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IMPLEMENTATION OF PASSIVE CONTROL STRATEGIES THROUGH SWEPT BLADES

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I. Introduction

The purpose of this study is to define guidelines for the benchmarking of wind turbines that use passive control methods to reduce extreme and fatigue loads on the structure. Passive control techniques can be divided in two branches: changes of the blade geometry and tailoring the material properties with blade layups. The objective of the current investigation involves exclusively the first type.

The core of the concept behind the passive control methodology considered in this study is to create a coupling between flapwise bending toward the tower and torsion towards feathering. This coupling has the capability to mitigate loads due to a decrease in the angle of attack. This beneficial effect is achieved changing the geometry of the blade creating a backward swept shape.

Information concerning the positive and negative effects on the loading of a wind turbine with swept blades can be found in literature [1] [2] [3] [4]. For example, the parametric study carried by Verelst and Larsen [2] provided a clear picture related to the quality of the load variation generated by the use of different swept blade configurations. Knowledge regarding an accurate estimation of the quantity of these load variations is missing. The reason is the differences in power output between the baseline and passive-controlled wind turbines. The geometrical bend-twist coupling effect reduces the angle of attack, and this reduction is responsible for a decrease in power output below rated wind speed. Hence, in order to properly quantify the load variations, the benchmarking has to be based on wind turbines with comparable power curves.

This study uses a simple method to provide the benchmarking of turbines with swept blades, with power curves comparable to a baseline with unswept blades. The method is based on a study conducted by Hansen [3]. In order to compensate the power loss below rated wind speed, new minimum pitch angle settings for the controller are evaluated. The swept blades are therefore pitched further towards stall with respect to the baseline blade in order to achieve similar power outputs.

The paper provides guidelines for this type of benchmarking with the final purpose of isolating the effects on the loading brought by the use of geometrical passive control methodology.

A comparison of wind turbines with various swept blades is reported. Results and methods to improve and better isolate passive control effects to quantify load variations are discussed.

II. Model

In this investigation, two in-house aeroelastic codes have been used: the linear aero-servo-elastic model for open- and closed-loop eigenvalue and frequency-domain analysis HAWCStab2 [3] and the nonlinear aeroelastic model for response in time domain HAWC2 [5] [6] [7].

The DTU 10 MW Reference Wind Turbine (RWT) [8] is used as a baseline for the current study.

As previously introduced, three different swept geometries are considered. All the properties of the wind turbines related to aerodynamic characteristics of the blade are kept the same for all the configurations analysed.

The sweep geometries are described by the following shape function:

$$s = \left\{ a\,\frac{z}{R_0} - b\left(\frac{z}{R_0}\right)^{c}, 0, z \right\}^{T} \qquad z \in [0;\ R_0]$$

where s is the pitch axis as function of the blade length, z is the coordinate along the pitch axis of the blade, $R_0 = 89.166\ m$ is the blade length in hub-coordinate system, a is a linear term for forward sweep added to compensate an otherwise large steady torque moment and b is the term for the backward sweep, which curve exponent is determined by c.

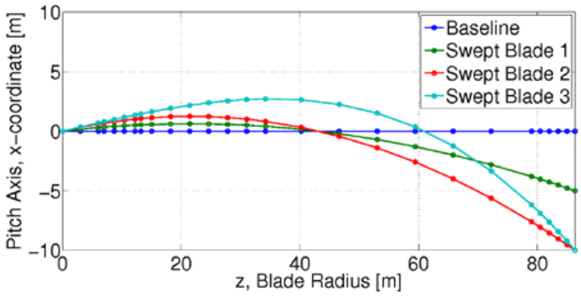

Figure 1: Pitch axis x-coordinate for the baseline and the backward swept blades

The pitch axes of the blade along the span for three different swept configurations are plotted in Figure 1, whereas the parameters for the different configurations are:

- Swept Blade Level 1 : *a = 5, b = 10, c = 2*
- Swept Blade Level 2 : *a = 10, b = 20, c = 2*
- Swept Blade Level 3 : *a = 10, b = 20, c = 3*

