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Inertial and aerodynamic tuning of passive devices for load alleviation on wind turbines

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Abstract. This paper describes tuning concepts for passive devices aimed at load alleviation in wind turbines. Two types of tuning are considered: inertial and aerodynamic. The first concept is illustrated with reference to a passive flap, while the second with reference to a passive tip. In both cases, the goal is to reduce loads with devices that are as simple as possible, and do not require sensors nor actuators. The main features and critical issues of each concept are highlighted and illustrated with reference to a large conceptual 10 MW wind turbine.

1. Introduction

Recent works [1, 2, 3, 4, 5] have shown that fatigue load alleviation on wind turbines is achievable by distributed devices installed on the blade, in the form of flaps or movable tips. The idea behind the use of such devices is that they should be able to induce a change of aerodynamic loading that counteracts disturbances. In the case of passive devices, their response is purely driven by their aerodynamic and/or inertial characteristics, without the use of actuators. Clearly, this goes in the direction of a reduced complexity, which might be beneficial for limiting manufacturing, operation and maintenance costs. Passive devices respond automatically to load fluctuations, independently of their origin. Hence, they might produce beneficial effects also in wake interference conditions, which typically happen in closely-spaced wind farms.

In principle, a passive response may be obtained by *inertial* or *aerodynamic* means, or a combination thereof.

The chord-wise position of the hinge line of a flap or a free-rotating tip affects the aerodynamic response of the device. In fact, if the hinge line is close to the aerodynamic center of the device, the aerodynamic hinge moment varies little with respect to changes in the angle of attack. This way, the device is relatively insensible to aerodynamic load fluctuations. Motion must therefore be induced by using inertial loads, typically by displacing the device center of gravity from the hinge line, possibly with the use of tuning masses. The advantage of this solution is that the device does not respond to deliberate changes in angle of attack, as the ones induced by the wind turbine control system.

On the other hand, if the hinge line lies in front of the device aerodynamic center, its response is primarily driven by aerodynamic instead of inertial forces. In this case, changes in pressure distribution due to local angle of attack fluctuations produce changes in the aerodynamic moment about the hinge line, that in turn counteract the originating disturbance. In this case, no added masses are typically necessary, as a proper tuning is obtained by purely aerodynamic means.

In the following, these concepts are illustrated by means of two examples.

2. Methods

The appended devices have been implemented and analyzed on the DTU 10 MW Reference Wind Turbine (RWT) in the high-fidelity aeroservoelastic simulation environment `Cp-Lambda` [6]. The structural dynamics is modelled by a multibody approach. A completely generic turbine topology formulation, based on the use of Cartesian coordinates and Lagrange multipliers, enables a straightforward modeling of flaps and tips, as well as many other non-standard solutions. Flexible elements, i.e. blades and tower, are described by composite-ready geometrical exact beam theory [7]. Aerodynamic loads are computed by the standard BEM theory with Theodorsen dynamic correction [8], as commonly done for design, load and aeroelastic evaluations. The supervision and control of the wind turbine is provided by an external library that implement the routines of Ref. [9]. The aeroservoelastic equations are solved by a monolithic procedure, ensuring the correct evaluation of the couplings among the various fields.

2.1. Inertial tuning of passive flaps

The first example of this work considers a passive flap. The idea behind this concept is that, when the blade accelerates in a out-of-plane direction, the flap automatically deflects, resulting in a change of airfoil camber (and therefore a change of airload distribution) that works against the blade motion. This type of behavior is obtained by offsetting a mass ahead of the hinge line.

In this case, aerodynamic balancing may be obtained by properly tuning the overhang, i.e. that part of the flap ahead of its hinge line. This helps fulfill the requirement that the device should not interact with the active on-board pitch system. Another important requirement is that the integration of the device on the blade should not imply a drastic change in the blade design and manufacturing. This may be obtained by adopting a standard trailing edge flap with an offset mass. Tuning of the mass should minimize the effects on the blade modes, and its motion should remain confined within the internal void existing between the suction and pressure sides of the airfoil.

