

# 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.

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## 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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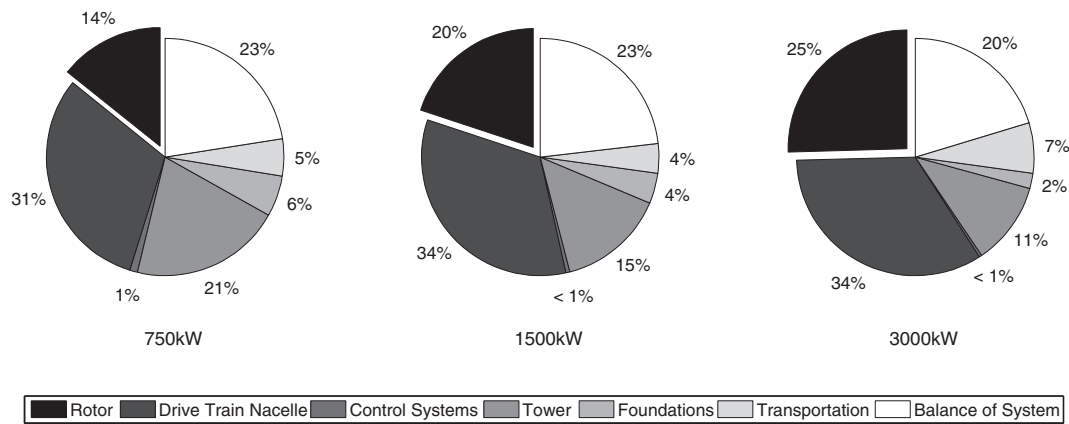


Fig. 1. Evolution of the proportional cost for the different wind-turbine subsystems, as size increases (data compilation from (NREL, 2005)).

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 leech 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

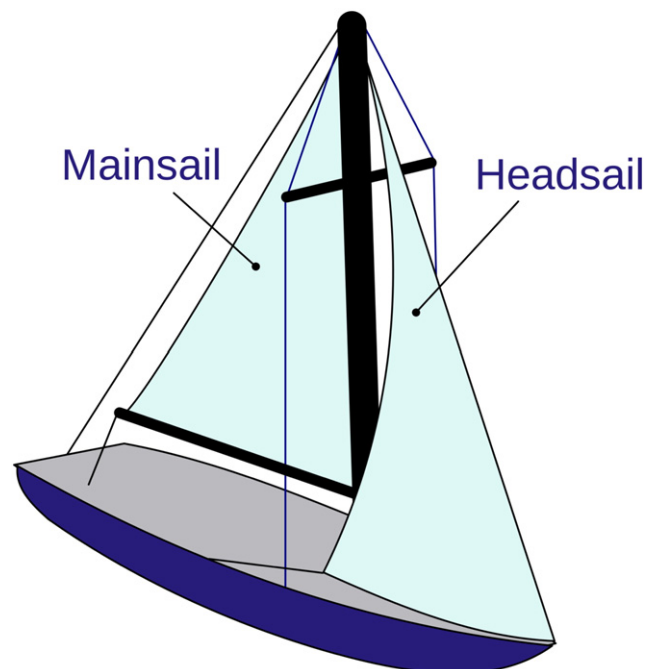


Fig. 2. Schematic of the basic layout of the Marconi rig (Murray).

