Assessment of load reduction capabilities using passive and active control methods on a 10MW-scale wind turbine

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Abstract. In the paper, the potential to alleviate wind turbine loads through combined implementation of different passive and active control methods is assessed. Passive control of loads is accomplished through blade designs with build in material and/or geometric bend-twist coupling (BTC). The first is materialized by introducing an offset angle on the plies of the unidirectional material over the spar caps of the blade, while the latter by sweeping the blade elastic axis with respect to the pitch axis. Active control of loads is considered through individual pitch control (IPC) or concurrent use of individual pitch and flap control (IPC+IFC). Different combinations of the abovementioned techniques are tested in the paper with the aim to obtain maximum possible load reduction levels but also confine key design parameters of the various methods within reasonable limits that by no means exceed manufacturing constraints. The performance of the different control options is assessed through aeroelastic simulations for the 10MW DTU Reference Wind Turbine (RWT). A subset of representative fatigue and ultimate design load cases (DLCs) of the IEC is simulated and load reduction levels are assessed with respect to the baseline RWT configuration with no aeroelastic control of loads.

1. Introduction
The goals of up-scaling modern turbines towards the vision of the 20 MW and compressing levelized cost (LCOE) of wind energy to levels far below those of the conventional power generation methods can only be achieved through technological breakthroughs and new innovative turbine concepts that render wind turbines lighter and cheaper. Over the last years the target of reducing wind turbines loads and therefore cost has been effectively supported through breakthroughs in control methods. There are two distinct categories of load control methods that have almost been given equal attention by the wind energy research community, namely passive and active load control methods.

Passive methods for controlling loads have been described by the wind scientific community through the term “Aeroelastic Tailoring (AT)”. AT is a design technique through which geometric or stiffness properties of a structure are matched with its aerodynamic characteristics in such a way that overall structural loads are reduced. In wind turbines engineering AT appears as a passive control design option either based on Bend-Twist-Coupling (BTC), or Flap-Edge-Coupling (FEC) [1], [2]. The term BTC describes the behavior of a structure that has been designed to undergo torsion deformation under the action of bending loads. The resulting change in sectional angle will affect the aerodynamic loading through a change in the angle of attack. Modern approach to BTC is to twist the blade sections towards decreasing the angle of attack, which corresponds to the so-called twist-to-feather concept. This method has demonstrated significant fatigue damage reduction potential. On the
other hand, FEC is a design concept in which when the blade is excited and undergoes vibration in one bending direction (e.g. edgewise) it also vibrates in the other bending direction (flapwise). As a result, a trading of aerodynamic damping from the highly damped flapwise motion to the poorly damped edgewise motion is established and thereby edgewise vibrations can be reduced.

There are two alternative ways for designing the so-called “aeroelastic blade” with BTC or FEC. (a) Material Based: by exploiting the anisotropic mechanical properties of the composite material. Composite-blade elastic anisotropy can be varied along the span through appropriate selection of the uni-directional (UD) material ply angle (Figure 1 left), thickness, and spanwise lay-up. (b) Geometry Based: the blade shape or the inner structure geometry can also be tailored to gain performance, load reduction and stability benefits. BTC coupling can be achieved by sweeping the elastic axis of the blade with respect to the pitch axis. BTC and FEC can be also accomplished by displacing the spar box (Figure 1 right). Passive control methods have been investigated both numerically [2], [3], [4], [5], and experimentally [6], [7], and they have proved their ability to reduce blade loads.

Active control of loads is usually realized through individual pitching of the blades or through the torque of the generator, by means of different types of sensors (i.e. load sensors, accelerometers, lidars or spinner anemometers) [8]. Active aeroelastic control of loads based on the above discussed pitch and torque actuators is considered as proven technology (especially when combined with standard load or acceleration sensors), which has been already applied to commercial turbines. Other, innovative actuators such as flaps have also been given a lot of attention by the wind community, mainly at simulation level. Individual flap control (IFC) but also combined IPC&IFC methods have been numerically tested by several researchers in the past years [9], [10]. Recently some experimental test rigs aiming at verifying flap actuators capabilities to reduce wind turbine loads have also been performed [11].