A preliminary investigation of the inertially-tuned flap concept was presented in Ref. [4] with application to the DTU 10 MW RWT. In this case, the study was conducted by means of a hybrid model: a complete 3D aeroservoelastic model of the wind turbine used for generating realistic operating conditions at a blade section, which are then in turn fed to a 2D typical section model of the airfoil equipped with the passive flap. One single passive flap was considered on the blade at 75% of the span. Tuning was performed by maximising fatigue load mitigation in the form of damage equivalent loads (DELs), by using normal turbulence model (NTM) conditions. The best performance was obtained at low frequencies, i.e. by tuning the hinge stiffness and the flap inertia such that their square-root ratio is as low as possible. The analysis of load spectra illustrates the fact that the system acts as a filter in a band from below the 1×Rev to above 3×Rev, i.e. in the most energetic frequency range of blade loads. Figure 1 gives a graphical illustration of the passive flap concept.

In the present work, the passive flap was implemented in the high-fidelity multibody environment, with the goal of demonstrating the feasibility of the concept in more realistic conditions.

Tuning of the device follows the indications of the preliminary study conducted in Ref. [4]. The overhang was selected in order to obtain aerodynamic balancing, i.e. a small hinge moment rate of change with respect to the angle of attack. The flap occupies the blade span between 70% and 80% and it has a natural frequency significantly lower than 1×Rev. The flap local chord is 25% of the total blade sectional chord. This choice appears to be a good compromise

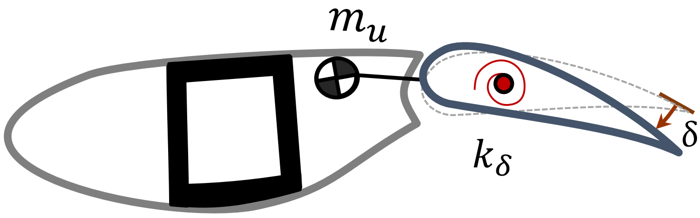

Figure 1. Passive flap with inertial tuning concept.

between having the required flap authority while at the same time reducing the interference with the blade structure. Referring to the sketch of the flapped blade section shown in Fig. 1, an offset mass ahead of the flap hinge was necessary in order to achieve a correct inertial tuning. Table 1 summarizes the principal flap parameters.

Table 1. Main parameters of the flaps installed on the DTU 10 MW RWT.

Parameter	Value
Span	8.3 m (η =[0.7,0.8])
Chord	25% of blade chord
Overhang	52% of flap chord
Offset mass	315 Kg
Offset mass distance	0.6 m
Max excursion	± 20 deg
Natural frequency	0.018 Hz

The entity of the mass was chosen in order to have a satisfactory flap behavior, while limiting the effects on the lowest blade natural frequencies. The distance of the offset mass with respect to the flap hinge line was chosen to be as large as possible, in order to maximize the offset mass accelerations and their moment arm with respect to the hinge line, without interfering with the aft shear web. The left part of Fig. 2 shows the tower root bending moment DEL variation trend, obtained by varying both the offset mass and its distance ahead of the hinge. These values were determined by standard power production simulations (DLC 1.1 [10]), considering wind speeds close to rated (from 9 to 13 m/s). The grey area indicates interference of the offset mass with the aft shear web.

The hinge stiffness was chosen as low as possible in order to keep the natural frequency of the passive flap considerably below the 1×Rev, as suggested by Ref. [4]. A constant preload at the hinge is also used, with the goal of limiting the mean misalignment of the flap with the rest of the blade over the whole range of operative conditions. The right part of Fig. 2 shows the effect of mean flap misalignment on AEP and DEL. To evaluate the AEP and DEL variation, an analysis of the mean misalignment was performed over the entire operation range. Selecting a null mean misalignment in the upper part of region II appears to be the best choice, since the loss of AEP is below 0.5% and the DELs of the main components of the machine are considerably reduced.