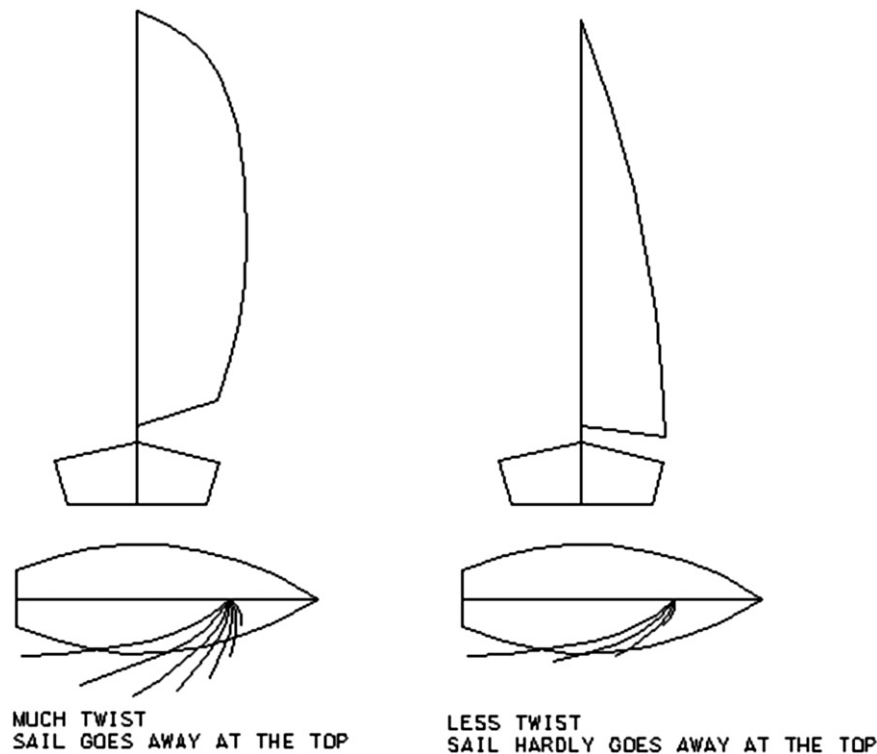


Fig. 3. Illustration of the change in shape of the mainsail by induced twist controlled by adjusting the tension on the leech (Geurts).

aerodynamic surface, where the gravitational pull on the boom replaces the elastic reaction of some structural member.

#### Passive pitch control: a form of mechanical adaptiveness

For many years, there has been a lot of interest in developing passive control of horizontal axis wind turbines through pitching of the turbine blades, by utilizing the inherent forces and moments acting on the rotor and, to a certain extent, this technique could be considered as a form of *mechanical adaptiveness*. Corbet and Morgan (1992) prepared a report dealing with such passive control. In the report they briefly talk about some of the turbines employing these control techniques. They use a mathematical model of a 2-bladed machine to examine and analyze the various passive control solutions systematically. In this approach each of the various forces acting on the blade is examined individually under the assumption that any complex passive control system can be simulated by a linear superposition of each individual solution. This numerical analysis is used to investigate various characteristics of the power control along with a study of the dynamic response of the passive control system and effects of the control system on structural loads. Some of the passively controlled turbines reviewed in the report are a two-bladed Northern Power System (NPS) 100 kW machine, four Dutch machines Berewoud from Delft Technical University, a 75 kW variable speed turbine from Lagerway, Flexhat and Flexcon and machines manufactured by Carter Wind Systems. Most of these machines use a combination of forces and moments to achieve the required power control and hence the systematic analysis dealing with each force separately is extremely useful to thoroughly assess these machines. The authors, however, have clearly stated that a lot of the information on these machines is not based entirely on documented data due to confidentiality, as also due to a lack of detailed records (Corbet and Morgan, 1992). Some of these control systems are discussed ahead to get an idea of passive control by pitching of wind turbine rotors.

The NPS 100 kW control system consisted of a passive hydraulic system controlling pitching of the entire blade span. A combination of blade thrust, aerodynamic pitching moment and an offset centrifugal

force was used to pitch the blades to feather. This can be achieved by moving the pitching axis upwind of the blade and offsetting the center of mass. An analysis of the same machine performed by Osgood and Hock (1988) suggested that the pitching moment decreased as the flapwise load decreased with increase in pitching angle. This is evident from Fig. 4 which shows a plot of the flapping loads against wind speed for different pitch angles. The controlling load restoring moment for such a system would require a negative spring rate to account for this decrease in pitching moment. However, it is not easy to follow such a non-linear profile exactly, therefore a constant restoring moment was used. As can be seen from Figs. 5 and 6, the NPS machine was unable to keep power constant. Fig. 6 is a plot for a mathematical model as discussed in the paragraph above, with flapping forces dominating to show the effect of using a linear restoring force. This is shown here keeping in mind that the NPS turbine predominantly used thrust loads to feather.

