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The adaptive-blade concept in wind-power applications

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ABSTRACT

One of the technological challenges in wind power is the development of a next generation of feasible upscaled turbines of cheaper construction that may further reduce generation costs. But limitations in the current blade technology constitute a technological barrier that needs to be overcome. As the size of the typical turbine increases, savings in weight and complexity in the rotor design and its auxiliary mechanisms, like the pitch-control actuators, become more important. The notion of *smart* or *intelligent* advanced blades that can control themselves and reduce (or completely eliminate) the need of an active control system is a very attractive prospect for future developments in blade technology.

The idea of wind turbine rotors which automatically adapt to the meteorological and working conditions is not entirely new. It has been around for the last two or three decades, and several control systems have been proposed to achieve this goal using either a purely-passive or a combination of active-passive means. Blade *adaptiveness* can be achieved by means of inducing coupling among modes of deformation of the blade which are usually only slightly coupled. For instance, coupling between bending and twisting can be used to control power production, to reduce vibration and extreme loads, and to improve fatigue performance. In this case, as aerodynamic loads begin to bend the blade, flexo-torsional modes induce a twist. This changes the angle of attack on the airfoil sections, reducing the lift force acting on the blade.

In this paper, we are going to review different aspects of the adaptive-blade concept development, covering a historical overview, recent advances, and future trends.

Introduction

A systematic trend in the wind turbine industry for the last 30 years has been to scale up the size of turbines, to increase energy capture by a single machine and thereby bring down cost of generation by economies-of-scale factors. Current state of the art turbines can have a power output of up to 6 MW with rotor diameters in excess of 120 m. There has already been talking among industry insiders of a next-generation of offshore giants ranging from 7.5 MW to 12 MW with rotor diameters up to 200 m UpWind project, (2010).

However, the industry faces huge technological challenges to keep the overall cost of generation down by upscaling. Blade manufacturing, involving a complex lay-up of composite laminates, is a labor intensive process requiring highly skilled workers and this would act as a bottleneck for increasing rotor diameters. As can be seen in Fig. 1, a compilation of data by NREL-DOE (2005) on the proportional cost of each subsystem, the share of rotor in the overall cost increases with the rotor size.

As the size of the turbines increases, savings in weight and complexity in the rotor design, and its auxiliary mechanisms, like the pitch-control actuators, become more important. The notion of *smart* or *intelligent* advanced prototype blades that can control themselves and reduce (or completely eliminate) the need of an active control system is a very attractive prospect for future developments in blade technology. The idea of wind turbine rotors which automatically adapt to the meteorological and working conditions is not entirely new. It has been around for the last two or three decades, and several control systems have been proposed to achieve this goal using either a purely passive or a combination of active-passive means (see (Karaolis et al., 1988; Corbet and Morgan, 1992; Kooijman, 1996; Griffin, 2002b; Locke and Contreras Hidalgo, 2002; NREL, 2008), among others).

The complex geometry and internal structure of blades often induce some form of coupling between various deformation modes. These coupled modes can be tailored to design *Adaptive* (sometimes also referred to as *Smart*) blades. The analysis of coupled modes in aeroelastic problems has long been studied while designing aircraft wings, since such couplings could be potentially dangerous if not properly accounted for at design stage. However, as it was mentioned above, this aeroelastic effect is now being used to help develop adaptive blades by increasing the coupling among the modes of deformation of the blade which are usually only slightly coupled. For instance, coupling between bending and twisting can be used to control power production, to reduce vibration and extreme loads, and to improve fatigue performance. In this

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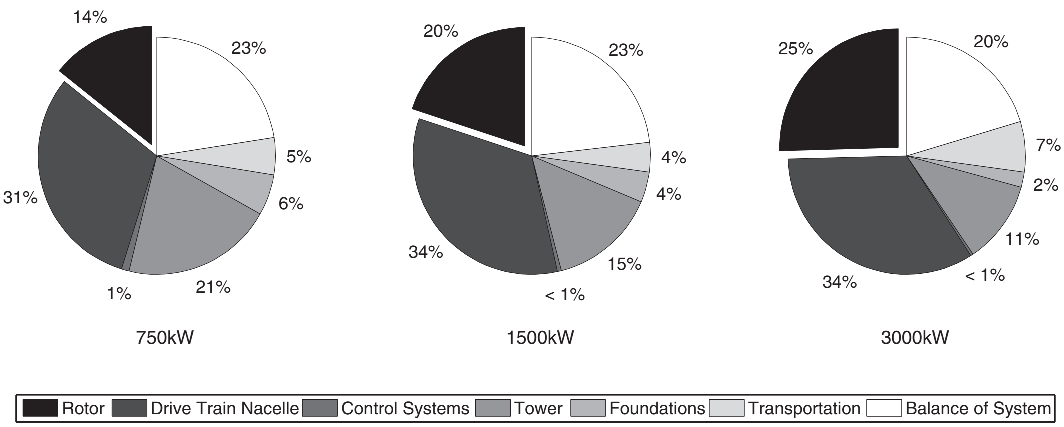

Fig. 1. Evolution of the proportional cost for the different wind-turbine subsystems, as size increases (data compilation from (NREL, 2005)).

case, as aerodynamic loads begin to bend the blade, flexo-torsional modes induce a twist. This changes the angle of attack on the airfoil sections, reducing the lift force acting on the blade.

