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Integration of prebend optimization in a holistic wind turbine design tool

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Abstract. This paper considers the problem of identifying the optimal combination of blade prebend, rotor cone angle and nacelle uptilt, within an integrated aero-structural design environment. Prebend is designed to reach maximum rotor area at rated conditions, while cone and uptilt are computed together with all other design variables to minimize the cost of energy. Constraints are added to the problem formulation in order to translate various design requirements. The proposed optimization approach is applied to a conceptual 10 MW offshore wind turbine, highlighting the benefits of an optimal combination of blade curvature, cone and uptilt angles.

1. Introduction

Optimization algorithms are emerging as powerful tools to design cost-minimizing onshore and offshore wind turbines [1, 2]. Recently, Bortolotti et al. presented an enhanced version of the design suite `Cp-Max` [3], a code that is able of simultaneously designing rotor, blade and tower of a wind turbine, accounting for the structural, aerodynamic and control aspects of the problem and their intimate couplings. The code has a high degree of automation and uses state-of-the-art models and procedures, including beams with arbitrarily curved shapes. However, the current implementation of the design methods does not consider prebend among the possible design variables. Therefore, blades are currently typically assumed as straight, and prebend is indirectly accounted for by an additional equivalent cone angle. This is not an entirely satisfactory approach because, when the maximum tip deflection is an active constraint of the design, the right amount of span-wise prebend could result in significant benefits originating from an increased tower clearance.

In this work, we discuss how to overcome this limit by embedding prebend in the integrated design framework of `Cp-Max`. The problem is non trivial, because prebend, cone and nacelle uptilt all contribute to blade-tower clearance. Although in principle they have different effects on other parameters, as rotor performance for example, it is clear that a naive implementation might result in an ill-posed optimization problem, given their competing and partially overlapping effects. To address this problem, prebend is here computed by maximizing the rotor area at rated conditions, as suggested by Bazilevs et al. [5]. The calculation of prebend is embedded in the overall wind turbine design, so that the best combination amongst all design variables can be computed.

2. Methodology

The architecture of `Cp-Max` consists of a nested optimization structure, which is sketched in Figure 1. The reader interested in the details of the formulation should refer to [3] and references therein. The outermost loop optimizes the macro parameters of the wind turbine, such as rotor diameter, hub height, cone and uptilt angles. The merit figure of this optimization process is the cost of energy (CoE), which is calculated from high fidelity cost models [3]. For each perturbation of the macro-parameters, a pattern of several inner loops is performed, in order to carry out the design of specific subsystems of the wind turbine. Each loop contributes to the overall merit function by feeding one or more parameters to the cost model. This way, the outer loop can actually monitor and control the whole underlying design process.
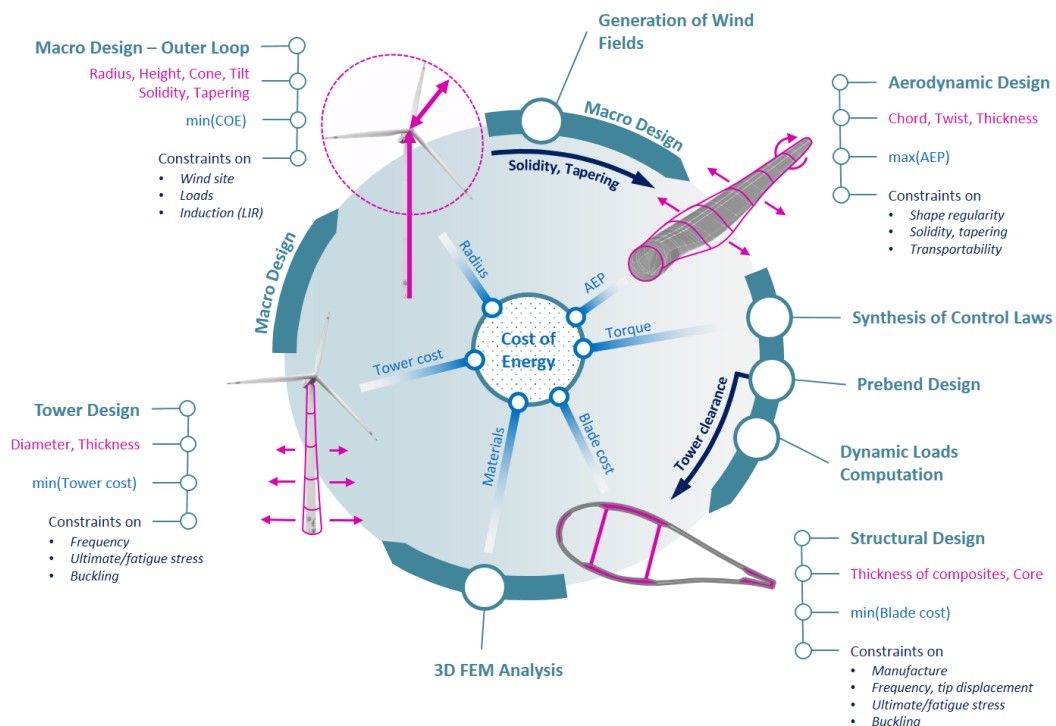

