Analysis of Tower/Blade interaction in the cancellation of the tower fore-aft mode via control

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Abstract

With the increase in size of wind turbines, there is increasing interest in exploiting the pitch control capability of variable speed turbines to alleviate tower fatigue loads. The most direct method is to modify the blade pitch angle in response to a measurement of tower acceleration. It is shown that the flap mode has a central role in determining whether this approach is effective since there is a strong interaction between the blade flap-wise mode and the tower fore-aft mode. Several different approaches to the design of the controller for the tower speed feedback loop are investigated. It is concluded that a reduction in the tower loads of up to 18% is possible for multi-megawatt sized wind turbines.

Keywords: Tower loads, flap loads, fatigue, feedback, control, pitch

1 Introduction

With the increase of size of wind turbines, as evident in the market penetration of multi-megawatt sized machines, there is increasing interest in exploiting the pitch control capability to alleviate fatigue loads. In particular, the alleviation of tower fatigue loads has received special attention due to the fact that in off-shore wind turbines the tower and foundations cost can account for roughly 40% of the total cost of the wind turbine. The most direct method is to modify the blade pitch angle in response to a measurement of tower acceleration to cancel the tower fore-aft mode. The analysis and design of controllers of this type are analysed in this paper.

2 Linear Models

The linear models for the wind turbine dynamics used in this paper are those reported in [1, 2]. These include all dynamic components significant for controller design and control performance assessment. In particular, it includes two modes for the tower, two modes for the blades and two modes for the drive-train. It also has models for the pitch and torque actuator and a model for the interaction of the rotor with the wind. The main differences to other linear models of wind turbines found in the literature is the explicit inclusion of the tower and blade modes. The tower modes are of special importance in the design of controllers for wind turbines since they introduce a pair of right half plane zeros which impose limitations on the generator speed loop [3, 4]. The blade modes are important since the flap mode interacts with the tower mode, as discussed in this paper, and the edge mode is strongly relevant in the determination of the first drive-train mode. An example of the wind turbine dynamics is shown in Figure 1.

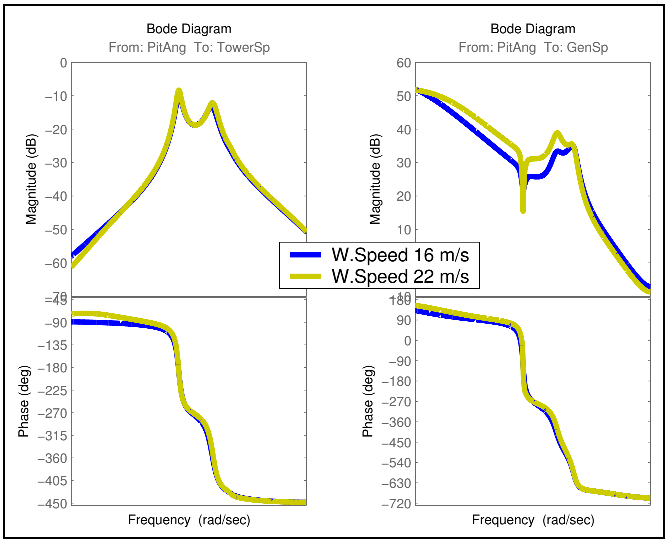
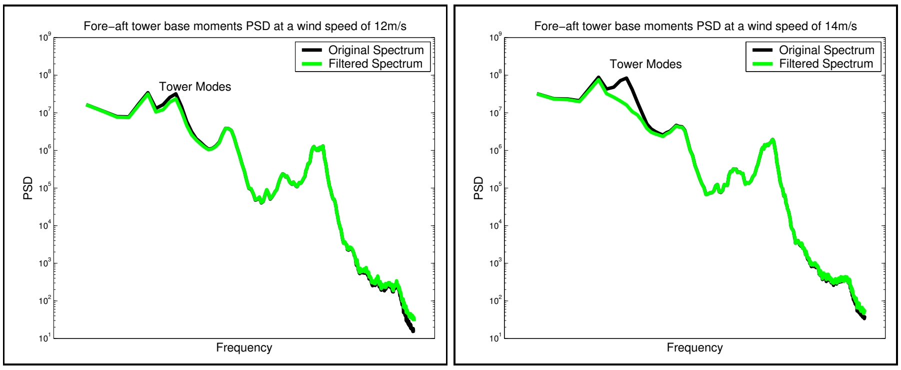