2.2. Aerodynamic tuning of passive tips

The passive tip concept is considered next, again with reference to the new large RWT rotor, where loads are now mitigated by a free pitching of the outer blade portion.

In this case, an aerodynamic tuning approach appears to be more suitable, since several factors make the inertial tuning difficult to implement. Indeed, a flap is characterized by the

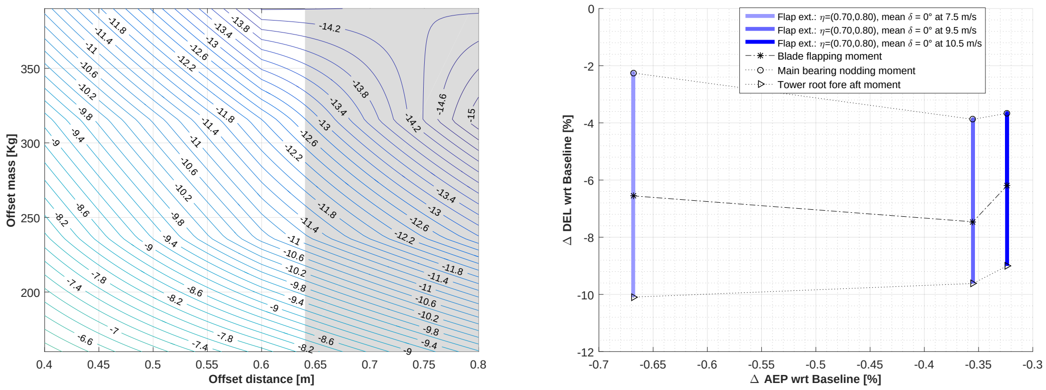

Figure 2. DEL-based tuning of the passive flap. Left: tower root bending moment DEL variation vs. baseline (values in %). Right: DEL and AEP variation vs. baseline at different hinge preloads.

hinge moment rate of change with respect to both angle of attack and flap deflection changes, two parameters that are in general largely uncorrelated and therefore independently selectable. On the contrary, a tip device is only characterized by its sole hinge moment rate of change with respect to angle of attack changes. In addition, since tip airfoils are usually non-symmetrical, the resulting hinge moment is non negligible. This requires a significant mass ballast to obtain the necessary inertial effects, ballast that in turn lowers the blade natural frequencies and may negatively affect loading.

The aerodynamic tuning of the device requires the choice of the hinge location as a best compromise between the weathercock tendency of the blade tip, which suggests a forward position, and a desire to limit inertial couplings, which suggests a hinge position close to the center of gravity of the tip. The spanwise extension of the tip was chosen as the outer 15% of the blade, resulting in a good tradeoff between tip effectiveness and loading at the tip hinge.

The passive tip concept is illustrated in Fig. 3, which shows the tip connected to the rest of the blade by a screw joint, as discussed later on.

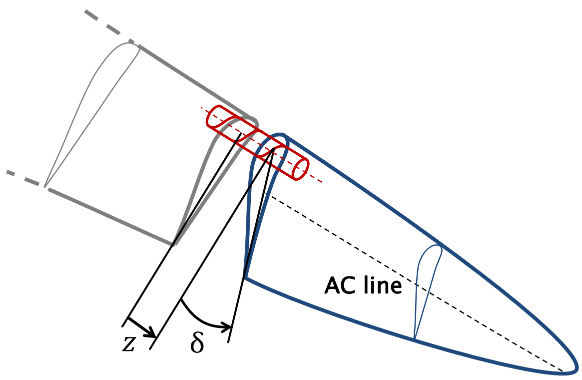

Figure 3. Passive tip with screw joint tuned by aerodynamic means.

To avoid affecting power production, the mean misalignment of the tip with respect to the fixed part of the blade should be minimized in region II, where maximum rotor efficiency is necessary. This can be achieved by a proper choice of the stiffness and preload at the tip hinge.

