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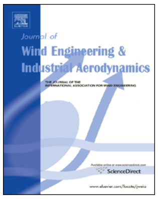

Fatigue and extreme load reduction of wind turbine components using smart rotors

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ABSTRACT

In this paper the reductions of fatigue and extreme loads of wind turbine components are analysed. An individual flap controller was designed to reduce cyclic loads. The load reduction potential was computed for power production and start-up load cases with normal and extreme turbulence, extreme gust events, and direction changes according to the certification specifications. Additional to the highly investigated reduction of the blade root fatigue damage equivalent load, also significant reductions could be shown for both shaft and tower loads. When applying smart rotors, most components experience a fatigue load reduction of 5–15%, with the exception of the flapwise blade root moment, which is decreased by 23.8% and the blade root torsional moment which increases 14%. For the simulated ultimate loads, the flapwise root bending moment is reduced by 8%, while tip deflections get reduced by 6%. The most significant extreme load reduction can be found for loads in the tower that relate to asymmetry of the inflow, namely tower torsion and the fore-aft moment at the tower top. The blade root torsional moment is increased significantly. The changes in the ultimate load of all other components remain below 2%.

1. Introduction

During the last years smart rotors have gained popularity in wind turbine research. These rotors exploit active aerodynamic devices, such as trailing edge flaps, to modify the flow around the blade.

Fatigue load alleviation is so far the most investigated problem of smart rotor research. Until recently, most studies have considered only very few load cases to determine the potential gain of smart rotors. Table 1 displays the flap dimensions and the analysed design load cases of peer-reviewed journal papers and Ph.D. theses. These simulations consist of the analysis of few, short period load cases such as used by Andersen (2010) or three load cases in the case of Barlas et al. (2012). Andersen reports the potential of flaps to alleviate 34% of the fatigue equivalent damage in flapwise loading, while Barlas finds slightly lower values up to 27%. While Andersen focuses on loads in the blade only, Barlas also reports a reduction potential in the tower fore-aft bending moment and the tower tip deflections. Lackner and van Kuik (2010) have expanded the approach to smart rotor control by combining flaps with individual pitch control (IPC) resulting in maximum blade root moment reductions of 22%. Bergami and Poulsen (2015) have employed a linear-quadratic controller with which they achieved a 16% fatigue load reduction of the root bending moment. Castaignet et al. were the first to also include a limited set of ultimate loads during power production in their analysis (D. Castaignet, 2011), unfortunately, a not further specified generic turbine was used, nor were the flap dimensions specified, such that a qualitative comparison with the results presented in this paper was not possible. A general trend was that extreme loads are also reduced, but not as effectively as fatigue loads.

In parallel to the numerical simulations, experimental work has been performed at Delft University of Technology to prove the technical feasibility of the smart rotor concept (van Wingerden et al., 2008; Hulskamp et al., 2011). During the wind tunnel experiments with a scaled rotor, fatigue load reductions of up to 59% have been achieved. This number, however, has to be viewed in context of the controlled wind tunnel environment with an extremely low turbulence level. Therefore, it cannot serve as an indication of the actual potential of smart rotors when considering utility sized turbines. Castaignet et al. (2014) have been the first to test a controller on a utility scale smart rotor in a field test. A Vestas V27 was retrofitted with three flaps with a span of 70 cm each on one of the blades, of which a single flap was operational during the experiment. The achieved blade root moment reduction of 14% during a 38-min simulation is lower than the achieved values in numerical simulations of Barlas et al. (2012) or Markou et al. (2011), but one has to bear in mind that the size of the flap is significantly smaller than in all other analyses as shown in Table 1. Castaignet et al. (2013) also simulate the load alleviation of the full scale smart rotor experiment, but find significantly lower load reductions.

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Table 1
Simulation set-up peer-reviewed papers and Ph.D. theses.

Author	Flap chord ratio (%)	Flap width % of radius	Wind (m/s)	Shear exp.
Andersen (2010)	10	15–30	11.4	0.14
Barlas et al. (2012)	10	18	7, 11.4, 15	0.2
Lackner and van Kuik (2010)	10	20	8, 12, 16, 20	0.2
Bergami and Poulsen (2015)	10	20	12–24	0.2
Castaignet et al. (2013)	13–18	5	Field test	Field test
Castaignet et al. (2014)	13–18	5	Field test	Field test
Bæk (2011)	10	20	5–25	0.2

Author	Turb. Int.	DEL reduction	Controller
Andersen (2010)	0.06	25–37%	PD/HPF
Barlas et al. (2012)	0.06	10.9–27.3%	MPC
Lackner and van Kuik (2010)	NTM	5.7–22.4	PID
Bergami and Poulsen (2015)	0.14–0.17	15.5% (average)	LQ
Castaignet et al. (2013)	Field test	14% (measured)	MPC
Castaignet et al. (2014)	Field test	5% (simulated)	MPC
Bæk (2011)	0.06–0.18	15–20%	IBC

NTW, normal turbulence model; PD, proportional-derivative controller; PD, proportional-derivative controller; HPF, high-pass filter; MPC, model predictive controller; LQ, linear quadratic controller; PID, proportional-integral-derivative controller; IBC, individual blade control.