In the present paper, combined application of different AT and active load control techniques is performed with the aim to assess maximum load reduction potential. A comparative analysis of different combinations is performed for the DTU 10MW RWT [12]. Geometric (through blade sweeping) and material BTC (through spar cap UD material ply angle offset) are combined with the aim to assess potential load reduction capabilities through their concurrent application. Active load control is based on standard individual pitch control (IPC), as well as on combined use of IPC and individual flap control (IFC). Both IPC and IFC are based on the decomposition of the blade root out-of-plane moments of the three blades (measured in the rotating reference frame) into yaw and tilt moments in the hub fixed system (expressed in the non-rotating frame) through application of the Coleman transformation.

![Figure 1: Ply angle of fibre orientation for BTC blades (left) and geometrically based FEC (right). Upper right figure shows the baseline cross section, while lower right figure the introduction of FEC by the appropriate displacement of the spar cap nodes.](image-url)
The reason behind combining different passive control methods lies in the fact that usually geometrical design limitations, associated with manufacturing processes, pose constraints that narrow the limits within which key defining parameters of the above methods can vary. For example, sweeping of the blades cannot exceed certain limits because the manufacturing cost of the curved mould would then become excessive and/or smooth lay-up of the fiber sheet rolls could be hampered. Not to mention transportation constraints. Also, very high material off set angles, besides leading to substantially reduced stiffness characteristics they can also result in increased material wastage. In this respect a combined application of various concepts could sum up to the same overall load reduction level without necessarily exceeding functional and cost effective ranges of the design variables.

Fatigue as well as ultimate load reduction potential is assessed through time domain aeroelastic simulations of the DTU 10MW RWT for a representative subset of IEC DLCs consisting of DLCs 1.2 and 1.3. Simulations are performed using NTUA’s in-house multibody, FEM, servo-aero-elastic tool hGAST [13] that is capable of simulating both material and geometric BTC [14], as well as active trailing edge (TE) flaps [15].

2. Passive and active control designs for load reduction

Passive and active control designs for load reduction, considered in the present work, are listed in Table 1. Passive control designs for load reduction are based on BTC, both material and geometric. For the class IA 10MW Reference wind turbine (RWT), first spar cap UD plies angle of 10° is considered. In order to enable BTC, mirrored layup with respect to the chord-plane is applied (see Figure 1 left). Common orientation of the UD plies is considered all along the blade span starting from 30% of the blade radius. Next, a combined material and geometric BTC blade is considered with UD plies angle of 5° and maximum sweep at blade tip set at 3m (Figure 2). Both designs have been chosen to produce the same torsion induced angle at rated wind speed of 11.4m/s and therefore are expected to provide similar load reduction levels.

![Normalized blade sweep distribution](image)

**Figure 2:** Normalized blade sweep distribution along the blade span for 1m displacement at blade tip.

| Index | Design | Ply angle [deg] | Tip sweep [m] | Average power variation [%] | Mass variation [%] |
|-------|--------|----------------|---------------|-----------------------------|-------------------|
| 0     | Baseline | 0              | 0             | 0.00%                       | 0.00%             |
| 1     | BTC (10°, 0m) | 10             | 0             | -0.20%                      | 1.23%             |
| 2     | BTC (5°, 3m) | 5              | 3             | -0.20%                      | 0.33%             |
| 3     | Baseline+IPC | 0              | 0             | -0.79%                      | 0.00%             |
| 4     | Baseline+IPC+IFC | 0              | 0             | 0.15%                       | 0.00%             |
| 5     | BTC (5°, 3m)+IPC+IFC | 5              | 3             | 0.06%                       | 0.33%             |