Figure 1: Description of the `Cp-Max` optimization framework.

As illustrated, after the necessary wind fields are generated for a specific radius and hub height, an inner aerodynamic design module identifies within the outer loop the blade aerodynamic shape producing the highest annual energy production (AEP) for a given set of aerostructural constraints. Then, an inner structural sub-loop sizes the structural components of blade and tower aiming at the minimization of initial capital cost (ICC) through the minimization of blade and tower costs. This problem is solved while respecting constraints that help to fully characterize the problem, and which account for sectional stresses, strains, fatigue damage, limits on eigen-frequencies, minimum blade-tower clearance, manufacturing and technological constraints, etc., based on need. Within this overall procedure, a model-based controller is tuned whenever the design changes, so that dynamic simulations of the wind turbine always produce coherent load conditions. In this framework, the prebend optimization module is placed just prior to the structural loop, after the computation of the power coefficient C_P vs. tip speed ratio (TSR) static performance curves, and before simulating the desired design load conditions (DLCs).

It must be noticed that each individual module, including the outer macro loop, can be

Table 1: Design variables.

Outer module	Inner module	Design variable	DOFs
Macro design		Tilt angle	1
		Cone angle	1
	Prebend design	Prebend shape	8
	Structural design	Thickness (composites)	71

Table 2: Design constraints.

Outer module	Inner module	Constraint
Macro design		-
	Prebend design	Max local steepness
	Structural design	Max tip displacement
		Frequencies
		Fatigue
		Ultimate stress/strain

arbitrarily switched on or off depending on the complexity of the design scenario. Tables 1 and 2 summarize the design variables and constraints employed for this study. In particular, although implemented, neither the aerodynamic nor the tower designs were performed in the preliminary investigation reported in this work, since the focus is here limited on the relationship between tilt, cone and prebend.

The criterion beyond prebend design is that, for each new rotor configuration, the wind turbine rated conditions are determined and known from previous steps, and specifically from the computation of the control trajectory. Thus, the blade curvature that returns the maximum rotor area under a uniform wind field can be estimated. The necessary calculations are performed by using static aeroelastic analyses of the complete wind turbine model, where the rotor is loaded under the aerodynamic and centrifugal forces corresponding to the rated operational point. Static simulations are preferred over dynamic ones because of their reduced computational effort.

The optimal prebend is computed by iteratively minimizing the out-of-plane blade deflection, as illustrated in Figure 2(a). The resulting ideal curvature of the undeformed blade is the one that corresponds to a straight blade in the uptilted rotor plane under operational loads at rated conditions.

