Fatigue load estimation and reduction for wind turbine

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Introduction

Fatigue is the structural damage that leads the components of a wind turbine to sudden brittle failure when it suffers cyclic loading [15]. As the size of wind turbines is growing, fatigue loads become more and more significant for the design of major structural components. Concerning fatigue in a wind turbine tower, the fore-aft tower foot bending moment is considered as the most critical load. The benefits of fatigue load reductions, which can be achieved by appropriate design of a wind turbine control system, are increasing [12]. The purpose of this study is to estimate fatigue loads in frequency domain [18] for control design, then to regulate the pitch angle in response to the measurement of acceleration of tower top oscillation, thus to reduce the fatigue damage from the tower bending moment.

Approach

The fatigue loads can be estimated by Dirlik method based on the PSD (Power Spectrum Density) in the frequency domain [16]. The PSD of the stress can be obtained from the Fourier transformation of stress measurement in time series. Then the stress-range probability distribution of the cycles is estimated from the probability density function (PDF) based on the spectral moments of the loads [17]. By applying Miner's rule, the fatigue damage of the structure subject to complex loading can be assessed from the stress-range probability distribution [15].

The H_∞ robust control based on a "Linear Parameter-Varying (LPV) model" [2] [3] [5] has been applied for fatigue load reduction control in this paper. It allows for parallel design of both rotor speed control and tower top active damping control loops. The control objectives for two control loops can conveniently be given in the frequency domain by means of weighting functions that allow defining the desired shape of the closed loop transfer functions [13]. In other hand, the motivation of the LPV model is to describe the nonlinearity and time variant of the real plant, so that a gain-scheduling controller [24] [25] achieved by this LPV model, fulfills good performance and stability for the real plant over the whole operating range [4]. Additionally, the model structural uncertainty [19] has been considered in this paper.

Main Body of Abstract

Fatigue load estimation

In this paper, the time series data of the tower foot bending moment are obtained from simulation carried out with the simulation tool Bladed [28]. Then, the fatigue damages caused by the tower foot bending moment shown in **Figure 1** are computed with simulation tool

Matlab [11]. If comparing the two pictures, it can be seen that the accuracy of the estimation by Rainflow-counting [26] highly depends on the length of the time series data. For very long time series, the damage distribution has a smooth shape according to the probability density. However, 600s simulation time the distribution of the fatigue damage calculated by Rainflow-counting in the high stress tail is not smooth, i.e. not represented very well in the statistical sense [27] [30]. This can be explained by the fact that these high stress load cycles have a very low probability but contribute significantly to fatigue damage [31]. The improvement can only be achieved by more data i.e. longer time series: 40 hours used for Rainflow-counting as shown in the top figure in **Figure 1**. The Dirlik method is providing this smooth shape already for relatively short time series. If short time series are used to extrapolate fatigue damage for longer operational periods, as is common practice in wind turbine engineering, the Dirlik method obviously is able to provide a better estimation than the Rainflow counting method.

The shapes of fatigue damage distribution plots in full stress region are very similar for both methods in 40 hours simulation, illustrated in **Figure 1**. **Table 1** presents the fatigue damage estimations using Rainflow-counting and Dirlik method based on simulation data of 40 hours' time series. Very similar results have been obtained from both methods.

Table 1: Comparison of estimated fatigue damage (normalized values) T=40 hours

Total reference damage	Standard system	Advanced system	Ratio of two systems
Rainflow-counting	270.1	233.6	0.865
Dirlik method	274.0	233.5	0.855

Fatigue load reduction

As presented in **Figure 2**, the increasing steps of fatigue load correspond to the peak values of the tower bending moment PSD at 1^{st}TEF (tower eigen frequency), 3p, 6p and 2^{nd}TEF. The fatigue damage estimation based on the PSD can thus provide information on how the fatigue damage is distributed over the frequency spectrum of the considered load. This information is very helpful to identify the essential sources of fatigue damage. According to these peaks, the weighting function [29], which determines the performance of active damping controller, has been designed to shape the magnitudes of the closed loop transfer function from wind speed to tower top acceleration at the same frequencies, as shown as black dashed line in the middle picture of **Figure 2**.

$W_{y,aT}$ consists of a constant gain and three notch filters: The constant gain is determined to reduce the peak at the 1^{st}TEF of the open-loop transfer function. The first notch below the 1^{st}TEF is used to avoid shifting of the first tower mode towards lower frequencies. The second notch at 3p aims to reduce the response to 3p harmonic excitation and the third notch at the 2^{nd}TEF to avoid amplification of the second tower bending mode.