To this end, aeroelastic analyses were performed scanning the entire operative range, and the loads required to keep the tip aligned with the rest of the blade were computed. The mean value of the torque load at each wind speed is considered to be responsible for the mean misalignment, and therefore it represents the preload that should be applied at the hinge.

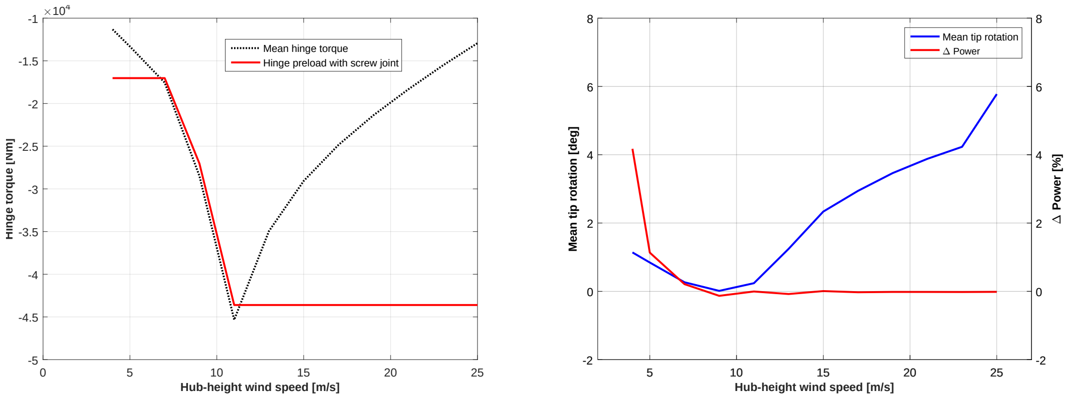

Figure 4. Left: tuning analysis of passive tip hinge preload. Right: mean tip rotation and mean power differences with respect to the baseline (with tuned hinge preload and stiffness).

Figure 4 shows on the left the results of the hinge preload tuning procedure over the operating range of the machine. Looking at the mean hinge torque, an optimal scheduling should be performed with respect to the wind speed. However this choice would possibly be complicated to implement, and it was therefore discarded. A simpler solution is instead to use a scheduling with respect to the rotor speed that, varying in region II, allows one to reduce the misalignment where it is most necessary.

The mechanical realization of the scheduling mechanism is based on the solution of Ref. [11], and it requires the use of a screw joint in order to generate a torque moment from the centrifugal force acting on the tip in the radial direction. This solution achieves a preload profile varying within region II from 7 m/s to rated wind speed, following the rotor speed profile. In region III the excess of power in the wind makes a larger tip misalignment acceptable without incurring in power losses, due to the compensation of the blade pitch control system, as shown in Fig. 5. The spring stiffness in the joint was chosen to keep the mean misalignment within reasonable values in region III, while at the same time looking at the DEL reduction effectiveness of the device. The right graph of Fig. 4 shows how the mean tip misalignment remains below 10 deg over the entire operation range, when the scheduled preload and the appropriate stiffness are used. Consequently the difference in power production, evaluated through standard power production simulations DLC 1.1, is negligible.

3. Fatigue analysis

The three configurations of the 10 MW RWT (hereinafter identified with the labels "Baseline", "Passive flap", "Passive tip") were compared in terms of fatigue loads by standard power production simulations DLC 1.1. The effects of the appended devices at the blade root is shown in Fig. 6. The left graph shows DELs over the entire operating range, while the right graph reports the variations with respect to the baseline for the flapped configuration and for the freely pitching tip. The latter highlights DEL reductions of up to 7% for the flap and up to 12% for the tip. The flap appears to be more effective at the lower wind speeds since it is driven by blade accelerations, which are more significant in the lower part of the operating range. On the other hand, due to its aerodynamically-driven response, the tip performs better at high wind speeds, i.e. at higher dynamic pressures.