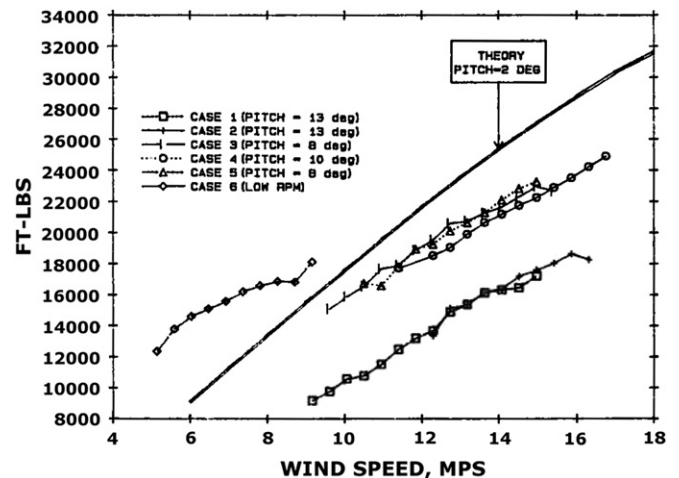


Fig. 4. Mean flapwise bending moment for an NPS 100 kW turbine blade against varying wind speed (Osgood and Hock, 1988).

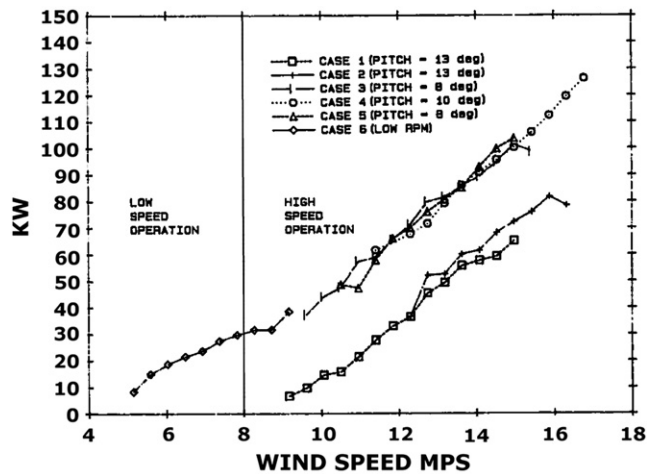


Fig. 5. Mean Power for an NPS 100 kW turbine blade against varying wind speed (Osgood and Hock, 1988).

Fig. 7 shows a layout of the Berewoud machine. This was a variable speed machine which used aerodynamic pitching moment to feather the blade. This was achieved by using an airfoil section with a high Coefficient of Pitching moment. The blades consisted of a flexible beam running through its center, giving it torsional as well as flapwise flexibility. Even though the power control satisfactory, the extreme flexibility caused severe elastic instability issues especially at low speeds, and hence these particular machines were not developed further (Corbet and Morgan, 1992). However, a similar concept was used in a Dutch project called the FLEXHAT programme. A beam element at the blade root provided only flapwise flexibility, unlike the Berewoud system where the torsional stiffness was also made low. This variable speed machine utilized the changing centrifugal load on a screw cylinder-spring arrangement to feather the blade tip. A primary reason for not resorting to a full span pitching is the large radial forces involved, possibly over 100 kN (Corbet and Morgan, 1992). A layout of this control system can be seen in Figs. 8 and 9.

Another variable speed machine similar in some aspects to the Berewoud system was a 75 kW Lagerway machine. It used a similar airfoil section as the Berewoud turbine for control by aerodynamic pitching. This machine also employed flapwise flexibility, but avoided instabilities by limiting this flexibility to a hinge and pitch bearings. Using aerodynamic pitching moment gives an extremely sensitive control influenced by minor errors in spring preload, friction, dirt, rain, insects etc. (Corbet and Morgan, 1992). The advantage in variable speed machines over fixed speed machines in such cases comes from the fact that the error is manifested in the rotor speed control and not in power control. This is easier to handle as long as over speeding can be

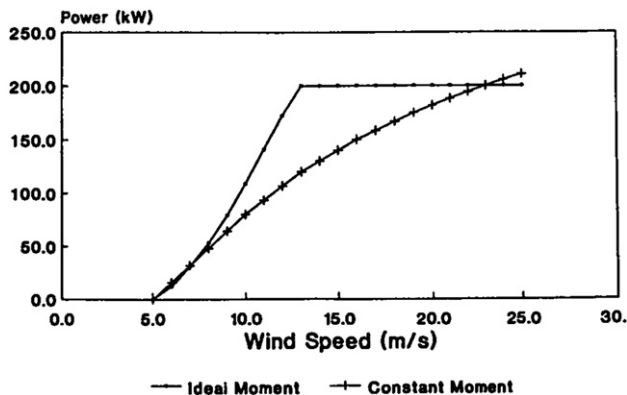


Fig. 6. Mean power vs varying wind speed for a modeled turbine with dominating flapwise forces undergoing positive pitching (Corbet and Morgan, 1991).