**Table 1:** DTU 10MW RWT passive and active control designs for load reduction
Re-orientation of the ply angles reduces blade flapwise stiffness. In order to restore stiffness of the original DTU 10MW RWT blade (baseline), additional plies are added leading to increased weight of the tailored blade. As indicated in Table 1 the mass increase is of the order 0.33% for 5° ply offset angle and 3m tip sweep, while it rises up to 1.23% when ply offset increases to 10°. It is worth noting that restoration of the blade stiffness is a rather conservative choice given that in all cases tailoring is expected to reduce loads and therefore a blade with even a slightly reduced stiffness is expected to be able to support resulting loads. The reason behind the above choice is that we wanted to have a common basis for comparison for the different blades (same stiffness and therefore same tip deflections) since we do not perform a full re-design of the blade. Such re-design would require satisfaction of both maximum stresses and deflections constraints of the reference blade. A blade re-twisting has been performed for both BTC configurations based on the average torsion angle at 10m/s wind speed. This maintains the same geometric angle of attack in all sections along the span and it is done in order to avoid excessive power losses in the partial load region, as a result of the blade twisting to feather. A more advanced re-twisting should be based on the effective angle of attack distribution along the span which should be the same for the original and the BTC blade. However, as reported in Table 1 average power reduction for the different BTC configurations does not exceed 0.2%. Average power has been computed on the basis of the NTM cases (DLC 1.2) assuming Weibull parameters C=11 m/s and k=2.

Active load control is based on standard IPC and on combined use of IPC and IFC [15], [16] that are superimposed on the standard power speed controller of the Inwind.EU 10MW RWT. The out-of-plane bending moment signals at blade root are transformed into yaw and tilt moments $M_{\text{yaw}}$ and $M_{\text{tilt}}$ by applying the Coleman transformation. 3p and 6p band-stop filters are applied to $M_{\text{yaw}}$ and $M_{\text{tilt}}$. The filtered moments are then passed through the integral control element (I) and the cyclic $\beta_{\text{yaw}}$ and $\beta_{\text{tilt}}$ angles are obtained. These angles are then back transformed into pitch ($\beta_p$) and flap angles ($\beta_f$) of the individual blades via an inverse Coleman transformation. The block diagram of the controller is illustrated in Figure 3. Since both controls are based on the same working principle, the same loop is used by IPC and IFC; however integral gains $K_p$ and $K_I$ are tuned separately for every control combinations (IPC or IPC+IFC) [15]. In the combined IPC+IFC, the aim of flap control is to assist pitch control and therefore reduce pitch duty cycle (a key objective for very large blades). As shown in Table 1, the isolated IPC and the combined IPC+IFC are first applied on the baseline model of the DTU 10MW RWT in order to assess their load reduction capabilities. Finally, all considered passive and active designs are combined in order to assess the over-all load reduction potential. Combined IPC+IFC is applied to the material and geometric BTC model with 5° offset ply angles and 3m tip sweep.

Trailing edge (TE) flaps are placed in the outer part of the blade of the DTU 10MW RWT. The blade of the reference turbine comprises FFA series airfoils. The relative thickness of the outer 35% of the blade is constant and equal to $t/c=0.24$. The TE flap extends to 30% of the section chord length and 22.5% of the blade radius (see details in Table 2).

![Figure 3: Block diagram of the IPC and/or IFC controller.](image-url)
In the present analysis constant controller gains have been used both for the individual flap and pitch control. They have been selected on the basis of a sensitivity analysis performed over the wind speeds range of 5-25 m/s. Controller gains used in the different control loops are summarized in Table 3. Flap motion is bounded in the range \([-10^\circ, +10^\circ]\). In addition, saturation limits have been imposed on the velocity of the flap motion to 20 m/s. In all configurations a delay of 0.1 s has been imposed on the flap motion in order to account for the dynamics of the flap actuator (through a first order filter in flap response).