A fair benchmarking has to be based on wind turbines with comparable power curves. New minimum pitch angle settings are calculated using HAWCStab2. The aim is to compensate the reduction of the angle of attack below rated wind speed pitching the backward swept blades toward stall. Figure 2 shows the power curves of the baseline and the turbines with swept blades. The lower plot shows the relative error in percentage between the baseline and the three sweep levels. The dashed lines represent the difference in power curves when all the configurations have the same minimum pitch angle (zero degree) below rated wind speed. The solid lines shows the relative error when new minimum pitch angles have been used. The power losses have been significantly reduced and the maximum error is around 2%.
This simple method for obtaining comparable power curves has an important downside: pitching the full blade below rated wind speed might push the part of the blade closer to the root to operate in stall condition. The coupling between flapwise bending toward the tower and torsion towards feathering produces a reduction of the angle of attack in the region of the blade closer to the tip. The angle of attack closer to the root is significantly less influenced by the coupling effect. Hence, when the backward swept blades are forced to pitch further toward stall below rated wind speed, the lift coefficient of the airfoils closer to the root, which work already at high angles of attack, approaches dangerously the stall region.
Lift coefficients along the blade span of the different DTU 10 MW RWT configurations used for the current benchmarking have been constantly monitored, to make sure that all the swept-blades wind turbines used for this study kept a behavior comparable to the baseline.

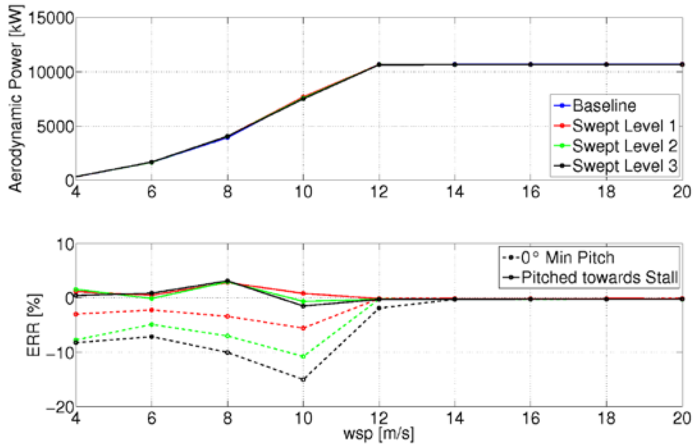

Figure 2: wind turbines Power Curves, Upper Plot - Relative Error between the power curves with comparison between configurations using same minimum pitch angles and HAWCStab2 new pitch settings below rated wind speed

III. Results

The load case used for the benchmarking consist of 10 minute simulations with turbulent wind speed from 4 m/s to 26 m/s (single turbulence seed is considered), tower shadow and no wind shear. Extreme and fatigue loads acting on the wind turbines are computed. Two sets of simulations have been run: one where the minimum pitch angle below rated wind speed is kept equal (zero degree) for all the configurations, and the other one where a new minimum pitch angle has been selected for each of the cases to minimize the discrepancies between the power curves.

Extreme blade root flapwise bending moment for the different sweeps are reported in Figure 3. The upper plot shows the values of this particular load for the different blade configurations. One bar (blue color) denotes the blade root flapwise bending moment for the set of simulations where the minimum pitch angles have been kept equal despite the blade geometry. The other bar (in red) shows the extreme blade root flapwise bending moment for wind turbine configurations with comparable power curves.

The lower plot shows the variation registered between the extreme loads calculated with and without taking into account wind turbines with similar power outputs. The maximum discrepancy in load variation from the baseline registered for the highest sweep level implemented with respect to extreme blade root flapwise moment is around 10%.

The maximum blade root torsional moment, shown in Figure 4, increases dramatically when a swept geometry for the blades is introduced. A similar effect on the extreme load variation seen from Figure 3 is reported. Torsional loadings are overestimated when a common pitch setting is used for all the configurations.

The extreme blade root flapwise bending and torsional moment are computed for wind speeds close to the rated. Therefore, the change in the minimum pitch angle below rated wind speed, introduced to compensate the power loss observed in wind turbines with backward swept blades, is responsible for the load variations observed between the two sets of simulations. Hence, a benchmarking without compensating the power losses of passive controlled wind turbines below rated wind speed brings to an overestimation of the extreme load alleviations due to the use of backward swept blades.

Life time (20-years) equivalent fatigue loads for the blade root flapwise bending moment (Figure 5) and for the blade root torsional moment (Figure 6) have been reported. Weibull distribution is considered. No relevant discrepancies between fatigue loads computed for the two sets of simulations are observed. For the blade root moments, the loading introduced by the action of the pitch actuator has the most relevant impact on the life time fatigue load, shadowing eventual effects due to a benchmarking done without considering turbines with lower power curves below rated wind speed.

