpower MM92 with highest hub height (100 m) responds very well to the tower damper and is chosen as prototype for the validation. Since tfa and tss dampers do not influence each other within certain bounds, always both algorithms are switched on and off in the measurements just like in simulation examples. Dampers switched off is named “original”, dampers switched on is named “with tower damper” in the figures below.

3.1 Qualitative considerations

Figure 3 shows the time response of an MM92 with 100 m hub height with and without tower damper at high wind and turbulence conditions. Both bending moments and accelerations are reduced significantly by tower damping. The frequency analysis of a 10 min time series each shown in Figure 4 and Figure 5 clearly presents the effect of both tower damping algorithms at different wind conditions:

The for-aft tower damper reduces the peak at tower eigenfrequency and also damps the peak of the frequency close to 1p of the for-aft tower acceleration. In return the damper generates a peak on the right next to 1p and tower eigenfrequency while higher frequencies are not influenced at all. It is not possible to avoid that peak shifting to little higher frequencies; nevertheless the overall fore-aft tower load is still reduced significantly.

The side-side acceleration is dominated by frequencies at tower eigenfrequency. The side-side tower damper reduces this frequency component a lot without any negative influence on other frequencies.

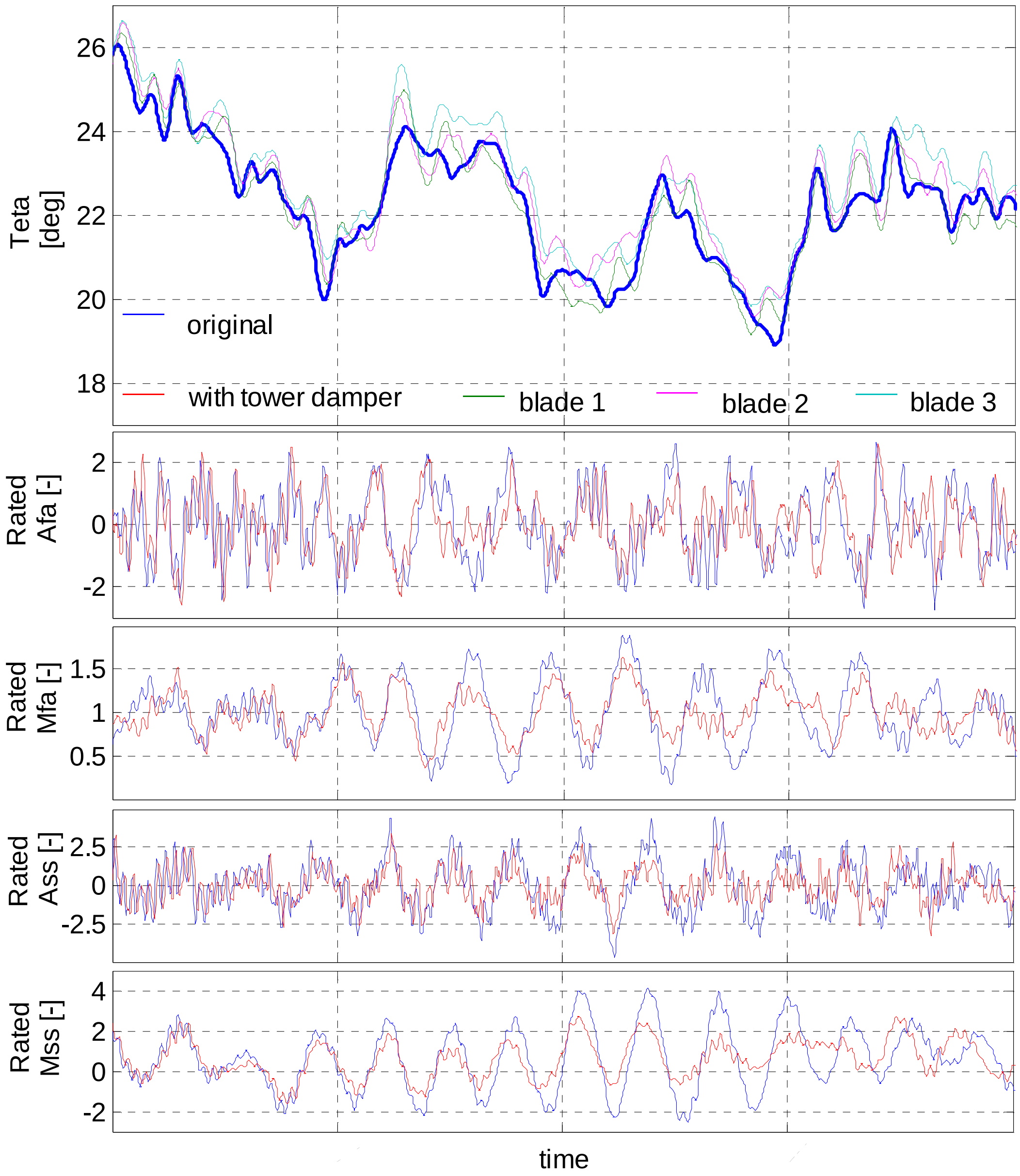

Figure 3: Simulated blade angle, side- side and fore-aft accelerations and tower bending moments rated to mean values of the original simulation with and without tower damper, v_{mean} = 24m/s

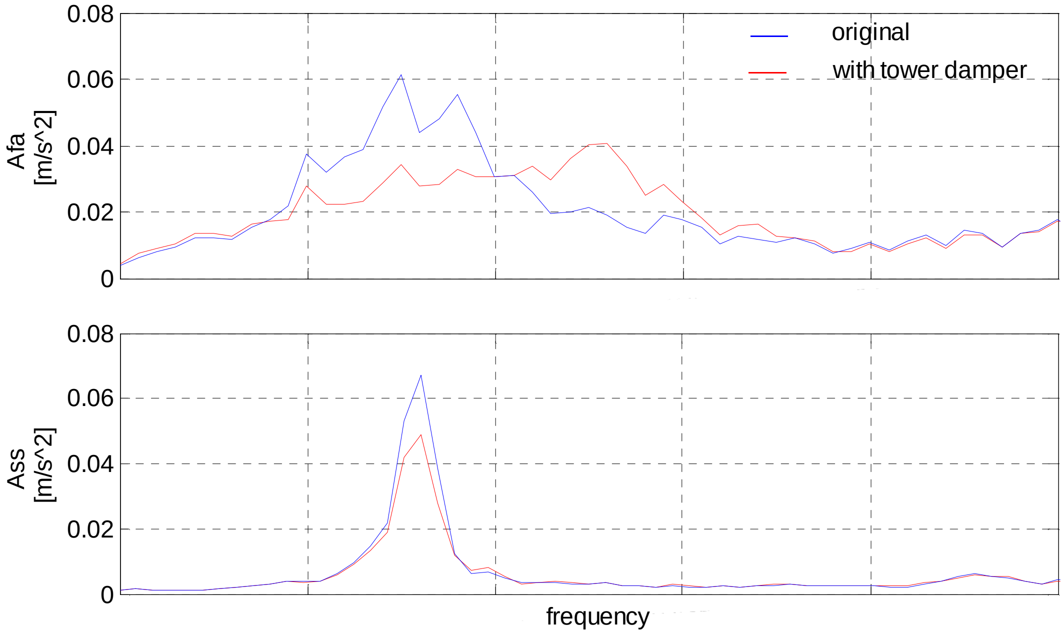

Figure 4: Frequency analysis of fore-aft and side-side acceleration with and without tower damper, v_{mean} = 12 m/s