### Table 2: TE flap layout applied on the DTU 10MW RWT

| Parameter                  | Value                     |
|----------------------------|---------------------------|
| Chordwise extent           | 30%                       |
| Deflection angle limits    | ±10\(^\circ\)            |
| Deflection speed limit     | 20 m/s                    |
| Spanwise length            | 20 m (~22.5\% of blade radius) |
| Spanwise location          | 60 m-80 m (from hub centre)|
| Airfoil                    | FFA-W3-241                |

### Table 3: Controller gains for the IPC and combined IPC+IFC loops

| Control Loop | Gain Value |
|--------------|------------|
| IPC          | \(K_p=1.0\times10^{-9}\) deg/s/Nm |
| IPC+IFC      | \(K_p=0.6\times10^{-9}\) deg/s/Nm, \(K_f=7.0\times10^{-9}\) deg/s/Nm |

### 3. Assessment of load reduction capabilities

Assessment of load reduction capabilities of the designs described in section 2 (see Table 1) is performed for the onshore version of the DTU 10MW RWT through time domain aero-elastic simulations using NTUA’s in-house multibody, FEM, tool hGAST. Both fatigue and ultimate loads in normal operation are considered in the analyses. Fatigue loads are assessed on the basis of IEC [17] DLC 1.2 (normal operation with normal turbulence conditions NTM), while ultimate loads are calculated through DLC 1.3 (normal operation with extreme turbulence conditions ETM). At all wind speeds, simulations for yaw angle 0\(^{\circ}\) have been performed and for three turbulent seeds per wind speed. It is noted that in many cases the driving DLC for ultimate loads is 6.2 (parked/idling rotor in storm conditions). Since the aim of the present study is to record the incremental effect on loads of different control strategies (passive and active) and as in the above mentioned DLC flap controller is deactivated we decided to leave this DLC out of the present analyses. It should be definitely included in future developments where structural design parameters and cost of the blade will be addressed. The simulated conditions are summarized in Table 4.

Fatigue loads are assessed based on the Damage Equivalent Loads (DELs) calculated assuming the following Weibull parameters: \(C=11\) m/s and \(k=2\). In Table 5 the lifetime DELs of the baseline DTU 10MW RWT are presented together with the percentage relative differences of the considered designs for load reduction with respect to the baseline. The percentage of reduction of the DEL of the flapwise bending moment at blade root is about the same for both passive control designs based on BTC (about 7\%). IPC and combined use of IPC+IFC significantly decreases flapwise DELs by 25.5% and 27.6% respectively. Concurrent use of IPC and IFC further decreases flapwise DELs by 2%. In case all control methods are combined the reduction further increase to 30.5%; so BTC provides about 3% additional reduction.

Overall blade root edgewise DELs are not significantly affected because they are mainly driven by gravity loads. Material BTC increases edgewise DEL. This is due to the mass increase (1.23\%, see Table 1). Combined applications of material and geometric BTC does not affect edgewise fatigue loads (mass increase is 0.33\%, see Table 1). Both IPC and IPC+IFC decrease edgewise DEL by 2.5%, while combined BTC+IPC+IFC decreases edgewise DEL by 1.4%.
Blade root torsion moment DEL slightly decreases through material BTC by 3.7% and further decreases through pure IPC by 11.6%. On the other hand, it significantly increases though material geometric BTC by 48.7% due to the aerodynamic moment caused by the off-axis placement of the chord sections due to sweeping. Almost the same level of increase (52.7%) is noted through combined IPC+IFC. This is because TE flap motion locally increases twisting moment of the blade sections equipped with flaps. Finally the combined BTC+IPC+IFC design increases torsion DEL by 71% due to the superposition of the effects of sweep and flap. The torsion moment is not expected to have significant contribution to the overall cross-sectional stresses, compared to the two bending moments and in particular the flapwise one. However, it is noted that the present analysis is restricted to resultant internal loads, not analyzing the developed stresses over the blade sections.