Obviously, compared to the standard control system, it can be seen that PSD peaks of the tower bending moment have been considerably attenuated by the fatigue reduction control system. As a result, the accumulated equivalent fatigue load estimated by Dirlik method over the frequency range has been reduced, as shown in the bottom plot in **Figure 2.**

In **Figure 3**, it is seen that all the singular values of the closed loop based on the detailed model from operating points 12m/s to 24m/s wind speed are located below the function $1/W_u$ [7]. Thus, the robust stability of the closed loop system with respect to additive perturbations [19] [21] expressed by the weighting function W_u can be guaranteed over the whole operating range of full load.

Conclusion

As compared to the Rainflow-counting method, the Dirlik method has the potential to be more convenient for application in control design, since it allows using the power spectrum of fatigue loads in the frequency domain. It is easy to identify the contribution of individual frequency components of the loading to the overall fatigue damage [17]. The controller can then be directly designed to reduce certain load components at their known frequencies. Moreover, since for linear systems the effect of different controllers on the PSD of load output signals can be directly computed in the frequency domain, the related change in fatigue damage can be estimated very efficiently without the need for time domain simulations [17].

The control systems considered in this paper aim at reducing the number and magnitude of load cycles especially for the tower of wind turbines. The tower has a major share in the overall wind turbine costs. If the tower design is determined by fatigue loads, the life time would be longer or the cost could be lower as the fatigue load is reduced.

Learning objectives

As a major contribution, this work demonstrates that it is possible to design collective pitch controllers that, additionally to basic rotor speed control and active damping of the first fore-aft tower bending mode [22], allow to reduce the fore-aft tower bending loads due to 3p harmonic excitation. This harmonic excitation often contributes significantly to the tower bending fatigue damage. However, the main point in this paper is to investigate the fatigue load estimation in frequency domain, which is then used for efficient control design for fatigue load reduction.

H_∞ and LPV based control design methods are powerful tools do find an optimum controller if the weightings between the different control objectives are known [1] [3]. In general, for a wind turbine there is especially a strong interaction between the objectives of rotor speed control and fatigue load reduction. It is not possible to find a controller that minimizes speed excursions in case of gusty wind situations and the same time minimizing fatigue loads on the tower. The decision how to weight the different objectives, however, will depend on many factors - e.g. wind speed and turbulence distribution, cost of replacements and maintenance. That means the tradeoff between the speed control and fatigue load reduction can be varied for different turbine types and different locations - e.g. onshore wind turbines and offshore wind turbines.

