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A novel adaptive blade concept for large-scale wind turbines. Part II: Structural design and power performance

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ABSTRACT

This two-part body of work considers wind turbines that increase annual energy production on account of an enhanced aeroelastic behaviour. In Part I, an aerodynamic analysis was performed to identify the theoretically ideal aeroelastic response of a reference blade. By so doing, the distributions of twist that maximise the power yielded at different wind speeds were obtained. Then, noting that the total twist is the sum of pre-twist, elastically-induced twist and pitch angle, a distribution of elastic twist was identified, that adaptively varies the blade's total twist to align with the ideal aeroelastic response, while also providing gust load alleviation capability. In Part II, the required elastically-induced twist is analysed from a structural point of view and adapted accordingly. In addition, a blade concept that realises the desired adaptive behaviour is proposed and the increase of power harvested is assessed by a provisional structural design.

1. Introduction

This two-part article presents a novel concept for a shape-adaptive wind turbine blade. The shape change is enabled by a passive, elastically-induced, twist that adjusts the blade's aerodynamics at different operating conditions, thereby enhancing the power yielded by the turbine and simultaneously favouring gust load alleviation. The reader is referred to Part I for a detailed derivation of the aerodynamic requirements for the proposed concept. The shape adaptation is obtained by designing structural bend-twist coupling into the blade and harnessing the variation of bending load between individual wind speeds. This structural design, and in particular tailoring the blade's bend-twist stiffness so as to embed the desired passive shape change into the structure, is the subject of Part II of this work.

In this study, two types of bend-twist coupling are exploited as a means to expand the aeroelastic tailoring options: geometric coupling and material coupling, obtained respectively by curving the blade's planform and building unbalanced composite laminates into the structure. Since the degree of bend-twist coupling is required to vary along the blade's length, tow steered laminates are considered and are a novel feature. Indeed, by means of tow steering [1], the angle between the laminates' fibres and the blade's axis can be changed spanwise, which, importantly for us, allows the bend-induced twist rate to also vary spanwise.

The remainder of Part II of this article is structured as follows. The next section describes a structural design that embodies the desired twist distribution (identified in Part I, Section 5). It is worth noting that, at this stage of the analysis, the blade's structural behaviour is idealised. Indeed, only the box-spar contributes to the flexural behaviour, itself a fairly common practise during the first design phases of WT (wind turbine) blades.

In Section 3 a demonstrative case study is proposed. Specifically, a realistic-type spar structure is designed to meet the targeted adaptive capability and also fit within an existing reference blade (i.e. aerodynamic envelope, see Part I). The power performance of this blade is assessed and compared against conventional blade designs.

Section 4 concludes this article by discussing achievements as well as limitations and pointers for future work.

2. Structural design

Before going into the details of the blade's structural design, it is convenient to recall some of the concepts introduced in Part I, both for the sake of clarity and of completeness of exposition.

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Therein, *optimum twist* curves were derived from an optimisation study on the sections' twist distributions for power maximisation at different wind speeds. These curves, however, are not viable, because they cannot be obtained by passive structural behaviour. Instead, *target distributions*—as shown in Fig. 1—were introduced as a practical alternative. Target and optimum curves differ when a nose-up rotation of the blade's sections is required to maintain maximum power production (please refer to Part I for details). In principle then, target distributions require only nose-down elastic twist to be added to the initial pre-twist, in order to align when the wind speed increases.

Lastly, *target distributions of elastic twist* were identified by considering the difference between individual target curves and imposing structural constraints, such as the clamped condition for the blade root.

The generic shape of the targeted elastic twist distribution is indicated in Fig. 2, where positive numbers correspond to a nose-down rotation of the section. Specifically, the figure depicts the distribution prescribed at rated wind speed. However, the curves at other operating conditions retain the same qualitative features: they increase, traversing from root towards a position close to the blade's mid-point, and then decrease towards the tip. To be precise, it is noted that an increasing–decreasing contribution of elastic twist allows the target curves to be matched only on the outer half of the blade. For further details and implications the reader is referred to Section 5.2 of Part I.

2.1. Structural concept and constraints

Bearing the above mentioned concepts in mind, it is now possible to introduce a structural design that realises the sought aeroelastic behaviour. As an alternative solution to that offered by previous researchers [2–7], who investigated the effects of imposing a monotonic nose-down elastic twist, in this work bend-twist coupling is tailored to induce an elastic twist distribution, that, not only varies radially (spanwise), but also changes the sign of its gradient.