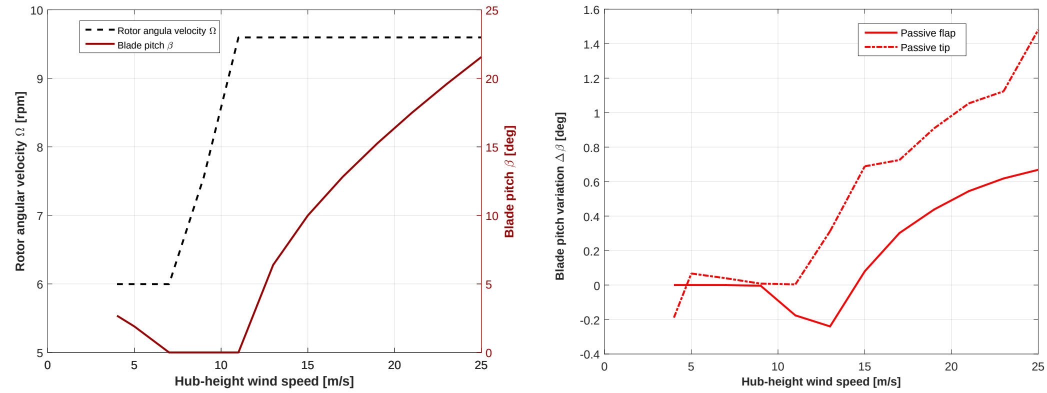

Figure 5. Left: regulation trajectory of the controller. Right: blade pitch variation with respect to the baseline for the two configurations with appended devices.

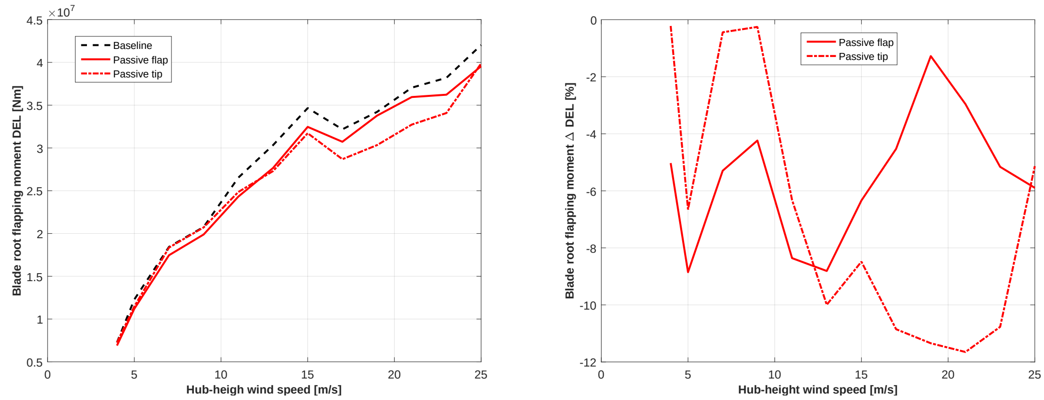

Figure 6. Fatigue analysis for blade root flap bending. Left: DELs for the three configurations. Right: DEL variations with respect to the baseline configuration.

Figure 7 shows the DELs at tower base. The right part of the plot shows variations with respect to the baseline. In this case, the flapped configuration appears to be more effective over the entire operating range, with reductions of up to 18%. In fact, being mostly inertially-driven, the flap also responds to accelerations induced by the tower top motion. In this case the passive tip configuration is less effective, with reductions of up to 8%.

4. Conclusions

The present work has described two tuning techniques of passive load mitigation devices for wind turbine blades. The idea behind the use of passive flaps and/or free pitching tips is that they should respond automatically to oppose perturbations. It was shown that this behavior can be obtained by two different means, i.e. inertially or aerodynamically. Although the physical mechanism behind the two concepts is radically different, both seem to offer promising performance at a low level of complexity. The two concepts were illustrated with reference to a large conceptual wind turbine, showing interesting load mitigating capabilities.