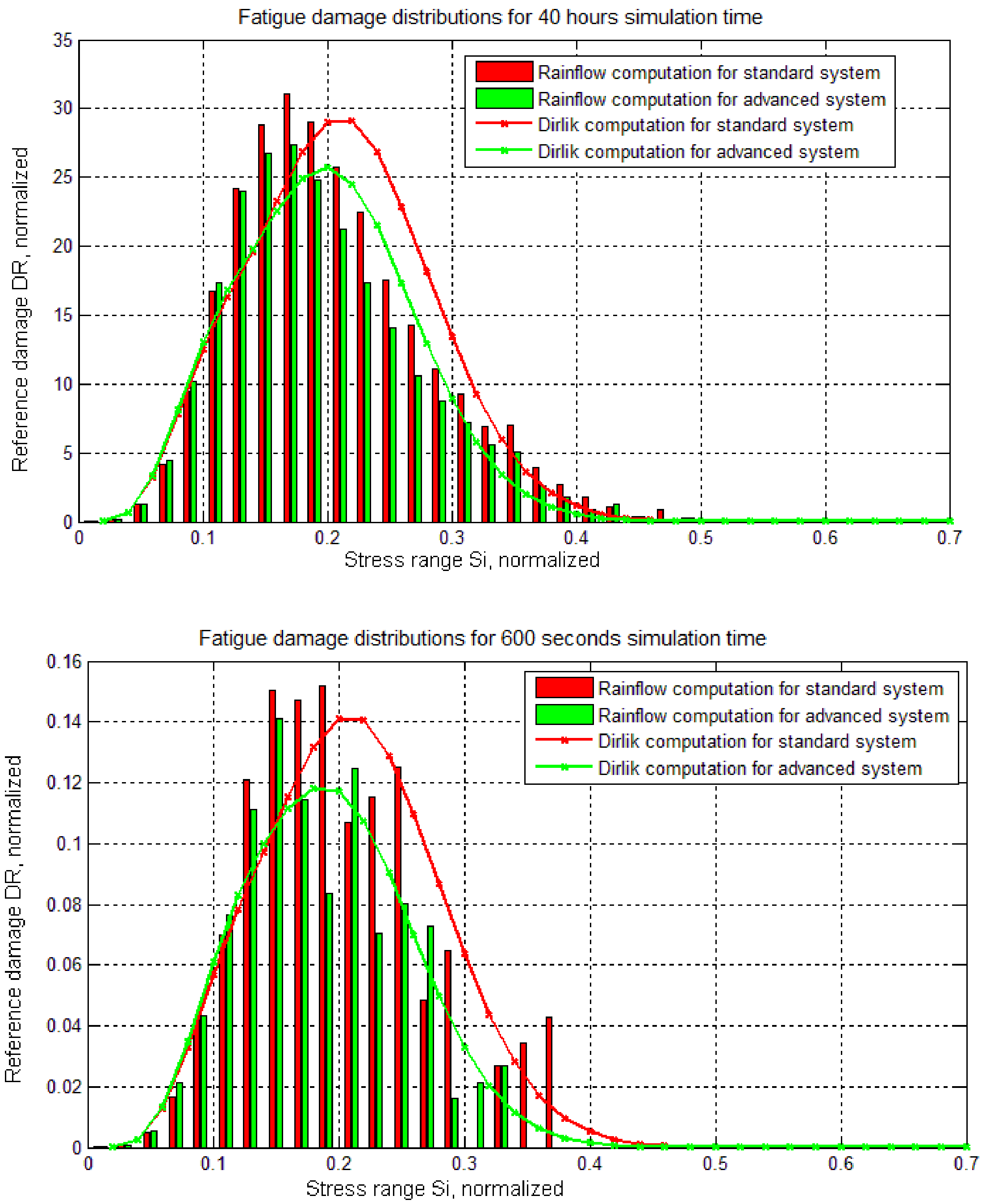

Figure 1: Distribution of fatigue damage contribution over stress range.

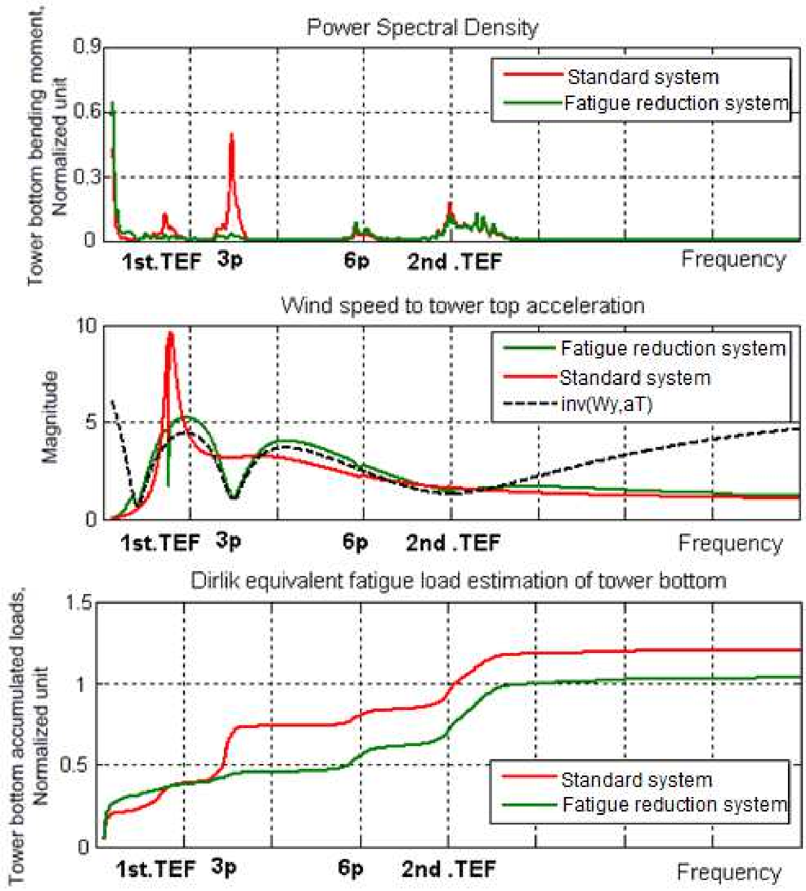

Figure 2: Top: PSD estimation of the tower bottom bending moment M_{TY}; Middle: Magnitude bode plot of closed loop transfer function from wind speed Δv_{Wind} to tower top acceleration a_T; Bottom: Accumulated fatigue estimation of M_{TY}.