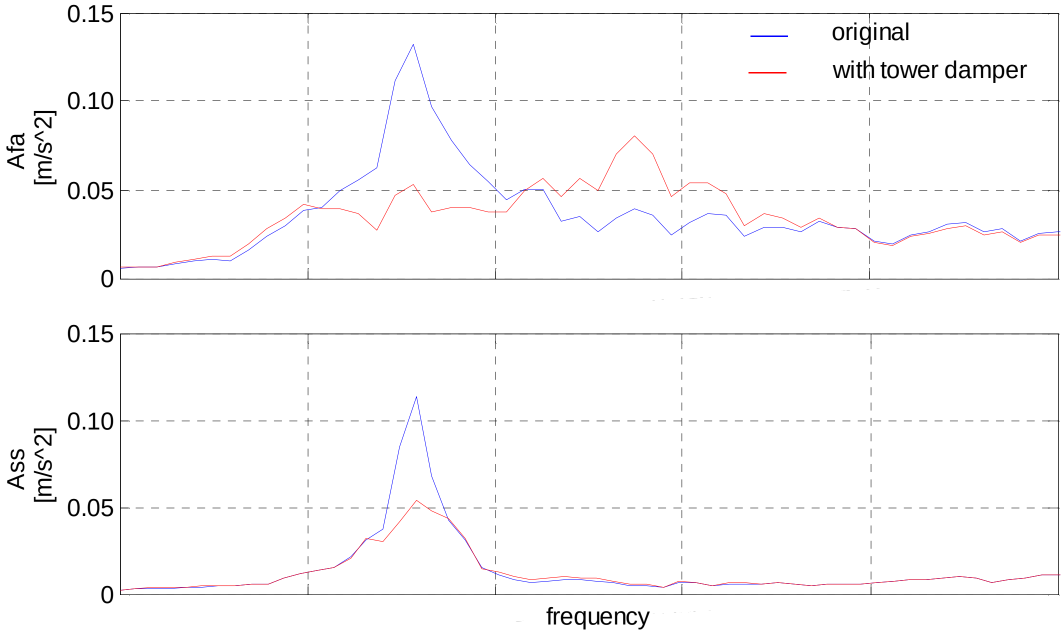

Figure 5: Frequency analysis of fore-aft and side-side acceleration with and without tower damper, v_{mean} = 18 m/s

3.2 Quantitative considerations

Figure 6 illustrates the results of the full fatigue load simulation using Flex5 with IEC 2A conditions as an example. Depending on the component material the resulting damage equivalent loads are calculated for Wöhler exponent m = 4 (steel) or Wöhler exponent m = 10 (composite). Further the weighted standard deviation of the pitch rate is calculated to demonstrate the pitch activity. The graphic shows the relative change of damage equivalent loads by using active tower damping.

$$rel.\,change = \frac{with\ \ tower\ \ damper}{original} - 1 \qquad \text{(in \%)} \qquad (1)$$

Obviously both damping algorithms operate as expected and reduce the relevant loads without considerable negative side-effects:

- Reduction of tower base side-side loads by more than 30%
- Reduction of tower base fore-aft loads by more than 10%

There is almost no influence on main shaft and blade root loads visible. Even the pitch activity does not increase significantly (approx. 1%) and the power curve is untouched. Additional extreme load simulations verify that there is no considerable negative influence on any values.

