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A novel adaptive blade concept for large-scale wind turbines. Part I: Aeroelastic behaviour

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ABSTRACT

This two-part paper introduces a novel aeroelastic approach to the design of large-scale wind turbine blades. By suitably tailoring the blade's elastic response to aerodynamic pressure, the turbine's Annual Energy Production is shown to increase, while simultaneously alleviating extreme loading conditions due to gusts. In Part I, we use a current blade as the baseline for an aerodynamic analysis aimed at maximising the turbine's yielded power. These results are then used to identify ideal aeroelastic behaviour. In Part II, we exploit material and structural bend-twist couplings in the main spar to induce appropriate differential blade twist, section by section, while bending flap-wise.

1. Introduction and rationale

In recent years, the cost of energy produced by alternative supplies has steadily decreased. This, together with several other socio-economical reasons, has made alternative energies increasingly competitive and, hence, a viable alternative to more traditional sources such as carbon, oil or nuclear power [1–6].

This trend is confirmed by industry growth figures. The wind energy industry, in particular, has grown and is predicted to grow steadily, both in terms of investments and installed capacity [7].

From an engineering perspective, the growth in this sector raises some interesting challenges as it creates the drive to build larger, more durable rotors that produce more energy, in a cheaper, more cost efficient way [8,9]. The rationale for moving towards larger rotors is that, with current designs, the power generated by wind turbines is theoretically proportional to the square of the blade length [9]. Furthermore, taller wind turbines operate at higher altitudes and, on average, at greater wind speeds. Hence, in general, a single rotor can produce more energy than two rotors with half the area.

Having said this, larger blades are heavier, more expensive and increasingly prone to greater aerodynamic and inertial forces. In fact, it has been shown that they exhibit a cubic relationship between length and mass [9], meaning that material costs, inertial and self-weight effects grow faster that the energy output as the blade size increases (see Fig. 1).

In this scenario, the demand for improvements in blade design is evident. The notion of increasingly mass efficient turbines, which are also able to harvest more energy, is indeed immediately attractive. The aim and rationale of our effort are set out in the next section while the current state-of-the-art is discussed in Section 1.2.

1.1. Design drivers and aim of the work

The power curve of a modern variable-speed wind turbine is typically characterised by distinctive operating conditions. These are the cut-in, rated and cut-out wind speeds and are shown in Fig. 2. Wind speeds above and below rated correspond to different operating regimes, in which the aerodynamic couple acting on the rotor and its angular speed are controlled to meet specific requirements. Below rated speed they can increase to maximise the yielded power, as the components of the turbine do not operate at their structural limit. Conversely, above rated, the angular speed and the couple are generally set by structural integrity reasons (e.g. limited fatigue loads).

In summary, a wind turbine blade is designed to maximise its aerodynamic performances below rated speed and to withstand extreme loads above it. This work presents a novel adaptive blade concept that, for the first time to the authors' knowledge, satisfies both these design drivers, exploiting aeroelastic tailoring principles to improve the performance of current blades.

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Nomenclature

a	dimensionless induced flow speed (induced speed divided by undisturbed wind speed)
α	angle of attack
α_{opt}	angle of attack that maximises the component T of the aerodynamic force
C_D	drag coefficient
C_L	lift coefficient
c	chord of the airfoil
D	drag force
Δr_j	spanwise width of blade element j
F	aerodynamic force resultant
f_{hub}	hub loss factor
f_{tip}	tip loss factor
L	lift force
N	aerodynamic force normal to the rotor plane
N_{blades}	number of blades in the rotor
N_{el}	number of blade elements in the aerodynamic mesh
ω	angular speed of the rotor
ϕ	inflow angle
R	rotor's radius
r	radial coordinate in the rotor plane
r_{hub}	radial coordinate of the hub section
r_{tip}	radial coordinate of the tip section
ρ	air density
T	aerodynamic force tangential to the rotor plane and perpendicular to the radial direction
θ	geometric twist of a blade's section
θ_{opt}	geometric twist of a blade's section that maximises T
V_0	undisturbed wind speed
V_1	resultant flow speed at a blade's section.

In particular, by suitably tailoring the blade's elastic response to aerodynamic pressure, the turbine's Annual Energy Production (AEP) is shown to increase, while also alleviating extreme loading conditions due to gusts. This is done by purposefully designing bend-twist coupling into the main spar, so as to have the blade sections twist appropriately while bending flap-wise. Specifically, the angles of attack of the blade's aerodynamic sections are designed to adapt to different wind speeds in order to maximize energy harvesting and gust load alleviation, respectively, below and above rated conditions.