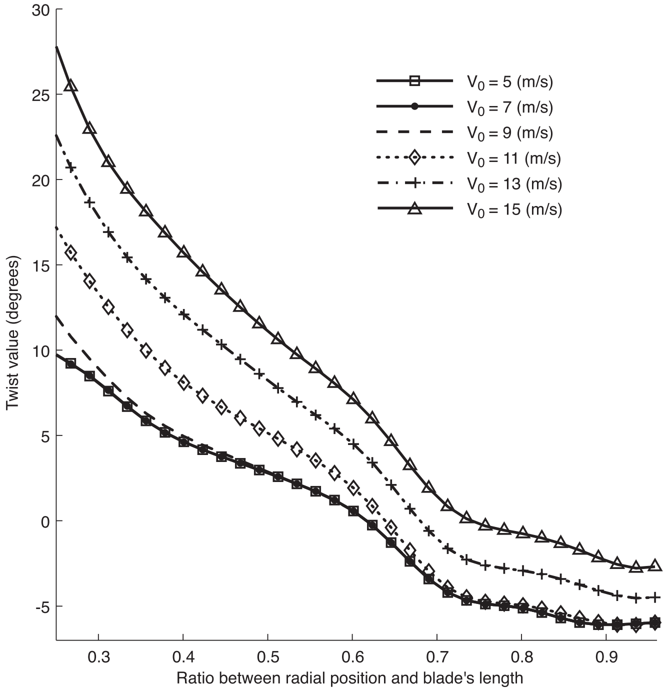

Fig. 1. Target twist distributions along the blade's axis, for fixed wind speeds.

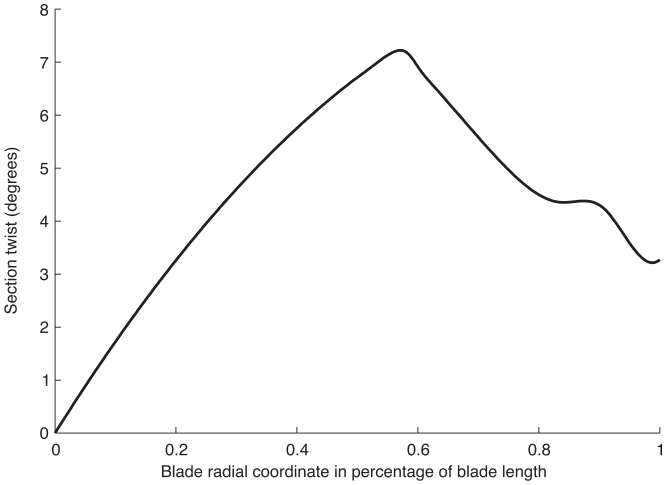

Fig. 2. Adaptive spar's induced twist distribution relative to the aerodynamic load at rated wind speed.

Structurally, this is done by merging material and geometric bend-twist coupling. The former is built into the structure by means of anisotropic composite materials. The latter is achieved by exploiting the properties of a curved beam. Specifically, unbalanced laminates, with plies at an angle from the blade's axis, are used in the spar caps to couple bending and twisting deformations. Similarly, a curved spar planform is used to harness the bend-twist coupling arising from the off-set among the shear centres of the different sections.

For the purpose of illustration, Fig. 3 shows a sketch of a blade with these two design features.

It is worth noting that the fibre paths shown in the figure are identical in both the bottom and upper caps. The underlying structural principle for shape adaptation uses the nose-down bend-twist coupling of a curved planform (swept backward) to then reduce it by suitably skewing the fibre angle in the outer half of the blade. In particular, if the fibre direction in the outer half of the blade is skewed backwards, the induced twist reduces running towards the blade tip. This fibre orientation, indeed, provides a local nose-up bend-twist coupling, which enables the inversion of the twist rate. Furthermore, by skewing forward the fibre angle in the inner half of the blade, the maximum induced twist increases, because this creates a nose down bend-twist coupling that locally enhances the coupling due to a swept planform.

To make sure that the proposed adaptive concept is also practical, stiffness and geometric constraints are applied during the design process. For example, the flap-wise displacement of the blade tip at rated wind speed is constrained to be less than 12% of the rotor's radius. This constraint excludes solutions excessively compliant in out-of-plane bending. In addition, the distance between points on the curved axis and the corresponding points on

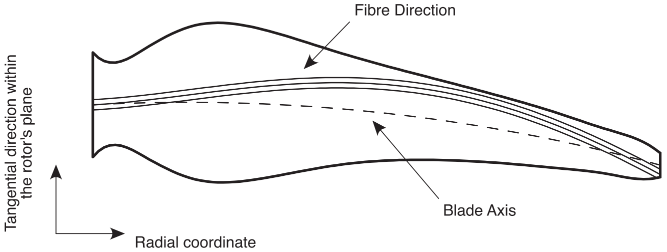

Fig. 3. Schematic fibre path over the curved blade planform. Not to scale.