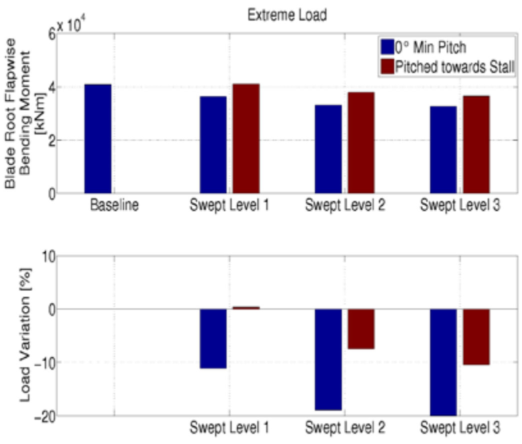

Figure 3: Extreme blade root flapwise bending moment. Load variation with respect to the baseline (lower plots) according to the configurations using the same minimum pitch angles (blue) and new pitch angles (red).

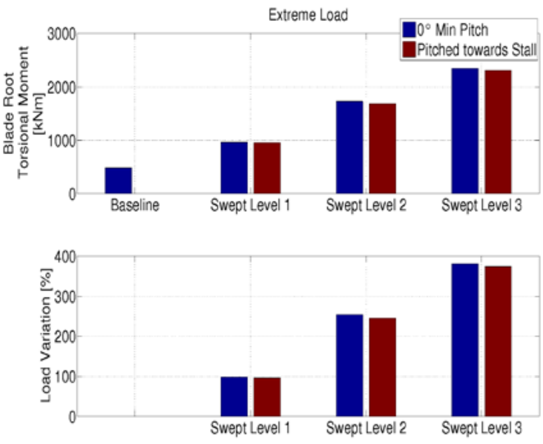

Figure 4: Extreme blade root torsional moment. Load variation with respect to the baseline (lower plots) according to the configurations using the same minimum pitch angles (blue) and new pitch angles (red).

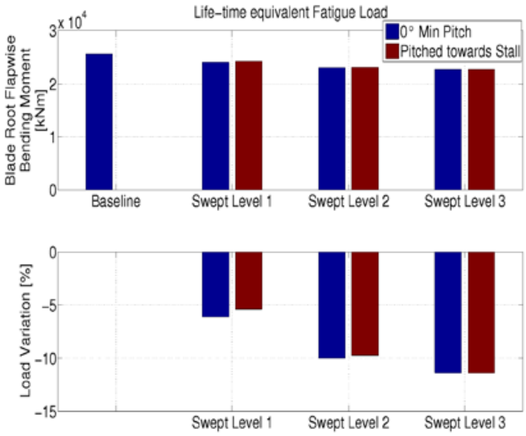

Figure 5: LTE Fatigue blade root flapwise bending moment. Load variation with respect to the baseline (lower plots) according to the configurations using the same minimum pitch angles (blue) and new pitch angles (red).

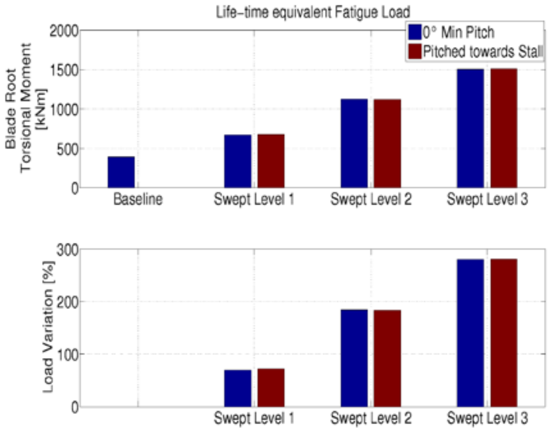

Figure 6: LTE Fatigue blade root torsional moment. Load variation with respect to the baseline (lower plots) according to the configurations using the same minimum pitch angles (blue) and new pitch angles (red).

The wind turbines with the backward sweep shapes chosen are characterized by excessive extreme and fatigue blade root torsional moments. Different changes in blade geometry must be investigated in order to overcome this issue.

It is important to remark that this type of benchmarking have to be based on wind turbines that produce the same power output below rated wind speed. The risk is a significant overestimation of the beneficial and negative effects brought by the use of geometrical bend-twist coupling. A load analysis that takes into account excessive discrepancies in the power curves cannot be trusted to evaluate the potential of passive control strategies.

IV. Conclusions

The current study showed the importance of providing definite guidelines for the benchmarking of wind turbines that use geometry-type passive control. Results have been reported with the purpose of comparing different configurations of wind turbines with backward swept blades. Main difference between the sets of simulations proposed was the implementation of a simple scheme able to provide the benchmarking with wind turbines characterized by comparable power curves. If the wind turbines used for the benchmarking produce less power below rated wind speed than the baseline, the beneficial load alleviations brought by the passive control method chosen can be overestimated. In order to give a correct estimation of the load variations brought by the passive control methodologies isolating its effects, the recommendation is that the benchmarking has to be based on wind turbines with similar power curves.

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