Future work will focus on a more comprehensive analysis of all effects of these devices, including their impact on ultimate loads. In addition, effects such as soiling and erosion of the aerodynamic surfaces were not considered in the current analysis, due to its preliminary nature. As the aerodynamic characteristics of the blade change due to aging, so the tuning of the

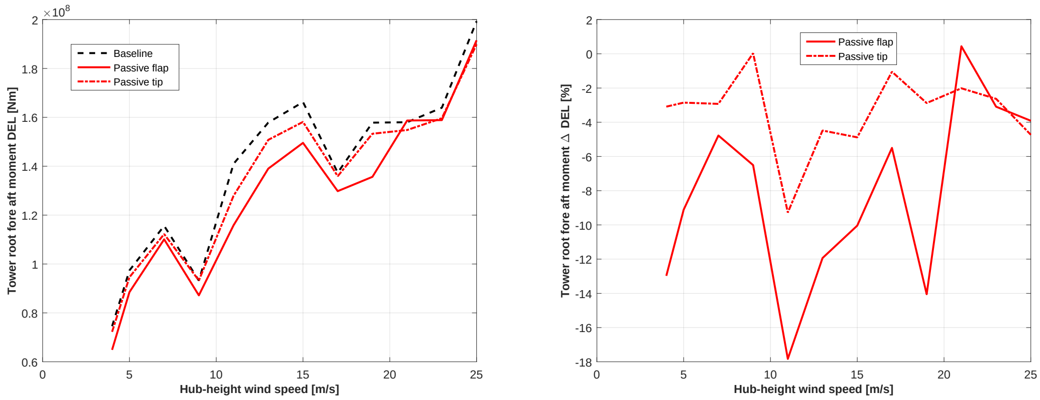

Figure 7. Fatigue analysis for tower base fore-aft bending. Left: DELs for the three configurations. Right: DEL variations with respect to the baseline configuration.

passive devices might have to be updated. This however does not seem to be an insurmountable problem, although a more detailed analysis is certainly necessary.

References

[1] Lambie B, Jain P and Tropea C 2011 Passive camber change for wind turbine load alleviation *49th AIAA Aerospace Sciences Meeting incl. the New Horizons Forum and Aerospace Exposition* **DOI: 10.2514/MASM11**

[2] Marten D, Spiegelberg H, Pechlivanoglou G, Nayeri C N, Paschereit C O and Tropea C 2015 Configuration and numerical investigation of the adaptive camber airfoil as passive load alleviation mechanism for wind turbines *33rd AIAA Applied Aerodynamics Conference* **DOI: 10.2514/6.2015-3390**

[3] Arrieta A F, Kuder I K, Rist M, Waeber T and Ermanni P 2014 Passive load alleviation aerofoil concept with variable stiffness multi-stable composites *Composite Structures* **116** 235–242

[4] Bottasso C L, Croce A, Gualdoni F and Montinari P 2015 Load mitigation for wind turbines by a passive aeroelastic device *J. Wind Eng. Ind. Aerod.* **148** 57–69

[5] Bottasso C L, Croce A, Gualdoni F, Montinari P and Riboldi C 2016 Articulated blade tip devices for load alleviation on wind turbines *Wind Energy Science* **Submitted**

[6] Bottasso C L, Croce A 2006-2014 Cp-Lambda: Users Manual *Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano*

[7] Bauchau O A 2011 Flexible Multibody Dynamics *Springer, Solid Mechanics and its Applications, Vol. 176*

[8] Hansen M.O.L.: Aerodynamics of Wind Turbines *Earthscan, 2nd Edition (2008)*

[9] Hansen M H, Henriksen L C 2013 *Basic DTU Wind Energy controller, DTU Wind Energy E, No. 0028*

[10] IEC 61400-1 2005 *International Standard IEC 61400-1*

[11] Stroub R H 1982 An analytical investigation of the free-tip rotor for helicopters *NASA Technical Memorandum* **81345**