Figure 1: Dynamics of a megawatt scale wind turbine from pitch angle to tower speed and generator speed

3 Potential

As a prior step to designing a method for cancelling the tower modes, it is important to have an estimation of the impact that this cancellation would have on the fatigue loads to provide a benchmark, against which to measure the performance of the different approaches considered. In order to obtain this benchmark a full set of simulations, run with a commercial aerolastic package, are undertaken with wind speed varying between 4 and 24 m/s. The fatigue loads on the wind turbine were estimated using the Rain-Flow Counting algorithm. For suppression of the first tower mode an ideal filter is applied to the simulation loads to remove the whole of the fore-aft mode. In this evaluation only the fore-aft mode during production cases is considered, as it has been identified as the main source of fatigue in the tower. Since the loads are assumed to be suppressed by adding a component onto the pitch demand, the tower loads are only filtered when the pitch control is active. Given this constraint it is found that an upper limit, since it is estimated by an ideal filtering, for the reduction of the fatigue loads is 17%. These results are based on a more extensive study carried out for the former NEG-Micon.

In Figure 2, two examples of this procedure are shown. Figure 2(a) shows the filtering carried out at a wind speed of 12 m/s, where the pitching is still not fully active, and in Figure 2(b) the same procedure is carried out for a wind speed of 14 m/s, where the pitch is active most of the time and, therefore, the tower mode is almost completely cancelled.



(a) Wind Speed 12 m/s

(b) Wind Speed 14 m/s

Figure 2: Tower base moment power spectrum

4 Tower feedback loop for the cancellation of the tower fore-aft mode

The cancellation of the tower feedback loop via control has received a good deal of attention over recent years, with several methods discussed in the literature [5, 6, 7, 8]. Essentially all methods involve a feed back of the tower speed, based on a measurement of tower acceleration, which thereby increases the aerodynamic damping of the tower, as in the structure depicted in Figure 3.

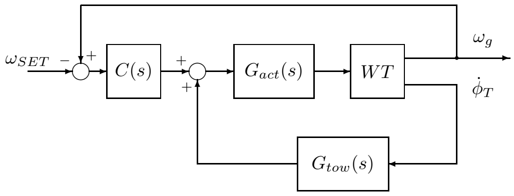


Figure 3: Inner loop for the cancelling of the tower fore-aft mode

In Figure 3 $C(s)$ is the generator speed loop controller, WT represent the dynamics of the wind turbine from pitch angle to generator speed, $G_{act}(s)$ is the pitch actuator, $G_{tow}(s)$ is the tower feedback loop, ω_g represents the generator speed output, $\dot{\phi}_T$ is the tower speed output and ω_{SET} is the generator speed set point.

The procedure followed for the analysis and design of the tower feedback loop is described below. Initially the tower feedback loop is designed as an addition, in the form of a fast inner loop, to the generator speed loop. In this approach it should not be necessary to redesign the speed controller in order to accommodate the control of the tower, since the range of frequency of the two controllers does not overlap. During below rated operation the control objective is to track the required operating curve relating torque or power to rotor speed. During above rated wind speed, the objective is to maintain constant torque or power plus constant rotor speed; that is, to reject disturbances arising from wind speed fluctuations. Typically the bandwidth of the generator speed controller is chosen to be about around 1 rad/s, well below the first tower mode. Consequently the generator speed control loop and the tower speed control loop should be active over different frequency ranges and not interact. Hence, the tower feedback loop filter should comply with the following restrictions:

- Separate the tower fore-aft mode from the measured tower signal and, scaled appropriately, feed it back as an additional pitch demand signal.
- Avoid coupling of the tower loop to the generator speed loop in order to not reduce the performance of the latter.
- Ensure that by cancelling the tower mode no other modes are excited and the overall tower fatigue is reduced.

The design and analysis of the tower feedback loop (TFL) is carried out with respect to the open loop dynamics, *i.e.* $G_{tow}(s)G_{act}(s)WT(s)$. The open-loop dynamics must ensure effective control action at the tower frequency, together with closed loop stability. However, the pertinent performance is that achieved when the outer feedback loop, with the existing generator speed controller present, is closed; see Figure 4, where WT_{cl} is the wind turbine closed-loop dynamics.