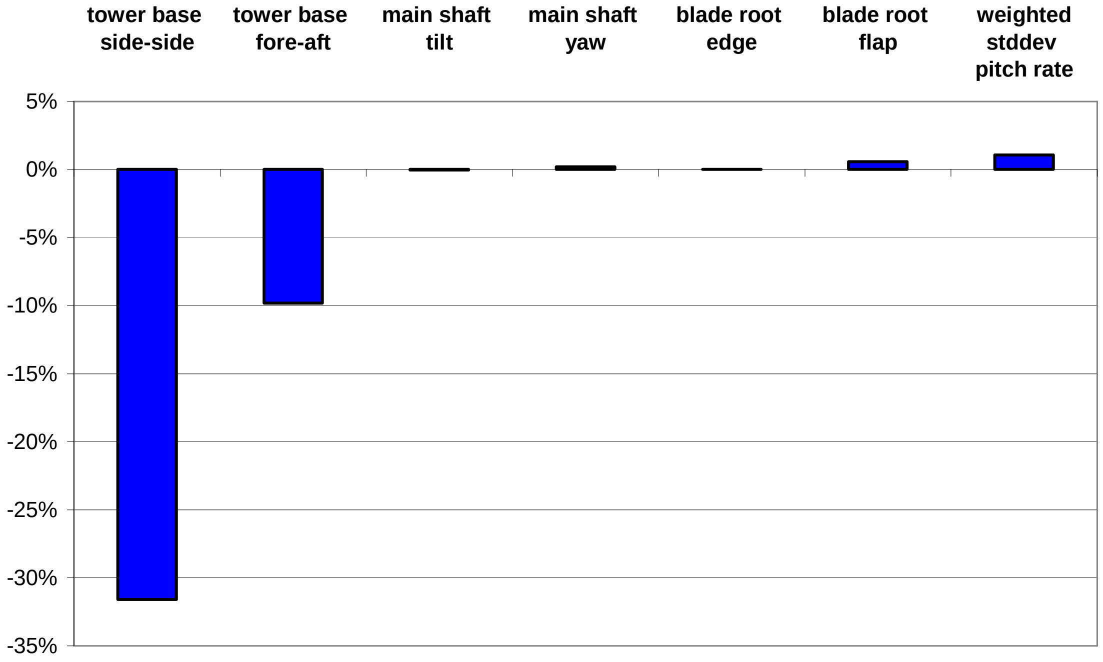

Figure 6: Relative change of damage equivalent loads by active tower damping in simulation, IEC2A, m = 4 for tower base and main shaft and m = 10 for blade roots

Further simulations with other wind conditions show, that in fact the absolute load reduction by tower damping decreases with reduced turbulence intensity, but the relative load reduction stays in the same range.

4. Measurement

The load measurement is made to prove the efficiency of the tower damping control algorithms. It is impossible to validate the behaviour in all load cases; especially extreme conditions cannot always be reached. Only active above rated wind, the validation of the tower damper needs a measurement site with high wind speeds.

