Load alleviation potential of active flaps and individual pitch control in a full design load basis

Thanasis K. Barlas, Leonardo Bergami, Morten H. Hansen, Mads M. Pedersen, David Verelst, Kenneth Thomsen, Helge A. Madsen

Aeroelastic Design group, Wind Energy department, Technical University of Denmark (DTU)

tkba@dtu.dk

Abstract

The load alleviation potential of the Controllable Rubber Trailing Edge Flap (CRTEF) is verified on a full Design Load Base (DLB) setup using the aeroelastic code HAWC2, and by investigating a flap configuration for the NREL 5MW Reference Wind Turbine (RWT) model. The performance of the CRTEF configuration is first compared against the one obtained with individual pitch control; a third configuration is also investigated, where CRTEF and individual pitch controller are combined. The CRTEF allows for a significant reduction of the lifetime fatigue on various load channels; the reduction for some of the extreme loads is also noticeable

Introduction

The article describes the aeroelastic simulation activities on the load alleviation potential of a trailing edge flap in a realistic setup, close to the industrial certification-type of simulations. The implementation, load basis and pre-/post-processing comprise a robust and concrete comparison of load alleviation concepts. Testing the performance and robustness of the smart blade technology is an important part of the INDUFLAP project which was finalized in 2014. Wind tunnel testing of an earlier prototype flap system was performed in 2009 and proved that the actuation concept works in a wind tunnel [1, 2]. The rotating rig testing of the latest prototype developed in the project is documented in [3, 4]. However, a big step from prototype testing to full scale turbine application is a realistic evaluation of the load alleviation potential of such a system in conditions close to industrial standards. The load alleviation potential of using active flaps on wind turbine rotors has been investigated in the past decade using various models, controllers, configurations and load cases. For an overview see [5]. In this report, the aeroelastic load simulations present a first approach for documenting such an evaluation on an overall realistic setup.

The main characteristics of the presented simulations are summarized as:

- Certification-type design load base setup close to industrial standards
- Representative wind turbine / flap system configuration
- Realistic controllers for full range of operation

The full Design Load Base (DLB) setup

In order to assess the load consequences of innovative features and devices added to existing wind turbine concepts or new developed wind turbine design concepts, it is useful to have a full DLB that follows the current design standard and is representative of a general DLB used by the industry in a certification process. The proposed DLB is based on the third edition of the IEC 61400-1 standard [7] and covers the typical cases for assessment of extreme and fatigue loads on the turbine components. The overview of the parameters defining the Design Load Cases (DLC) is presented in [6]. The suggested implementation of the DLCs is considered accurate translation of the IEC recommendation and a good choice for research

investigation, close to certification-type of load analysis. For cases with flap controls, the standard list of DLCs is augmented with some additional cases, simulating reference fault cases related to the flap system.

The standard DTU Wind Energy Design Load Case post-processing method for the DLB has been utilized. The pre-processing tools are available in [8].This procedure and algorithms applied are described in detail in [9].

Wind turbine model configuration

The NREL 5MW Reference Wind Turbine (RWT) [11] is used for the simulations in the aeroelastic code HAWC2 [12], as a representative modern multi-MW wind turbine model which has been used extensively for comparison studies involving blade aerodynamic controls. In this investigation, the IEC class has been changed from originally used IB to IA for evaluation of the load reduction potential in more aggressive wind conditions.

The simulated flap configuration is chosen based on prior studies [12] and enlarged (from originally 20%) to 30% of the blade length (**Figure 1**), in order to explore a more extended flap configuration.
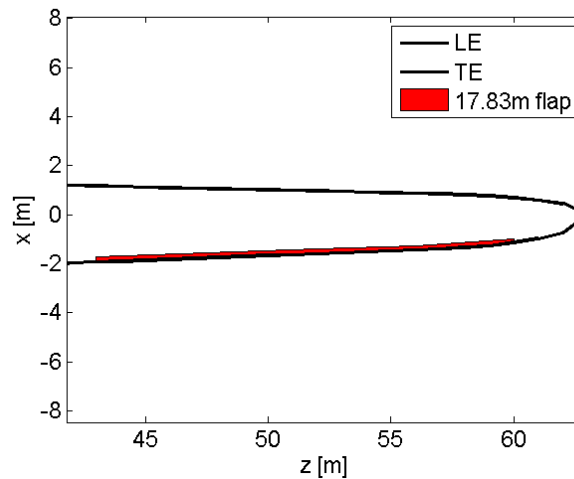

Figure 1 - Flap geometry implemented on the 61.5m blade of the NREL 5MW RWT.