The sensitivity function for the tower feedback loop in Figure 4 provides information about robustness of the loop to parameter uncertainty as well as the frequency-dependent disturbance rejection properties of the closed-loop system. A high value of the sensitivity function indicates low disturbance rejection, indeed it indicates disturbance enhancement when positive. A design criteria is that regions in which this is the case should not coincide with structural frequencies that could be excited. Furthermore, since

$$\text{PSD with TFL} \equiv \text{PSD without TFL} \cdot |G_{eq}(j\omega)|^2 \tag{1}$$

where PSD is the Power Spectral Density and $G_{eq}(s)$ is the sensitivity function in Figure 4. Hence the sensitivity function also serves to provide an estimate of the power spectrum of the tower loads, and thereby, of the effect of the inner feedback loop on fatigue. The ability to estimate the PSD of the tower loads with different controllers gives the possibility of estimate the effect that these controllers would have on fatigue, by using one of the frequency-domain methods for fatigue estimation [9] such as the Dirlik method [10].

In addition, the dynamics of the outer generator speed feedback loop are modified by the presence of the inner tower speed feedback loop, as depicted in Figure 5.

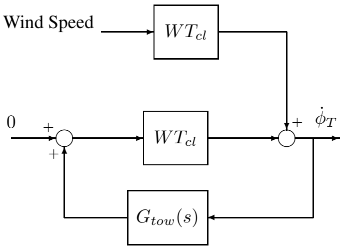


Figure 4: Block diagram including disturbances

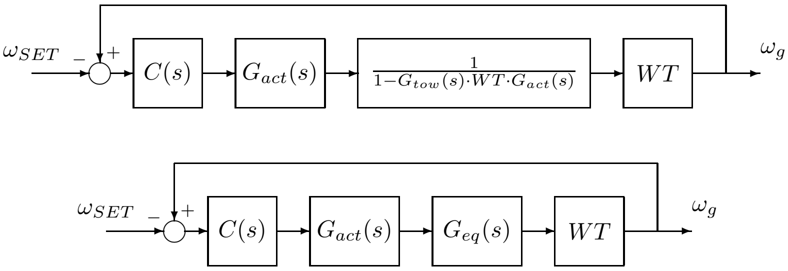


Figure 5: Block diagram of controller, plant and TFL

The modification is again simply that the sensitivity function of the tower speed feedback loop, specifically, the open loop transmittance, is cascaded with G_{eq} . The resulting open loop dynamics can be analysed to asses any loss of performance in the control of the generator speed.

5 Basic Design Approach

In the most basic approach the cancellation of the tower mode is carried out by adding a component proportional to the tower speed onto the pitch control action; that is, by setting G_{tow} in Figure 3 to a constant. Bearing in mind the restrictions on the tower feedback loop discussed in the previous section, for a constant gain to be effective the following conditions should be met:

1. The tower mode must be the only mode present in the tower acceleration signal, or the other modes must have much lower gain.
2. There must be no coupling between the tower feedback loop and the generator speed control loop.

However, as is apparent from the following discussion, the consequence of the interaction of the flap mode with the tower fore-aft mode is that neither of these conditions are met, and the effectiveness of this basic approach is reduced.

The Bode and Nyquist plots for the transfer function representing the dynamics from pitch demand to tower speed are shown in Figure 6. The peak in the Bode plot at lower frequency is due to the tower mode and the peak at higher frequency is due to the blade mode. The prominence of the latter is dependent on some parameter values that are wind-speed dependent and, therefore, may not always be as prominent. It should also be noted that a right-half plane zero is present at a frequency between the two peaks causing them to be 180^o out of phase. A similar pattern is observed in the dynamics relating wind-speed to tower-speed. Feeding back the tower speed signal with just a constant gain would imply that, since the tower mode has to be placed above $0dB$ for the control action to be effective, the rapid phase loss between the tower and the blade mode can very easily cause the Nyquist plot to encircle -1, leading to much reduced stability margins or even instability, see Figure 6. It is stressed that this sensitivity stems from the phase loss rather than the blade peak itself. In essence, the need to raise the tower peak above $0dB$ is being compromised by the presence of the nearby right half plane zeros.