1.2. Background

Owing to the increased mass and loads associated with larger wind turbine blades, prior research has focused on reducing either weight or aerodynamic forces.

For instance, Refs. [11–14] performed structural optimisations aimed at minimising the mass of some, or all, of the turbine's components. Other authors [15–20] looked at the possibility of alleviating extreme aerodynamic loads (i.e. gust loads), in order to relax prevailing design constraints by passive adaptive concepts. Similarly, Refs. [21,22] considered flexible and morphing airfoil sections as a means for load alleviation and improved energy production, respectively.

Here, we only report on studies in which load alleviation is obtained in a passive adaptive manner, i.e. by exploiting the capabilities that structural anisotropy and geometrically induced couplings provide. For example, Refs. [15–20] designed the main spar's torsional and bend-twist stiffnesses to induce a rotation towards feather (nose-down) of the blade's sections, thereby reducing the angles of attacks (AOA) and, consequently, the aerodynamic forces acting on the profiles. For a given blade length, this approach provides benefits, but has proven to be detrimental in terms of Annual Energy Production (AEP) [18]. Indeed, on the one hand, alleviating the gust-induced loads above rated wind speed damps the power oscillations, the structural vibrations and allows the reduction of the ultimate design load due to the *50 year gust*. On the other hand, below rated speed, i.e. when the system does not operate at its design limit and power maximisation is the main goal, the same working principle causes a power loss. It must be noted, by allowing the blade length to increase, the power loss can be overcome at the expense of the benefits to the load. At the limit, in which the adaptive and classic designs have the same ultimate load, the power yielded by the former is greater.

In all of the aforementioned studies the elastically induced twist has a monotonic distribution that increases along the length of the blade, running from root to tip. The required coupling is achieved by using unbalanced composite laminates in some cases [16–18], or with swept blades in some others [15,19,20].

Some researchers also explored the opportunity of towards stall bend-induced twist (nose-up). A notable example is given by Ref. [23]. In this case, stiffness coupling causes a decrease of the sections' twist, which is more pronounced traversing from the blade's root to tip. Strictly speaking, this work was concerned with constant speed wind turbines, but its conclusions can be generalized: such a solution, despite enhancing the AEP, gives a notable increase of gust-induced and fatigue loads.

To conclude, it is noted that an adaptive blade that improves both yielded power and extreme loads requirements has not yet

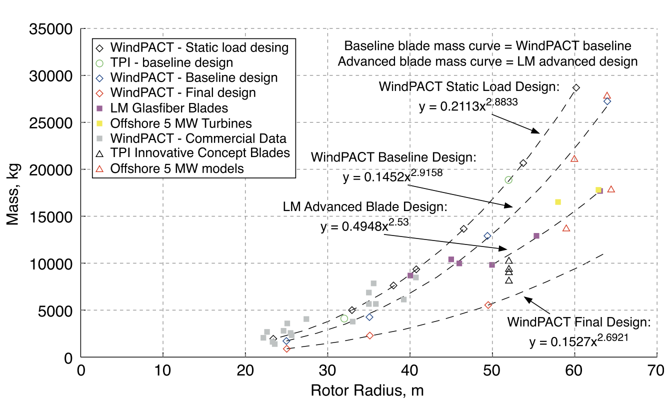

Fig. 1. Blade mass vs. rotor radius. Adapted from Ref. [10].

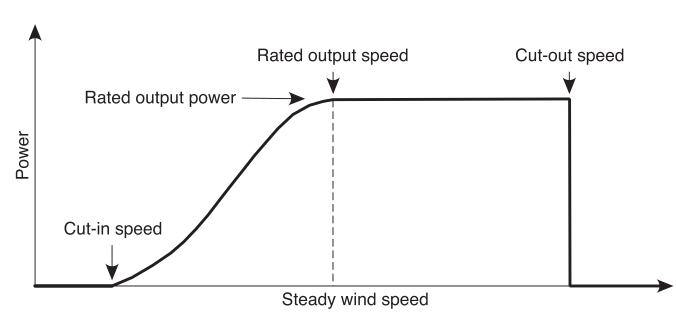

Fig. 2. Typical trend for the power curve of a pitch controlled wind turbine.