The unsteady aerodynamics associated with the active flaps is accounted for by using the ATEFlap dynamic stall model in HAWC2 [13, 14]. The variation of steady lift, drag, and moment coefficients introduced by the flap deflection is based on 2D CFD simulations performed with the code Ellipsys2D [15]. The exact shape of the deformed flap is shown in **Figure 2**. The actuator dynamics are implemented as a linear servo model in HAWC2, for a first order system with a time constant of 0.1s. This corresponds to the characteristics of a Controllable Rubber Trailing Edge Flap (CRTEF) actuator.
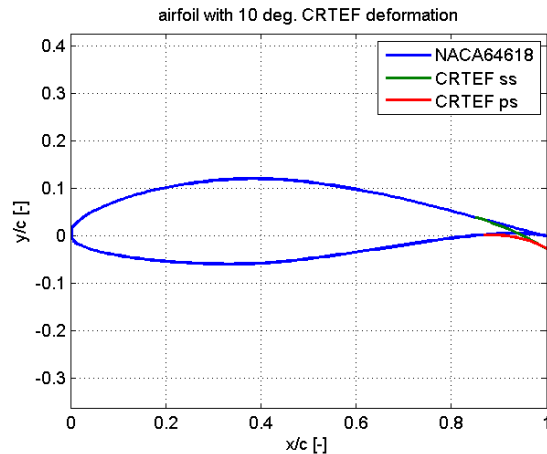
Figure 2 - NACA64618 geometry with a 10%c flap (10o positive flap deflection).

Controllers

The baseline controller of the NREL 5MW RWT is originally described in [**10**]. Due to the fact that the original controller is not designed to handle operation in the full IEC DLCs, the basic DTU wind energy controller is used as described in [**16**]. The controller features both partial and full load operation as well as switching mechanisms between modes of operation, utilizing measurements of rotor speed, tower accelerations and pitch angles as inputs and the generator torque and collective pitch angle as outputs. Gain scheduling is employed for the pitch angle in full load operation. Furthermore, the controller includes procedures for cut-in, cut-out, overspeed and tower acceleration. A servo model for the pitch actuator is also included, as described in [**16**]. Finally, fault procedures for handling the relevant IEC fault cases are included.

The individual pitch control is added on top of the baseline controller based on [**17**]. It utilizes flapwise blade root bending moment signals and azimuth position to control the individual pitch angles based on a tilt-yaw PI control loops. The individual pitch controller is tuned using a Ziegler-Nichols scheme based on the response of a high-fidelity linear aero-servo-elastic model of the turbine and its controllers, obtained with HAWCStab2 [**18**].

Prior studies have explored advanced flap controllers together with various design configurations. In this study a simple flap controller close to industry standards is chosen, which can also operate at the full DLB, in a realistic setup. The flap control algorithm drives the flap on each of the blade independently from the other. For each blade, the input to the flap control algorithm is the high-pass filtered blade root bending moment in the flapwise direction and the output is the deflection of the flap on the same blade, accounting for delays and limitations of the flap actuator. The reference flap signal is then proportional to the filtered bending moment and its first time derivative (PD control). The gains are scheduled as linear functions of the mean pitch angle, and an additional gain scheduling is introduced to limit the flap activity below rated power. The actuators dynamics are then modelled as a first order low pass filter. The flap controller is not active in partial load operation or fault cases.

The PD flap controller gains are tuned based on the response of a high-fidelity linear aero-servo-elastic model of the turbine and its controllers, obtained with HAWCStab2 [**18**]. The gains for the PD flap controllers are found with a Ziegler-Nichols tuning method. In the case of the combined controller, the flap controller is added on top of the individual pitch controller. The individual pitch controller operates on the rotor level (tilt and yaw moments) and the flap controllers operate on each blade independently. The two controllers are implicitly separated by increasing the cut-off frequency of the high-pass filter on the flap control from 0.05Hz to 0.1Hz, thus forcing the flaps to react at higher frequencies, and thus avoid interaction with the individual pitch system. The top level schematic of the combined controller is shown in **Figure 3**.
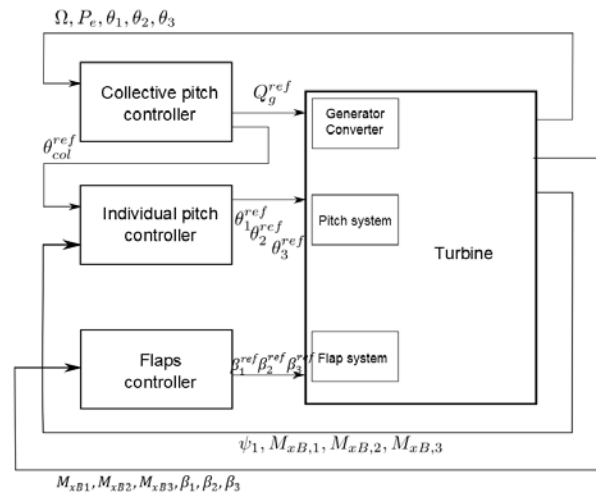
Figure 3 - Combined individual pitch and flap controller.