A very prominent peak is apparent in the sensitivity function, see Figure 7. Its frequency is very close to the frequency at which the open loop plot crosses -180^o, between the tower mode and the flap mode. This peak is obviously also present in the closed loop dynamics, see Figure 7.

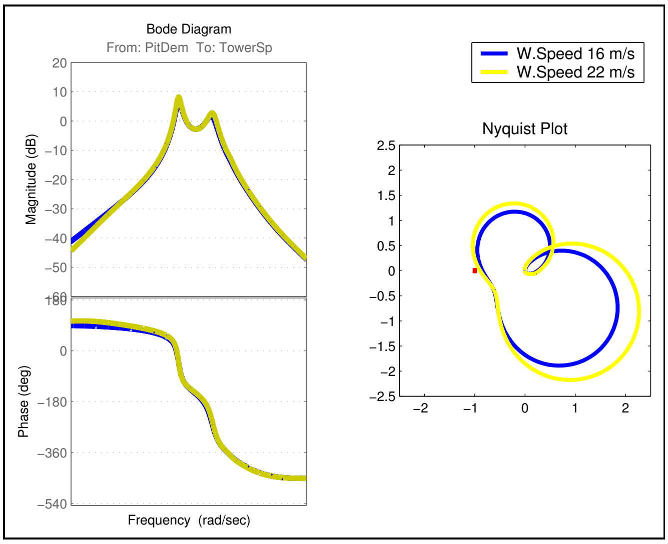
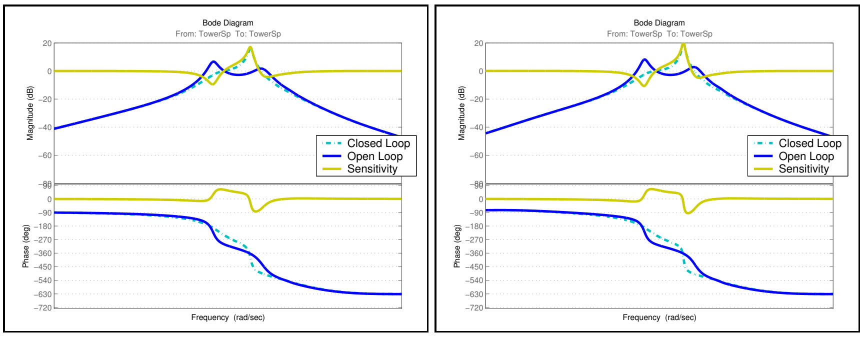


Figure 6: Tower feedback loop open loop



(a) Wind speed 16 m/s

(b) Wind speed 22 m/s

Figure 7: Closed tower feedback loop and sensitivity function

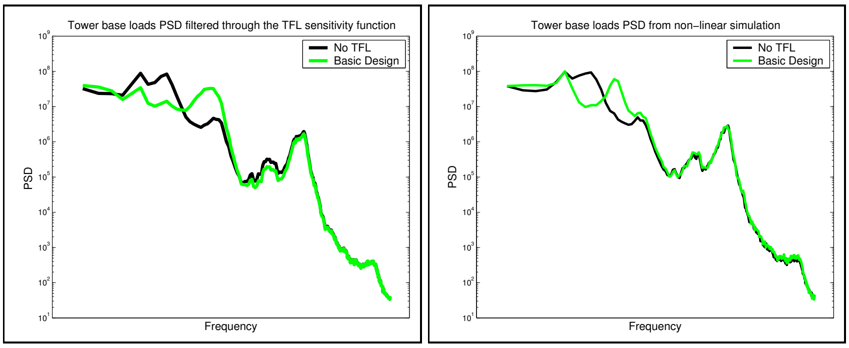
In Figure 8(a), using the procedure described previously, the impact of the tower speed feedback on the tower fatigue is estimated. The power spectra with the feedback loop present is estimated by filtering the spectra from a simulation without the tower speed feedback. The peak in the sensitivity function manifests itself as a similar prominent peak in the spectra.

In Figure 8(b) the results of running the full non-linear simulation with the tower speed feedback are shown. The estimation using the sensitivity function gives a very good approximation of the spectral shape.

In order to compare the performance of this form of feedback with the benchmark set in Section 3 a full set of runs in the same conditions as before is done, this time implementing the tower feedback loop as described in this section. The result is that the tower fatigue loads are increased by a 4%.