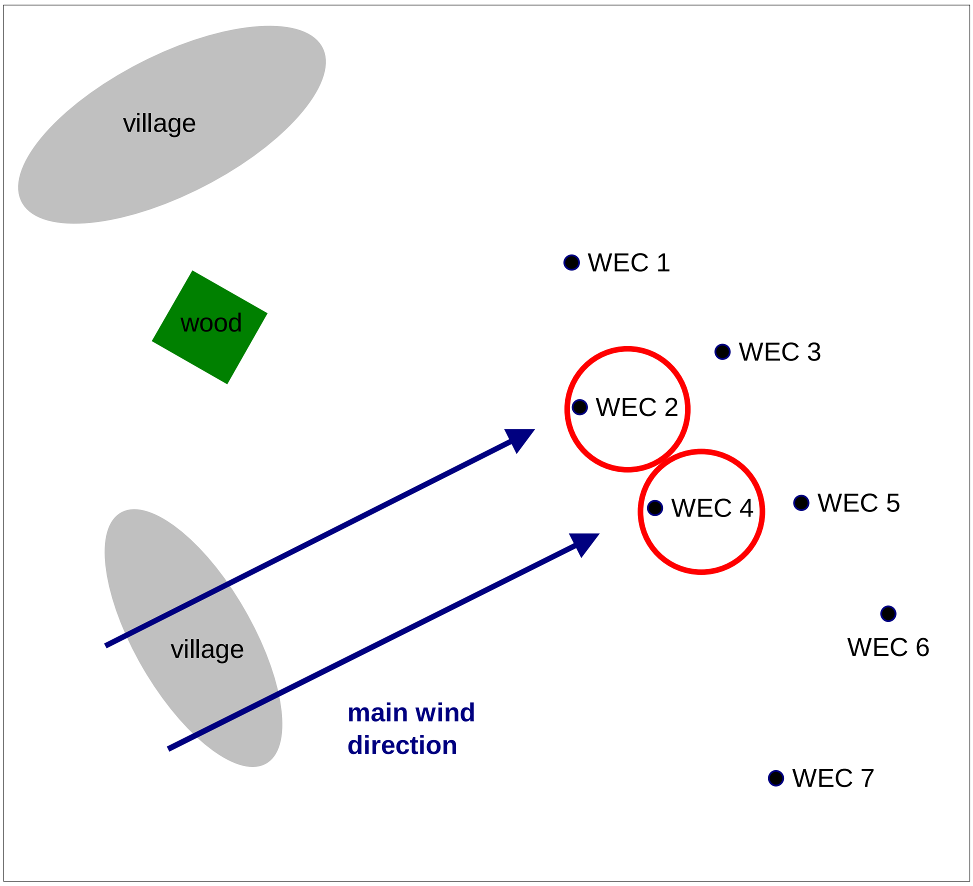

Figure 7: Measurement site

Finally two neighbouring turbines WEC 2 and WEC 4 in the state Brandenburg are chosen (see Figure 7). The inflow on both turbines in main wind direction is quite similar regarding some turbulence by the village but no bigger disturbances. These special site conditions make it possible to work without a met mast. One of the test turbines operates with active tower damping and simultaneously, the other turbine operates without active tower damping. To eliminate the influence of turbine and site particularities e. g. rotor imbalances, the turbines are switched in a 6-hours cycle. The measurements with tower damper combined from both turbines are evaluated against the measurements without tower damper from both turbines. The loads are measured over 10-minute periods, and damage equivalent loads are generated through rain-flow counting procedures.

The load measurement is carried out according IEC 61400-13 with a reduced set of considered load cases and sensors. Only power production is taken into account while the tower base bending moments are measured with strain gauges. Reference accelerometers are installed in the nacelle to validate the sensors for the tower damping.

4.1 Considered measurement data

For evaluation of fatigue loads, only measurement time series are evaluated in which on one turbine, the tower damper is activated permanently, while on the other it is deactivated permanently. Data of both turbines with original controller are combined, as well as data with tower damper. Each time series contains 10 min of data. The data is arranged according to the 10 min mean of anemometer wind speed of the respective turbine and classified as show in Figure 8.