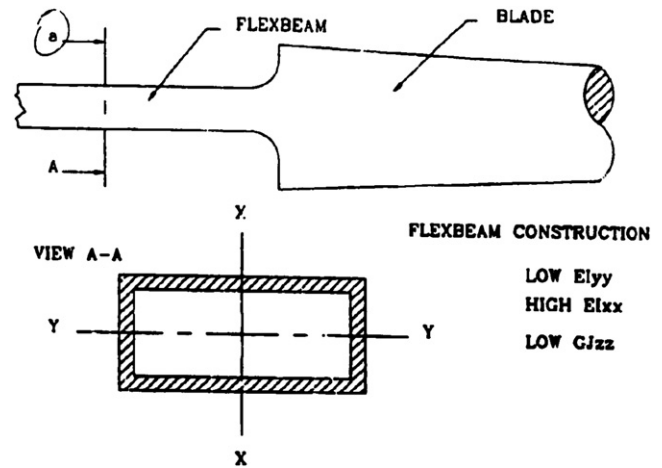


Fig. 7. Flex-beam construction of the Berewoud turbine (Corbet and Morgan, 1992).

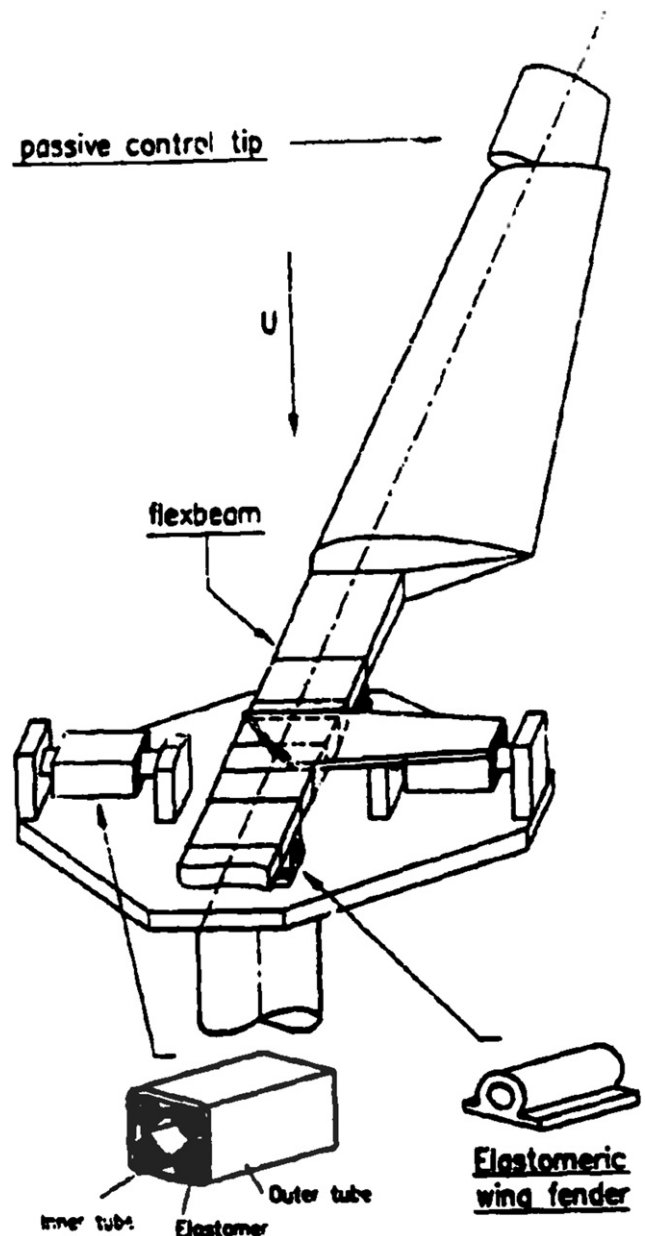


Fig. 8. Flex-beam design for the FLEXHAT project (Corbet and Morgan, 1992).