A further issue with this type of controller, concerns the second condition stated at the beginning of this section. For the controller to be effective, it must not affect the generator speed loop performance. In Figure 9 the Bode plot and Nyquist plot of the transfer functions for the generator speed open loop dynamics are plotted with and without the modification caused by the tower feedback loop, namely G_{eq}.

The tower feedback loop induces an increase in the gain at the critical frequency, rendering the system unstable. It should be noted that the generator speed controller has additional filtering at intermediate frequencies to protect the actuator. This has been omitted to emphasise the impact of the tower feedback loop by rendering the closed-loop system unstable. With the additional filtering it remains stable but with very small stability margins.



(a) Estimated

(b) Simulation

Figure 8: Estimated spectrum from filtering with the sensitivity function and spectrum of a simulation

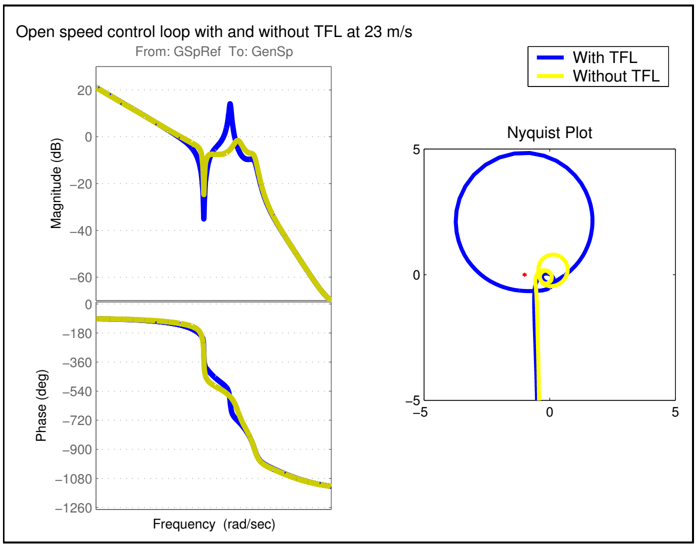


Figure 9: Generator speed loop

6 Alternative design of the tower feedback loop

As discussed above, the consequences of the coupling of the flap mode to the tower mode is that feeding back a signal proportional to the tower acceleration, not only does not achieve a reduction on the tower fatigue loads, but it increases them. A new approach for a tower feedback loop is discussed in this section which actually achieves a reduction in the tower fatigue loads. The intention is still to feed back a signal proportional to the first tower fore-aft mode, but isolating it from the flap mode. In order to achieve this, the filter of the form shown in Figure 10 is chosen for G_{tow} in Figure 3. The filter consists of a *bump* centred at tower frequency to enhance the part of the signal correspondent to the first tower mode, and a wash out filter that has two main objectives: filter out low frequency signals, to avoid sensor problems such as drifts or offset in the measurement signal, and provide some phase advance at the region of the tower frequency, shifting the additional peak that arises from the tower feedback loop to higher frequencies, where it is less damaging. The peak at the left of the bump is placed at $1P$ frequency, to reduce locally the value of the sensitivity function.

In Figure 11 the open tower feedback loop and the Nyquist diagram result of implementing this filter as the tower filter is shown. It can be seen how the open loop now keeps the flap mode well under $0dB$.

The closed loop dynamics and sensitivity function for the alternate approach are shown in Figure 12. The dynamics for both the sensitivity function and the closed loop system show, in comparison with 7, less prominent