A first effort to evaluate the whole turbine with all its components has been done by Bæk (2011), who is the first to approach the load reduction potential in a more global sense. Bæk performs two types of analyses. The first one is a stochastic investigation of the effect of turbulence seeding on the load reduction results. For this purpose, he performed 100 simulations at 11.0 m/s. It is found that the standard deviation for a 10-min simulation of load reduction in the blade root bending moment is 3%.

In a second analysis step, Bæk evaluates power production load cases with a normal and extreme turbulence model for wind speeds from 5.0 to 25.0 m/s. For each wind speed a 10-min simulation is performed. At the same time more wind turbine components are taken into account. Besides the traditionally evaluated flapwise and edgewise blade root moments, he also considers moments at the tower base, shaft torsion, hub moments, and the three moments at the tower top. Bæk carried out three distinct analyses, namely the dependency of these loads on wind class and turbulence intensity. Besides a reduction of the damage equivalent flapwise blade root bending moment of 15%, also a significant reduction of fatigue loads at the hub and the tower top were found. While being relatively independent on the wind class, the turbulence intensity proves to influence the results more significantly. Similar to Lackner and van Kuik (2010), Bæk also investigates the effect of combining individual pitch control and active flaps. He finds that, certainly for fatigue loads, the combination of individual pitch control with individual flap control (IFC) can considerably improve the performance of smart rotors, with hub fatigue load reductions of more than 40%. Extreme loads remain a site notice in Bæk's work as their results are not discussed in detail, but only presented in two subfigures. The most significant extreme load reduction is achieved for the tower top tilt moment, which gets reduced by approximately 30%.

In this paper the load reduction of a controller for fatigue load alleviation will be analysed in detail. For this end, a broad spectrum of design load cases both for extreme and fatigue loads have been analysed. Contrary to previous work, not only fatigue loads will be addressed, but also the effect that a controller designed for fatigue loads has on extreme loads. A second novelty is the investigation of extreme events such as gusts or direction changes. Combining these leads to a more complete picture of the effect a smart rotor has on wind turbines loads.

Firstly, the aeroservoelastic analysis set-up will be presented followed by a description of the controller. Then a discussion is presented on the load cases included in this analysis. The result section of this paper is split into 2 parts. First, fatigue loads are investigated, which is similar to previous analyses, except that more turbine components will be addressed. Turbine components with significant reduction or an increase in load will be further discussed. This is complemented by a study of ultimate loads due to extreme turbulence, gust occurrences and direction changes. Again, components with changes in loads will be discussed in more detail. In a final step the results are disseminated and the implication for turbine design discussed.

2. Numerical simulation and controller design

2.1. Aeroelastic turbine analysis tool DU-SWAT

The numerical analysis was performed by an in-house tool of TU Delft named Delft University Smart Wind turbine Analysis Tool (DU-SWAT). This tool was designed with special focus on smart rotor research and controller implementation. The mathematical formulations, validation and verification are described in detail by Bernhammer (2015). The code is an extension and improvement to the first generation of aeroelastic codes of TU Delft (Barlas, 2011). The differences are an increase in structural degrees of freedom and incorporation of an unsteady aerodynamic model for thick airfoils (Bergami et al., 2014) and an increased number of flaps that can be modelled on each blade. The code is non-linear both structurally and aerodynamically. It employs a Blade Element Momentum (BEM) method, which is based on the two dimensional unsteady aerodynamic Adaptive Trailing Edge Flap (ATE-Flap) model (Bergami et al., 2014). This model combines the dynamic stall model of Andersen et al. (2009) with the adaptive trailing edge flap model developed by Gaunaa (2007). The dynamic stall model is an extension for trailing edge flaps of the Beddoes–Leishman type stall model that has been adapted for thick airfoil geometries by Hansen et al. (2004). This two dimensional model was coupled to a dynamic inflow model of Snel with Prandtl tip loss and root flow corrections (Burton et al., 2001).

The input to the two dimensional unsteady aerodynamic model has been created in Rfoil (van Rooij, 1996). Rfoil is a software tool for airfoil analysis based on Xfoil (Drela, 1989) with improved stall prediction and corrections for rotational effects. For the airfoil analysis each section is analysed separately, with Reynold's number based on rated wind speed. For each section the lift, drag and moment polars have been obtained for angles of attack from -20° to 20° in steps of 0.5°. This procedure has been repeated for different flap deflection angles, thereby creating lift, drag and moment surfaces. The pressure time constant $\tau_p = 1.5$ and the boundary layer time constant $\tau_B = 6.0$ are used in the model for separation dynamics. The model and the implementation to the DU-SWAT has been intensively studied by Gillebaart et al. (2014). Flap rates have been limited to 20°/s, a value comparable to the rotational velocities achieved by field tests (Berg et al., 2014).

The DU-SWAT employs multi-body dynamics to solve the structural behaviour. The structural stiffness is concentrated in springs in between different elements, while the mass and inertia are lumped in the body attached reference frame. The structural deformations are formulated in a co-rotational framework, such that geometric non-linearities of the structural deformation can be captured. The spring–damper systems between the elements have all rotational degrees of freedom, such that not only bending, but