In order to limit the number of degrees of freedom required for describing the shape of the prebent blade, prebend curvature is modeled by means of a Bezier curve of arbitrary degree, so that the locations of the control points are the actual unknowns of the optimization subloop. Figure 2(b) shows, as a way of example, a blade shape described by a third-order curve. A list of constraints is also optionally included in the problem formulation. This may include various design, manufacturing, transportation and geometric requirements, including maximum prebend, maximum steepness and shape regularity. This is an important feature of the prebend design module, mainly because current cost models are not able to account properly for manufacturing and transportation costs associated to a prebent shape. Hence, a balanced set of constraints can be useful to more correctly account for the various effects of a certain prebend. The proposed algorithmic architecture aims at identifying the wind turbine rotor design achieving the best trade-off among all requirements as expressed by the CoE, while satisfying all constraints. Within the loop, the structural layout of the blade is recursively optimized by the structural module of `Cp-Max`, which ensures that each solution is actually an ICC-minimizing one.
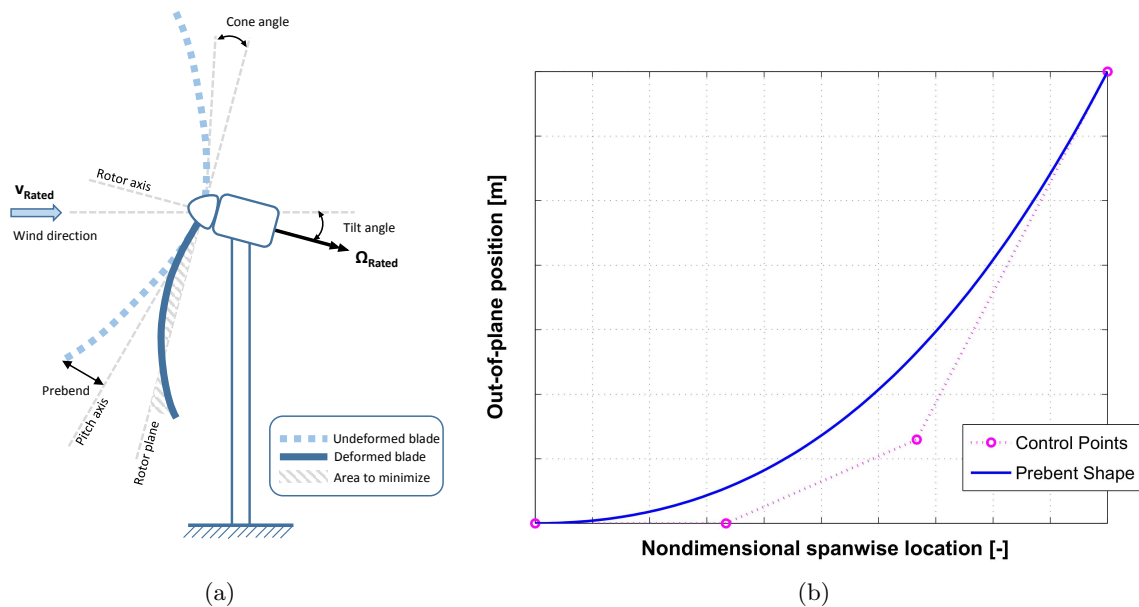
Figure 2: Definition of the prebend optimization problem (left) and description of prebent shape by Bezier polynomials (right).

It must be noticed that an alternative to the discussed area-maximizing criterion could have been the inclusion of the prebend parameters to the set of macro design variables. In fact, this would have created a direct feedback between the prebend design and the overall cost of energy. However, this form of the algorithm would result in higher computational costs with respect to the method implemented here, given that the whole design pattern would have to be repeated for each variation of the macro variables.

3. Results

3.1. Design of a 3.4 MW wind turbine

The proposed formulation is first used to design a 3.4 MW wind turbine, developed in the context of the IEA Task 37 [3, 6]. A set of DLCs based on the IEC guidelines [4] is reported in Table 3 and is considered for the dynamic loads computation. A comparison is established between the initial design with straight blades and the new optimum, found by including predend among the optimization variables. The macro parameters of the two designs are listed in Table 4.