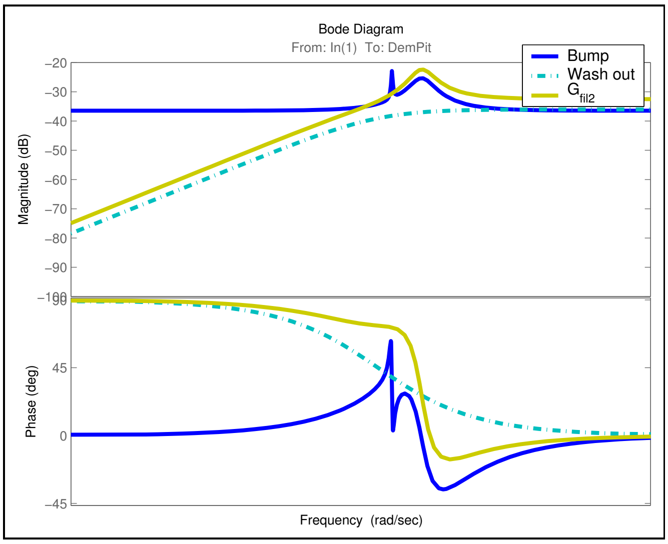


Figure 10: Alternative design of the tower filter

peaks. This is due to the fact that the flap mode has a very low gain in this implementation and to the fact that the phase is increased by the wash out filter causing the positive part of the sensitivity function to be shifted to the right.

The estimation of the power spectra of the tower loads by filtering with the sensitivity function is again very effective when compared to the results of the simulation, as depicted in Figure 13. The peak this time is considerably smaller than with the previous implementation, and that is properly reflected in the fatigue estimation results. For this modified controller a fatigue reduction of 8% is achieved.

As a last performance measure, the coupling with the generator speed loop induced by this tower feedback loop is investigated. In Figure 14 it can be seen that there is almost no coupling and little reduction in performance.

7 Alternative Approaches: Integrated Controller Design

The results in previous sections are obtained whilst constrained to use an existing generator speed loop controller. This is due to the controller being initially designed to control solely the generator speed and the tower feedback loop being only designed as an addition to the main loop. As has been shown, the generator speed loop and the tower speed loop interact strongly. Since the reduction of fatigue loads in the tower is of great interest, it is highly desirable to include this aim in the control design objectives from the beginning of the design process and re-design the generator speed loop accordingly. Some preliminary results of such a Coordinated Controller design are currently avaliable. It completely decouples the tower feedback loop from the generator speed loop to the extent that even without tower feedback a reduction in fatigue loads is already achieved. Since both loops are now highly independent the tower feedback loop is more effective. In the preliminary results a greater fatigue reduction, roughly double than that of current tower feedback loop, is achieved. This algorithm and its results will be reported elsewhere.

8 Discussion and Conclusions

The most direct method of exploiting the pitch control capability to alleviate tower fatigue loads is to modify the blade angle in response to a measurement of tower acceleration. This approach is analysed using a simple linear dynamic model of the wind turbine. It is shown that the flap mode has a central role in determining whether the tower feedback loop is stable or unstable. However, the importance of this role is not usually recognised in the literature, probably because the situation described here does not necessarily arise in smaller wind turbines. Its importance is due to a phase difference of 180^o between the flap mode and the tower mode. The associated change in sign of the feedback loop results in instability when the gain of the feedback loop exceeds $0dB$ at

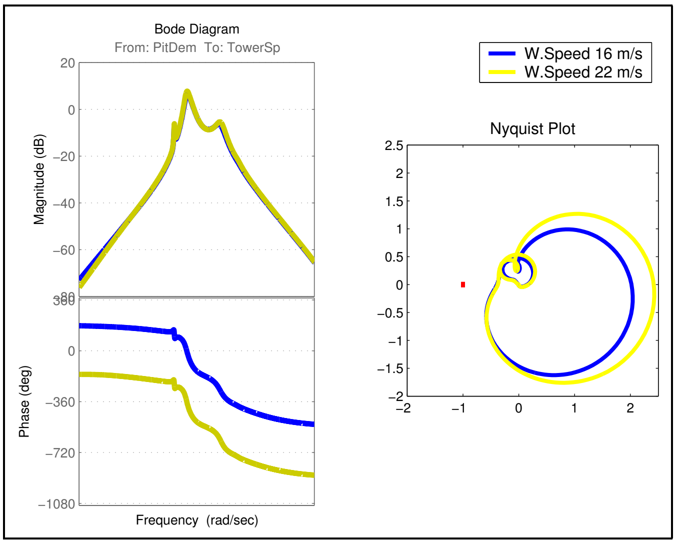
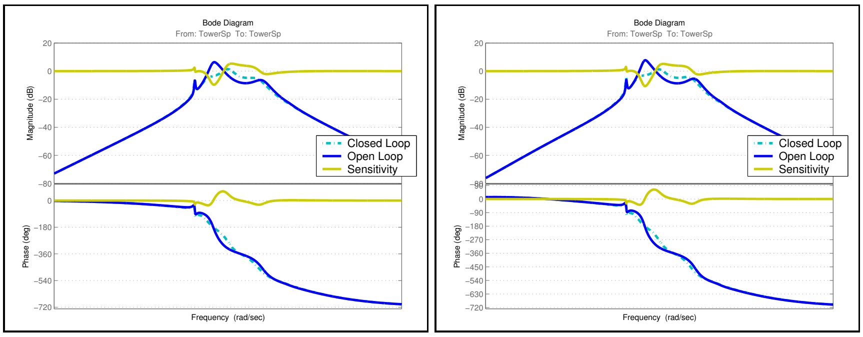