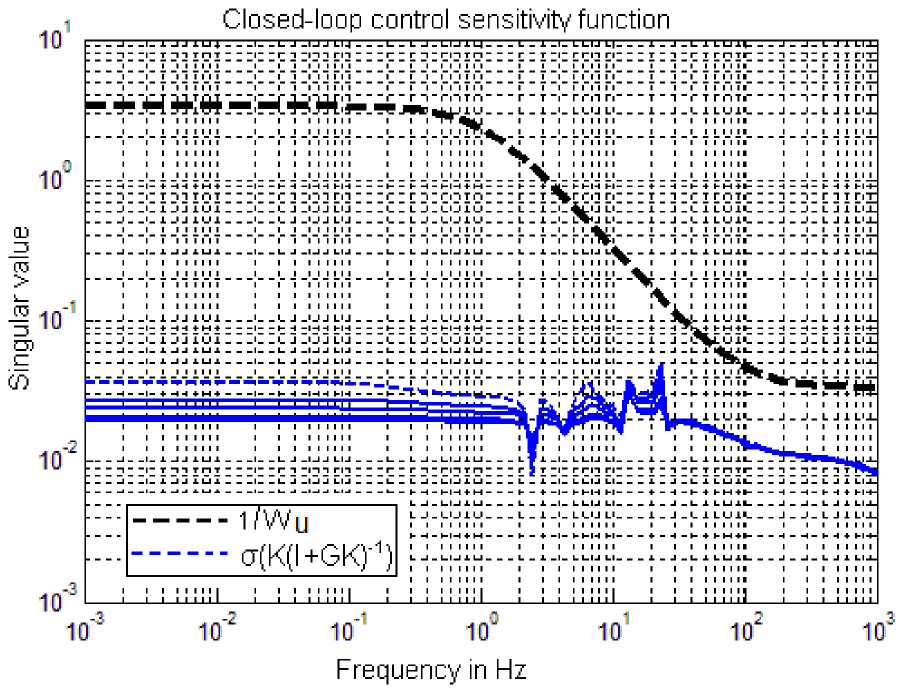

Figure 3: Singular values plots of the LPV closed-loop control sensitivity function for unstructured robustness analysis over the full-load operating range (blue), inverse weighting function (black).

References

[1] P. Apkarian, P Gahinet, “Self-scheduled H∞ Control of Linear Parameter-varying Systems,” Proceedings of the American control conference, Maryland, p.858-860, June 1994.

[2] F.Bruzelius, C. Breitholtz, Gain-scheduling via Affine Linear Parameter-Varying Systems and H∞ synthesis, Proceeding of the IEEE conference on decision and control, Orlando, US, Dec, 2001.

[3] Pascal Gahinet, Explicit Controller Formulas for LMI-based H∞ Synthesis, proceedings of the American control conference, Baltimore, Maryland, June 1994.

[4] Pierre Apkarian, Richard J.Adams, Advanced Gain-Scheduling Techniques for Uncertain System, IEEE transactions on control system technology, vol.6, No.1, Jan, 1998.

[5] Pascal Gahinet, Pierre Apkarian, Parameter-Dependent Lyapunov Functions for Real Parametric Uncertainty, IEEE Trans. Auto. Contr., June 1994.

[6] P. Gahinet, P. Apkarian, A Linear Matrix Inequality Approach to H∞ Control, International Journal of Robust and Nonlinear Control, 1994.

[7] Apkarian, P, Tuan, H. D, Parameterized LMIs in Control Theory, SIAM Journal of Control&Optimization 38(4): 1241-1264, 2000.

[8] Fabien Lescher, Jing-Yun Zhao, Pierre Borne, *Switching LPV Controllers for a Variable Speed Pitch Regulated Wind Turbine*, International Journal of Computers, Communications & Control, Vol. I, No. 4, p. 73-84, 2006.

[9] E.A.Bossany, Garrad Hassan, *Wind Turbine Control for Load Reduction*, Wind Energy, p.229-244, 2003.

[10] Fernando D. Bianchi, Hernán De Battista, Ricardo J. Mantz, *Wind Turbine Control Systems*, p.29-31, p.125-130, p.151-155, p159-162, Springer, 2007.