Results

The results of all cases are analyzed according to the post-processing procedure [**8**] and compared. The loads from normal operation DLC 1.2 are extrapolated to 50 year return loads, using the procedure by Natarajan and Holley [**10**]. The following configurations are considered and compared:

- Baseline
- Individual pitch control
- Flap control
- Combined individual pitch and flap controls

The analysis is focusing on comparison of overall extreme (including partial safety factors (psf)) and lifetime fatigue loads from the full DLB, as well as comparison of short-term statistics of load and actuator activity channels. Moreover, the lifetime pitch bearing damage and pitch and flap activities are included.

All the three control concepts significantly reduce the lifetime fatigue loads for certain load channels, like the flapwise root moment (M_xBR), which is the load channel targeted by the load control algorithms. The load reduction is achieved at the cost of higher actuators activity: the pitch activity for the individual pitch configuration is ten times higher than the baseline one, but the pitch bearing equivalent damage [**9**] increases only by a factor of two, as the flapwise load variation is reduced. The flap control case present a slight increase of the pitch activity, thus indicating some interaction between the controllers; nevertheless the pitch equivalent damage is reduced (-3.4%), as the loads on the bearing are alleviated. The combination of both flap and individual pitch returns the highest fatigue load alleviation, and also allows to ease the demand on the pitch actuators, whose total travelled distance is 20 % lower than in the individual pitch control case. The overall comparison of lifetime fatigue load levels is shown in **Figure 4**.
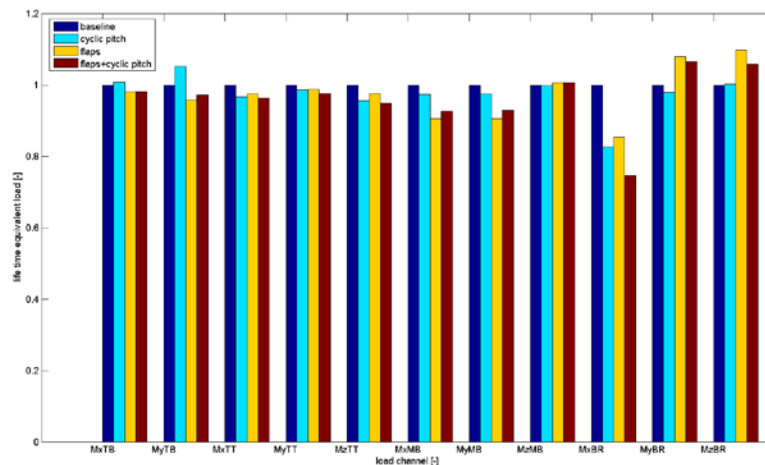
Figure 4 - Comparison of lifetime fatigue loads between cases (loads normalized by baseline loads).

As expected, the flap controls result in increased blade torsion loads due to the increased pitching moment. The impact on extreme loads is less clear, where on average flap and combined controls show increased or decreased loads in few channels and generally show no impact. The individual pitch controller results in increased loading in some channels and no impact on most of them.

Based on the design load cases showing extreme loads, it is seen that they are mostly connected in blade fault or parked cases. More detailed fine tuning of controller parameters on a case specific way could potentially eliminate some of these cases.

Conclusion

The three load control concepts (flaps, individual pitch, and combination of the two) have been evaluated in the full IEC-type of DLB revealing a realistic impact on design loads. The main conclusions of this study are summarized below:

- The individual pitch and flap controllers have a significant fatigue load alleviation impact on of blade, main bearing and tower loads, ranging from 2% to17%.
- The combined individual pitch and flap controller shows the best fatigue load alleviation performance, with alleviation up to 25 % on the blade root flapwise bending moment, around 7 % on the main bearings, and from 2% to 5% on the tower loads.
- The individual pitch controls increases the pitch activity and fatigue damage, while the flap and combined controllers decrease it compared to the baseline and to the individual pitch cases respectively.
- Individual pitch control can decrease extreme loads in certain channels up to 11%, while flap controls up to 11% and combined control up to 14%. The impact on extreme loads is very sensitive to specific controller parameters on fault cases.
- All cases show practically no impact on the AEP.

Suggested future work should focus on fine tuning of controllers for handling of extreme load cases, especially parked and fault cases, implementation of flaps on a more flexible and representative wind turbine model, and evaluation of advanced model-based combined controllers on the full DLB.

Acknowledgements

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