Table 3: List of DLCs considered in the design.

DLC	Condition	Wind	Faults
1.1	Power production	NTM	-
1.3	Power production	ETM	-
2.1	Power production plus fault	NTM	Grid loss
2.3	Power production plus fault	EOG	Grid loss
6.1	Parked, idling	EWM (50 yr)	-
6.2	Parked, idling	EWM (50 yr)	Grid loss
6.3	Parked, idling	EWM (1 yr)	-

Figures 3(a) and 3(b) show, respectively, the optimal distribution of prebend and a comparison of some representative load metrics for the two cases. For this blade, a 6th order

Table 4: Main design results for the 3.4 MW wind turbine.

3.4 MW wind turbine	Straight	Prebent	Variation
Nacelle uptilt angle [deg]	6.00	4.84	-19.3 %
Rotor cone angle [deg]	4.00	2.02	-49.5 %
Prebend at blade tip [m]	0.00	3.55	-
Blade to tower clearance [m]	11.70	12.00	+2.5 %
Max tip displacement [m]	8.22	8.62	+4.9 %
Blade mass [kg]	13143	12880	-2.0 %
Blade cost [k$]	104.30	103.70	-0.6 %
AEP [GWh/yr]	14.58	14.64	+0.4 %
CoE [$/MWh]	39.67	39.51	-0.4 %

Bézier curve is used to allow for an accurate modeling of the curvature. In terms of constraints, only a loose requirement on the maximum steepness of the prebend is enforced, with the goal of guiding the solution in the vicinity of the blade root and tip. No specific constraint is on the other hand set on the maximum prebend at the tip, nor on the sign of the curvature. It is interesting to observe that the optimal prebend shape features a wide region where the blade is on the downwind side of the rotor disk. This is indeed a consequence of the geometric formulation shown in Fig. 2(a), in which the minimization of the distance from the uptilted rotor plane forces the shape of the blade to bend backwards where structural displacements are low, namely in the vicinity of the root region.
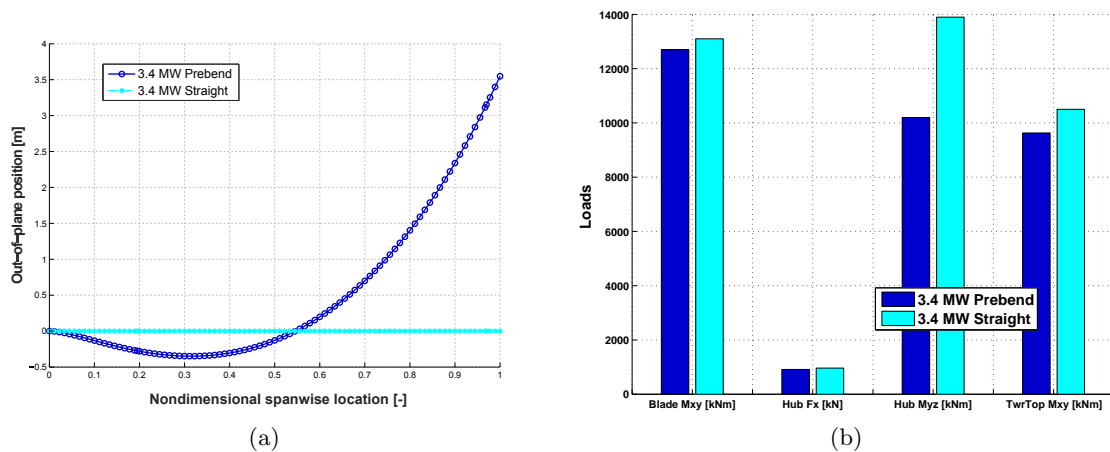

Figure 3: Optimal prebend (left, axes not to scale) and some key loads (right) for the 3.4 MW wind turbine.