A slight reduction in the tower fore-aft bending moment DEL of about 4% is obtained though both BTC designs, while both IPC and IPC+IFC active load control methods slightly increase it by about 2%. The reason is that active control loop has been only designed to reduce blade loads, so no control logic exists in the control loop that could effectively be used for the alleviation of the tower loads. If additional logic is implemented, adding also flap motion at 2p frequency, tower loads would also decrease. It is noted that the increase in the DEL of the fore-aft bending moment is rather marginal. Combined BTC+IPC+IFC slightly decreases tower base fore-aft DEL moment by 2.4%.

A slight reduction is also noted in the side-side bending moment DEL through material and material + geometric BTC by 1.9% and 1.1% respectively. As in the case of the tower fore-aft moment, IPC and IPC+IFC increase side-side DEL by 5.4% and 6.6% respectively, while the rate of increase slightly decreases thought BTC+IPC+IFC to 5.2%.

Tower yawing moment DEL decreases by about 4.5% through both BTC designs, by about 1.5% through IPC and IPC+IFC and by 7.8% through combined BTC+IPC+IFC.

In Table 6 the ultimate loads of the baseline DTU 10MW RWT are presented along with the percentage relative differences of the considered designs for load reduction (with respect to the baseline).

Ultimate flapwise bending moment decreases through all control options, by 4.7% and 3.6% through material and material + geometric BTC, by 4.5% and 7.4% though IPC and IPC+IFC and by 10% through BTC+IPC+IFC. For the considered configurations BTC, IPC and IFC load reduction methods contribute almost equally to the final combined design.
An about 2% increase in the ultimate edgewise bending moment is obtained with both BTC designs most probably due to the increased blade mass, while IPC and IPC+IFC reduce edgewise load by about 9%. Combined BTC+IPC+IFC leads to reduced ultimate edgewise moment by 4.1%.

A significant torsion moment increase is obtained by 39% through IPC+IFC due to the effect of the TE flap, by 93% through material+geometric BTC due to the effect of sweep and by 104% through combined BTC+IPC+IFC. Lower increase is obtained by material BTC (7% increase), while pure IPC slightly decreases ultimate torsion moment by 0.6%.

Overall the ultimate combined blade root moment decreases following the same trend with the flapwise moment. Reduction levers vary in the range 3-5.5%, while maximum reduction (8.1%) is again obtained through combined BTC+IPC+IFC.

A slight reduction in the ultimate tower base fore-aft and combined bending moments by 3% and 1% is obtained through material and material+geometric BTC. Pure IPC reduces ultimate tower base fore-aft and combined bending moments by 0.3%-0.4%, while IPC+IFC increases them by about 8% and combined BTC+IPC+IFC by 0.4-0.6%.

Ultimate side-side bending moments are slightly reduced by IPC and IPC+IFC (0.6%-1.8%), while increase through material BTC, material+geometric BTC and combined BTC+IPC+IFC by 1.4%, 3.4% and 1.2% respectively, affected by the increased edgewise moments. It is noted that the side-side ultimate moment is about 1/3 of the corresponding fore-aft and therefore it does not significantly contribute to the combined ultimate moment.

Ultimate tower yawing moment is not affected by BTC but it is significantly reduced by 19% through IPC and IPC+IFC and by 26.3% through BTC+IPC+IFC.

Generally it is concluded that progressive combination of different load control methods (passive and/or active) lead to cumulative load reduction levels. The effect on loads through superposition of different control methods is as expected nonlinear (load reduction levels attained by each method are not summing up when combined) and this is a critical observation for designing an optimum combination. A closer to linear behavior is noted on fatigue loads as compared to ultimate loads. Instant load peaks determining ultimate loading strongly trigger non linearity of dynamics and aerodynamics.

In Figure 4 the statistics of the TE flap angle (minimum (min), maximum (max) and standard deviation (sdv)) are presented both for NTM and ETM conditions for the IPC+IFC design (without BTC). It is seen that the flap angle reaches the saturation limits of +/-10 deg at wind speeds higher than the rated speed (11 m/s). The difference in the sdv characteristics between the NTM and the ETM case is relatively small. This indicates that independent of the turbulence of the wind, the flap angle continuously varies between the upper and lower bounds for wind speeds within the full load region.