The desired effects of coupled deformations can be achieved either by structural or by geometrical changes in the blade design. What could be called *Structural Adaptiveness* involves modifying the internal layout of the blade structure, the anisotropy of the structural material, the material distribution, and its fiber orientation (Locke and Contreras Hidalgo, 2002). *Geometrical Adaptiveness* involves redesigning blade geometry by giving it a curved shape to achieve bend-twist coupling NREL (2008). Various combinations of these techniques can be used to fine tune the deformations and achieve the required controlling effect.

In this paper, we are going to review different aspects of the adaptive-blade concept development, covering a historical overview, recent advances, and future trends.

Morphing wings and sails: early examples of adaptiveness

Aerodynamic surfaces that change their shape in order to control the forces acting on them are sometimes referred to as *morphing wings*. This notion has been used intuitively by birds for millions of years. By changing the camber of their wings, birds may alter the lift coefficient of their wings according to the situation. This bio-inspired mechanism has been suggested as a way to control the lifting surfaces of airplanes and unmanned air vehicles, and could easily be adopted for use in wind turbine blades.

In terms of human usage of wind as a source of energy, sail propulsion constitutes the earliest and longer-lasting example of wind power. Actually, taking into account the accumulated use of sail power for commerce, war, fishing, and recreational navigation, we should not be surprised if the total amount of Jules generated by sales since ancient times surpass, by far, the Jules of electricity generated hitherto by all modern wind turbines installed in the world.

Curiously, since the very beginning of sailing, the notion of morphing wings, and even the notion of adaptiveness were present. Being flexible members, sails could be trimmed (especially in the hands of an experienced crew) into a very wide variety of shapes by playing with the tension, position, angle, and length of the lines on the ship's rig. There have been many types of rig built and operated along history, some of them allowing for more shape control than others. Among the most interesting examples, we may single out the operation of the main sail on the extremely-widespread *Marconi* (also called *Bermuda*) rig, which equips the great majority of the sail-boats on the water today (see Fig. 2).

In the Marconi rig, the main sail is a piece of fabric, approximately-triangular in shape, attached to the mast at the front side (called the luff), and attached to the boom at the bottom side (called the foot). The third side of the triangle (called the leech) remains stretched mostly by a combination of the weight of the boom and the downward projection of the force exerted by the line attached at the boom end (called the main-sheet). The main-sheet mostly controls the azimuthal position of the main sail, and so, the angle of incidence of the wind on the sail, but its downward pull also controls the leech tension, and so, the twist of the sail. When the wind is high, the downward pull of the main-sheet is increased in order to stretch the leach and flatten the sail as much as possible, reducing its curvature, and so the lift force preventing overpowering of the boat (see Fig. 3). This is a typical example of morphing wing in which the camber of the airfoil shape is adapted to the flow regime. But the same mechanism could be used to create some kind of adaptive twist control that may take care automatically of temporary overpowering by gusts. If the downward force on the main-sheet is reduced and the boom is allowed to swing up and down, every time that a gust hits the vessel, the boom is pulled up by the wind force. This decreases the tension on the leech and allows the upper section of the sail to twist to leeward, catching less wind and temporary reducing the power on the sail (sometimes called wind-spillage in the sailor's jargon). When the gust is over, the weight of the boom moves it down, returning the sail to its original shape. Here is an elegant example of power-control adaptiveness by variation of the twist of an

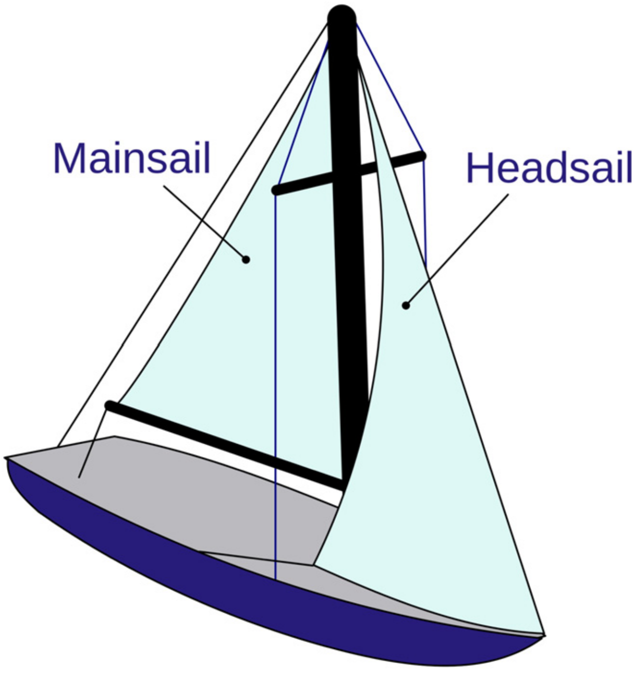

Fig. 2. Schematic of the basic layout of the Marconi rig (Murray).