[11] G. Balas, R. Chiang, A. Packard, M. Safonov, *Robust Control Toolbox 3 Use’s Guide*, The MathWorks, Inc, 2005-2007.

[12] W.E. Leithead, S. Dominguez, *Analysis of Tower/Blade Interaction the Cancellation of the Tower fore-aft Mode via Control*, Proceedings of the European Wind Energy Conference (EWEC), London, UK, 2004.

[13] U. Mackenroth, *Robust Control Systems: Theory and Case Studies*, Springer, 2004.

[14] B. Jasniewicz, M. Geyler, *Wind Turbine Modeling and Identification for Control System Applications*, Proceedings of the European Wind Energy Conference (EWEC), May 2011.

[15] Secil Ariduru, *Fatigue Life Calculation by Rainflow Cycle Counting Method*, Thesis submitted to the graduate school of natural and applied sciences of middle east technical university, Dec 2004

[16] Turan Dirlik, *Application of Computers in Fatigue Analysis*, Ph.D. Thesis submitted to department of engineering university of Warwick Coventry, England, 1985.

[17] Patrick Ragan, and Lance Manuel, *Comparing Estimates of Wind Turbine Fatigue Loads Using Time-domain and Spectral Methods*, p83-99 wind engineering volume 31, No.2, 2007.

[18] Herbert J. Sutherland, *On the Fatigue Analysis of Wind Turbines*, Sandia National Laboratories, Albuquerque, New Mexico, SAND99-0089, and Unlimited Release printed June, 1999.

[19] Sigurd Skogenstad, *Multivariable Feedback Control*, Wiley, 2005.

[20] T.G. van Engelen, *Design Model and Load Reduction Assessment for Muti-rotational Mode Individual Pitch control (Higher Harmonics Control)*, EWEC, Athens, 2006.

[21] Steen Tøffner-Clausen, Palle Andersen and Jakob Stoustrup, *Robust Control*, Aalborg University, Fredrik, Bajers Vej 7, DK-9220 Aalborg Ø, Denmark, 2001.

[22] F. Lescher, H. Camblong, *LPV Control of Wind Turbine for Fatigue Loads Reduction Using Intelligent Micro Sensors*, American Control Conference, 2007.

[23] P. Caselitz, T.Krueger, J. Petschenka, K. Stoerzel*, Reduction of Fatigue Loads on Wind Energy Converters by Advanced Control Methods*. EWEC Proceedings, Dublin, 1997.

[24] W. Shan, M. Shan, Gain Scheduling Control Design for Active Tower Damping and 3p Harmonic Reduction, European wind energy conference & exhibition, Copenhagen, Denmark, April, 2012.
[25] W. Shan, M. Geyler, Gain-Scheduling Control for Individual Blade Pitch Control Design for Load Reduction on Large Wind Turbine, 2nd international youth conference on energetic, Budapest, 2009.
[26] ASTM, *Standard Practices for Cycles Counting in Fatigue Analysis*, American Society for Testing and Materials Standards, E1049-85, 1985.
[27] A.R. Henderson and M.H. Patel, *Frequency Domain Fatigue Damage Estimation Methods suitable for Deterministic Load Spectra*, British Wind Energy Conference 21, Cambridge, 1999.
[28] E. A. Bossanyi, *GH Bladed User Manual*, Garrad Hassan and Partners Limited, 2003.
[29] Jia Yingmin, *Robust H_∞ Control*, Science Press, 2007.
[30] Herbert, J. Sutherland, *Frequency-Domain Synthesis of the Fatigue Load Spectrum for the NPS 100-KW Wind Turbine*, Proceedings of Wind Power 92, AWEA, Washington, D. C., 1992.
[31] H. J. Sutherland, *On the Fatigue Analysis of Wind Turbines*, issued by Sandia National Laboratories, 1999.

List of Symbols

K(s)	Transfer function of the controller	W_u	Weighting function for control output requirement
M_{TY}	Fore-aft tower foot bending moment	$W_{y,aT}$	Weighting function for output y:a_T requirements
ΔV_{wind}	Local change of effective wind speed	a_T	acceleration of the tower top
G(s)	Transfer function of the nominal model	H_∞	Control algorithms is based on the infinity norm
LPV	Linear parameter varying	SISO	Single input and single output
MIMO	Multiple input and multiple output	PSD	Power spectral density
PDF	Probability distribution function	1^{st}.TEF	First tower eigen frequency
3p	Third per revolution	2^{nd}. TEF	Second tower eigen frequency
6p	Sixth per revolution		