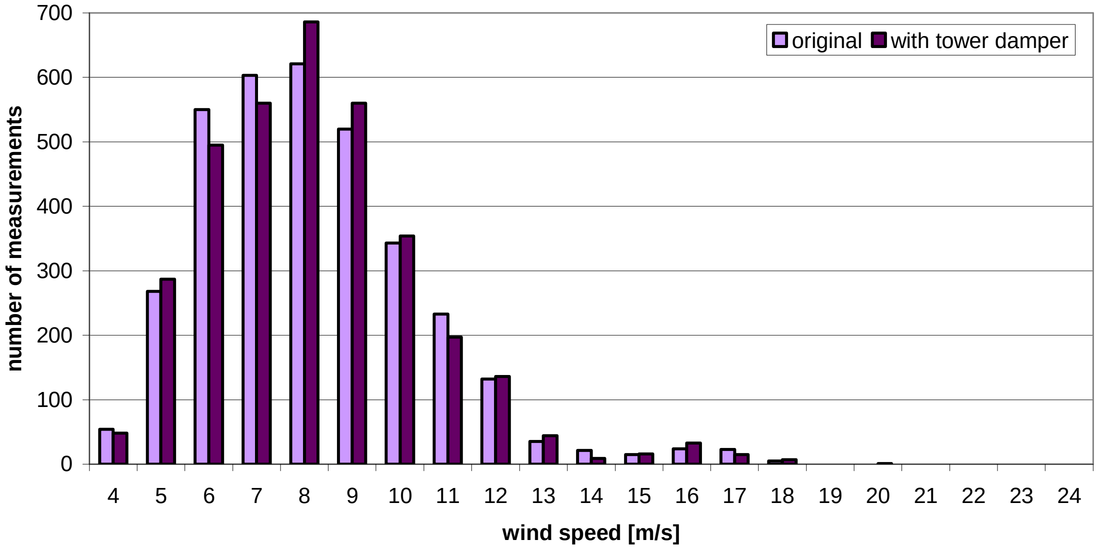

Figure 8: Measurement classification

As a basis for computing rain-flow counts a mean wind speed of 8.5 m/s according to IEC 61400-1 ed.3 class II has been taken into account. As measurements do not cover the whole operating wind range, the time portions for high wind speeds with no data available are summed up and dispensed evenly to the more frequented wind bins above rated wind speed. This is done for compensating the underestimation of tower damper influence because the range without measurements is a relatively large portion of time where the tower damper would be in operation.

Thus the times from bins where no measurements exist are added up and dispensed evenly onto the more frequented above-rated wind speed bins (see orange and green areas in the picture below).

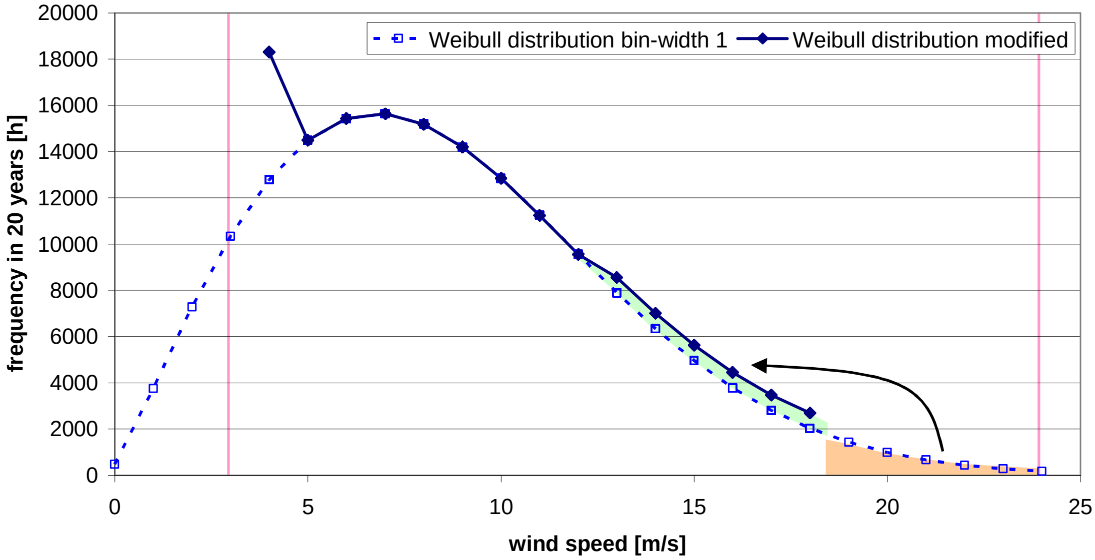

Figure 9: Modified Weibull distribution

4.2 Fatigue load evaluation

The absolute values for damage equivalent loads in measurement and simulation are not comparable. This is due to the fact that simulation was done with environmental conditions according to IEC 2A with relatively high turbulence intensities, while the measurements were done at a site with relatively free inflow and thus low expected turbulence intensity. Since the relative load reduction by tower damper does not differ much with turbulence intensity, it is possible to compare the measured load reduction with the simulation results.