As illustrated in Table 4, the main effect of the introduction of the prebend curvature among the optimization variables is a drastic reduction in cone and uptilt angles. Indeed, prebend curvature is more aerodynamically efficient than these two angles, and a new aerostructural tradeoff emerges for the rotor design. The rotor equipped with prebent blades shows a higher blade-tower clearance, which was previously an active constraint, together with a slight increase in AEP equal to 0.4%. The higher clearance also allows for small blade mass savings, equal to 2%. Finally, loads are reduced at blade root as well at the hub, as reported by Fig. 3(b). Overall, CoE savings equal to 0.4% are achieved thanks to the introduction of blade prebend curvature within the optimization space.

3.2. Design of a 10 MW wind turbine

The same approach is then repeated on a conceptual 10 MW wind turbine [8], again focusing on a comparison between blades with and without prebend. The same list of DLCs reported in Table 3 is considered, and Fig. 4(a) shows the optimal prebend distribution found for this rotor, while Table 5 summarizes the results in terms of wind turbine configuration.

The solution of the 10 MW turbine is different from the 3.4 MW case. The modeling and optimization of prebend curvature causes indeed again a reduction of the tilt angle. However, in this second case the optimal cone remains unchanged. At the same time, the blade/tower clearance is now increased ($+36\%$), which in turn allows for a significant reduction in terms of blade mass (-11.3%) and blade cost (-4.8%). Figure 5(b) shows a comparison of the distributions of the thickness of the spar caps and of the blade deflections under rated loads between the initial and final designs. Results again indicate that reductions are possible in terms of loads for the prebent blade compared to the straight optimal one. As illustrated in Fig. 4(b), loads at the blade root and tower top are generally reduced, while the hub combined and tower base moments are slightly increased. All differences are however limited, namely in the range of $\pm 6\%$.

Table 5: Main design results for the 10 MW wind turbine.

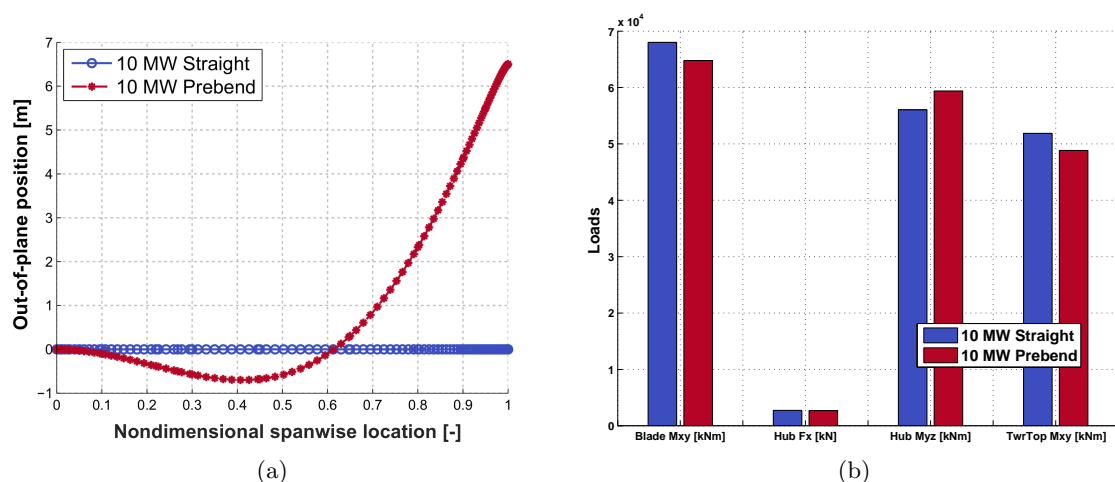| 10 MW wind turbine	Straight	Prebent	Variation
Nacelle uptilt angle [deg]	4.90	4.20	-14.2 %
Rotor cone angle [deg]	2.50	2.50	0.0 %
Prebend at blade tip [m]	0.00	6.50	-
Blade to tower clearance [m]	14.80	20.20	+36.5 %
Max tip displacement [m]	10.40	14.40	+38.5 %
Blade mass [kg]	45324	40782	-10.0 %
Blade cost [k€]	316.40	301.10	-4.8 %
AEP [GWh/yr]	48.98	49.09	+0.6 %
CoE [€/MWh]	69.94	69.70	-0.3 %