In Figure 5 the sdv of the pitch motion is presented both for NTM and ETM conditions for the baseline turbine (without passive of active control for load alleviation), the pure IPC and the IPC+IFC designs. It is seen that the lifetime sdv of the pitch motion calculated with the following Weibull
parameters: C=11 m/s and k=2 increases by 70\% through pure IPC compared to the “baseline” design. When IFC is applied simultaneously with IPC, the lifetime sdv of the pitch motion increases by 15\% compared to the “baseline” case. So, a significant saving of the duty cycle of the pitch actuator is obtained with a penalty in torsion moment due to flap induced twisting moments.

**Figure 4:** Flap angle variation for combined use of IPC+IFC for wind speeds [5-25m/s] at normal wind conditions and [11-25m/s] at extreme wind conditions.

**Figure 5:** Pitch angle standard deviation (sdv) comparison for wind speeds [5-25m/s] at normal wind conditions and [11-25m/s] at extreme wind conditions, demonstrating the pitch duty cycle saving with the combined use of IPC+IFC.

**4. Conclusions**

Combined applications of different passive (through Aeroelastic Tailoring based on material and geometric BTC) and active (through IPC and IFC) load control techniques are assessed in the paper in terms of load reduction capabilities. A comparative analysis is performed for the DTU 10MW RWT through time domain aero-elastic simulations using NTUA’s in-house multibody, FEM, tool hGAST, under normal operation during power production in normal and extreme turbulence conditions. Application of BTC through offset of the plies of the UD material on the spar caps and/or blade sweep leads to a reduction of the blade root flapwise and tower base fore-aft lifetime fatigue loads by about 7\% and 4\% and ultimate loads by about 3\%-5\% and 1\%-3\% respectively. Material offset and blade sweep can be effectively combined seemingly giving an accumulative effect. The same load reduction achieved with a ply offset angle of 10\° can be also obtained when combining 5\° ply offset angle with 3m blade sweep at the tip of the blade. This indicates that both material and geometric BTC can be combined in order to achieve maximum possible load reduction levels but also confine key design parameters of the various methods within reasonable limits that by no means exceed manufacturing constraints.
Blade flapwise fatigue load reduction of about 25% is attained with both active control strategies tested in the present study (IPC and combined IPC+IFC). Overall, tower fatigue loads slightly increase by 2% because the proposed control loops have only been designed for alleviation of the blade loads while they are not aiming at tower loads. Minor is the effect on ultimate loads by both control concepts. As a result of the combined application of IPC and IFC a 7.4% reduction of the blade ultimate flapwise load is obtained. The combined application of IPC+IFC while it results in the same blade load reduction as IPC it considerably reduces pitch mechanism duty cycle measured based on pitch angle sdv. The increase in the lifetime sdv of the pitch motion is 70% through IPC, while it is reduced to 15% when combined IPC+IFC is considered.

Combined application of BTC (through 5° ply angle offset and 3m tip sweep) +IPC+IFC leads to an overall reduction of blade flapwise fatigue and ultimate loads by 30.5% and 10% respectively, while tower fore-aft fatigue (2.4% reduction) and ultimate (0.4% increase) loads are not significantly affected.

It is worth noting that sweeping of the blade and flap activity in IFC causes an increase in torsion DEL by about 50% and in torsion ultimate load by 93% and 39% respectively. Combined BTC+IPC+IFC torsion DEL increase is 71% and ultimate load increase is 104%.

On-going work aims to compare the different concepts at the level of developing stresses within the blade structure. The ultimate goal will be to optimize the blade structure and geometry for reduced cost, assuming constraints on stresses equal to those of the RWT blade. This can be done through an integrated optimization loop in which the best combination of control methods will be considered.

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