Figure 11: Tower feedback loop open loop with the alternative implementation of the filter



(a) Wind speed 16 m/s

(b) Wind speed 22 m/s

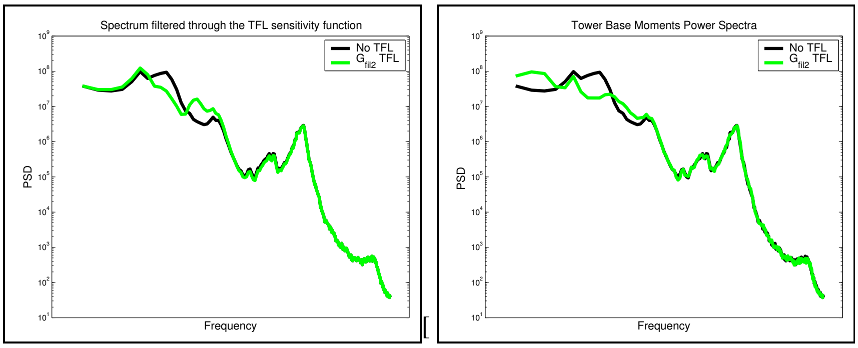
Figure 12: Closed tower feedback loop and sensitivity function

the flap frequency. The analysis and the linear models are validated using non-linear simulation and measured data from a multi-megawatt machine. A modified approach to the cancellation of the tower fore-aft mode is discussed. A filter is included in the feedback loop and the tuning procedure described. In addition, more general methods, that permit implementations on a machine with a minimum of tuning, are proposed. The results are summarised below.

- The cancellation of the tower mode by a signal proportional to the tower speed leads to an increase in fatigue loads
- A G_{tow} designed to make the tower mode more prominent and isolate it from other modes is effective, achieving a fatigue reduction of the 8%
- A Coordinated Controller design, having as control objectives both control of generator speed and reduction of tower loads from the beginning of the design process, has the potential to improve on the previous figure: preliminary results indicate an attainable reduction of 18%

9 Acknowledgments

The support, both financial and technical, of NEG-Micon/Vestas for this work is gratefully acknowledged.



(a) Estimated

(b) Simulation

Figure 13: Estimated spectrum from filtering with the sensitivity function and spectrum of a simulation

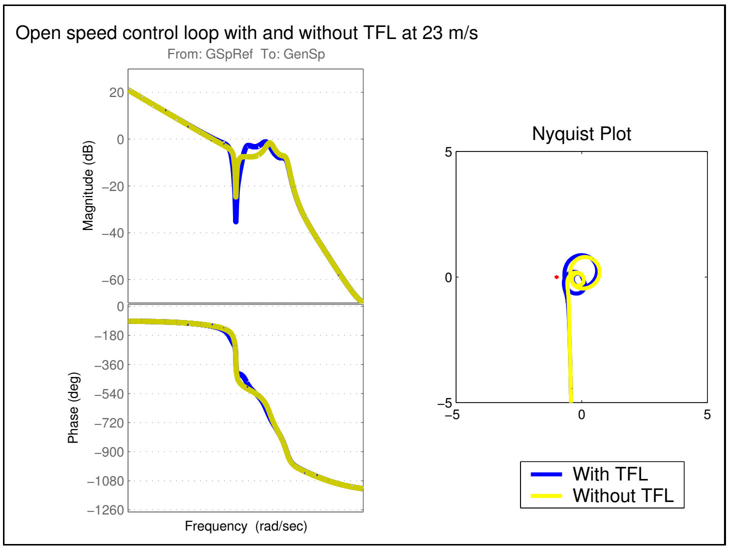


Figure 14: Generator speed loop

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