Figure 4: Prebend (left, axes not to scale) and some key loads (right) for the 10 MW wind turbine.

The different behavior of the optimizer between the two cases can be explained from the different effect of the constraint enforcing the first flapwise blade frequency to be higher than

the 3P. This constraint is an active design driver in the 3.4 MW rotor, while it is not for the 10 MW one. For the latter case, the introduction of prebend curvature allows for a growth in blade-tower clearance without incurring in excessive losses of aerodynamic performance. In turn, this results in a net gain in aerostructural efficiency.
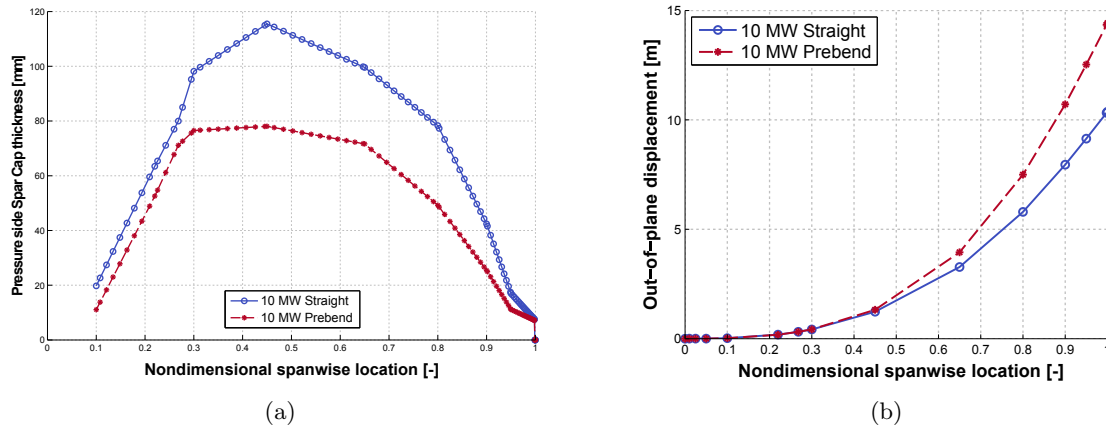

Figure 5: Spar cap design (left) and maximum tip displacement (right) for the 10 MW wind turbine.

4. Conclusions

This paper has presented a way of including the optimization of blade prebend curvature within a multi-disciplinary wind turbine design algorithm. Aim of the new procedure is to identify the optimal undeformed flapwise blade shape that results in the maximum rotor swept area under rated operating conditions. This problem is integrated with the optimization of cone and uptilt angles to study the influence of prebend curvature on these two other important design parameters.

Two applications are presented, and results confirm that introducing the effects of prebend within a detailed design procedure significantly modifies the optimum aerostructural turbine rotor design configuration.

It is finally worth noticing that the optimized shape of the prebend blade is in both cases a consequence of an only mildly constrained optimization. Future applications should consider the effects of additional requirements, as for example transportability and/or manufacturing, and define a set of geometric constraints accordingly. All these constraints are straightforwardly handled within the proposed methodology. In addition, it should be noted that the two studies reported here have been performed adopting a simplified set of DLCs. A more thorough assessment of the dynamic response of the blade is now ongoing, in order to verify the design in a wider spectrum of operational conditions. Future developments will also consider the extension of the procedures by including the description of blade sweep, in order to optimize passive load alleviation configurations.

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