Figure 10 shows the relative mitigation of measured and simulated damage equivalent loads according to equation 1 for the modified Weibull distribution. The relative mitigations of fore-aft tower loads in the simulation is a little bit bigger than the measured one while the simulated side-side tower load mitigation is somewhat smaller than in the measurement. Considering general uncertainties in load comparisons the load mitigations match unexpectedly well. The power curve is not influenced by the tower damper, neither was increased pitch activity noticed.

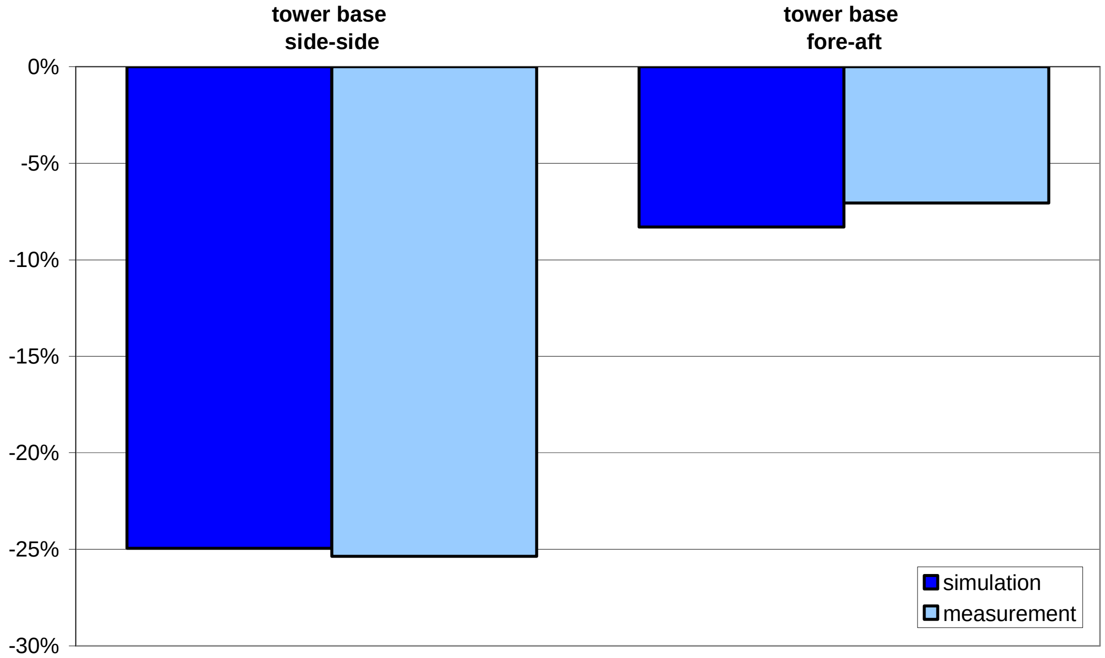

Figure 10: Relative mitigation of damage equivalent loads by active tower damping in simulation and measurement for modified Weibull distribution, m=4

4.3 Quantitative considerations of measurement data

The frequency analysis of measured fore-aft and side-side acceleration with and without tower damper approve the performance of the tower damper as well: Similar to Figure 4 and Figure 5**,** the fore-aft acceleration in Figure 11 and Figure 12 with tower damper shows the peak on the right next to 1p and tower eigenfrequency while these frequencies are damped significantly. The tower eigenfrequency peak of the side-side acceleration is reduced by the tower damper without affecting any other frequencies.

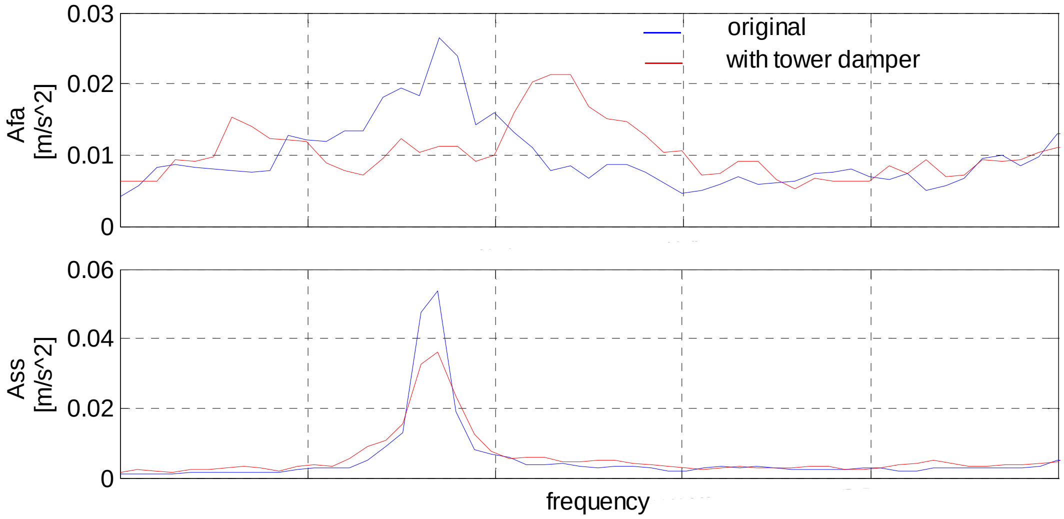

Figure 11: Frequency analysis of measured fore-aft and side-side acceleration with and without tower damper, v_{mean} = 12 m/s

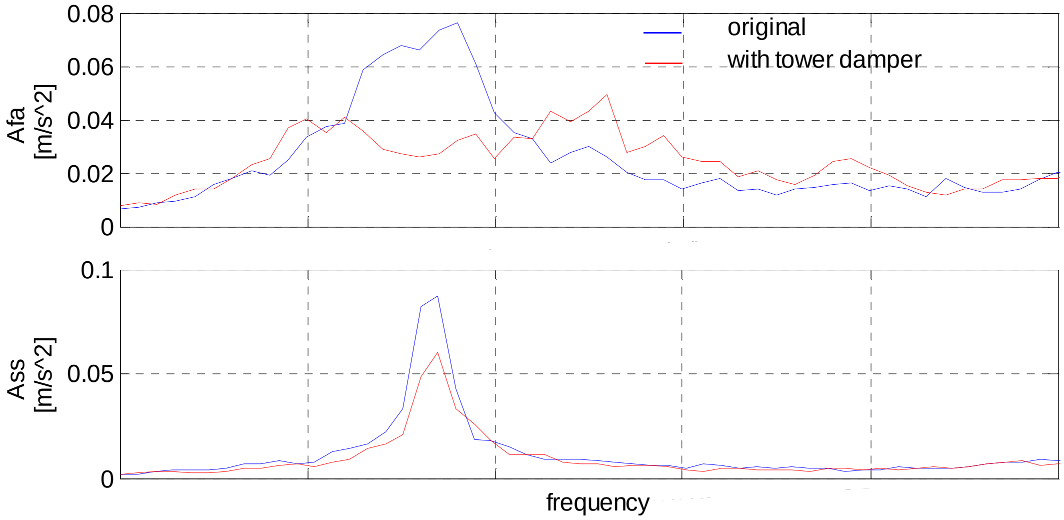

Figure 12: Frequency analysis of measured fore-aft and side-side acceleration with and without tower damper, v_{mean} = 18 m/s

5. Conclusion

Simulations show that the tower damping algorithms allow a reduction of tower fatigue loads without significant negative side-effects to other loads. Especially the reduction of side-side loads by using the new side-side tower damper is high. Load measurement results demonstrate that the predicted load reductions by simulation can be obtained in reality. Now the algorithms may be applied to series turbines, e. g. to upgrade an established turbine type to match higher wind class conditions, which is done presently. The active tower damping should be considered too, when designing costly offshore towers and foundations, even though another validation might be advisable as especially side- side excitations by waves are much stronger than by wind.

6. References

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