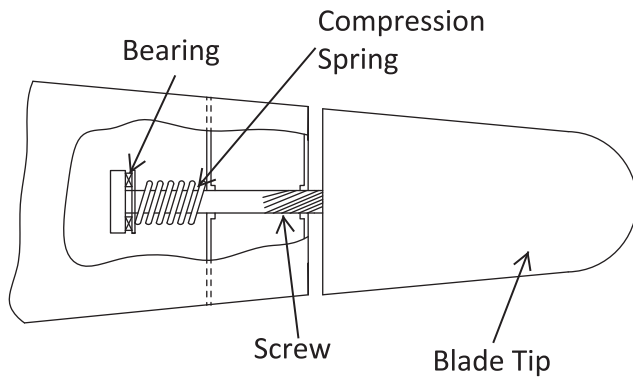


Fig. 9. FLEXHAT tip actuation mechanism. After (Burton et al., 2001).

avoided. An important aspect of these three variable speed machines was that the flexibility resulted in highly improved fatigue strength. However, they were supposed to be kept running even at very high wind speeds to allow stiffening of the flexible blades by centrifugal forces. The Lagerway machines showed a possible vulnerability to high thrust loads if brought to a standstill under severe winds. Since the flexibility was concentrated at the roots, with the blade itself not particularly flexible and flapping restricted by bump stops, a loss in centrifugal stiffening would introduce high thrust loads at the root. This was one of the reasons that a lot of such turbines including the FLEXHAT would be designed for extreme loads rather than fatigue limits (Corbet and Morgan, 1992). This could also be a point in favor of structural adaptive blades, on which the flexibility is distributed along the whole span instead of being concentrated at the roots.

The 10 m, 15 kW turbine developed by Flexcon was controlled by negative pitching, in other words, by pitch to stall. The pitching axis in this machine was positioned behind the aerodynamic center. This caused the aerodynamic thrust to pitch the blade in a nose up direction causing stall. This pitching action acted against a reducing restoring force provided by a cam and spring arrangement, possibly preventing dynamic instabilities common to stall controlled systems. The report presents an analysis of such an arrangement considering a case where out of plane forces dominate, giving an interesting insight into change in pitching moments with different pitching angles. It seems that the pitching moment required for maintaining a constant power was extremely complex and non-linear as seen in Fig. 10 (Corbet and Morgan, 1992).

As with Fig. 6, Fig. 10 is also based on the mathematical model mentioned previously, where the flapping forces dominate for a negative pitching configuration. The Flexcon machine however, used a linear approximation to this relation in the restoring moment mechanism. As in

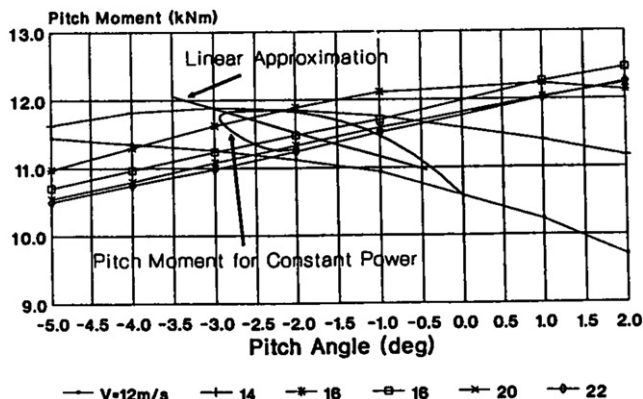


Fig. 10. Variation in pitching moment with increasing negative pitching (Corbet and Morgan, 1991).

the Lagerway turbines, the Flexcon machine also had flapwise flexibility at the root, and so had to be allowed to run at higher wind velocities.

Another stall controlled turbine was a 300 kW machine manufactured by Carter Wind Systems. This, however, was basically a fixed pitch machine, incorporating a large degree of torsional and flapping flexibility at the root. This led to a huge reduction in peak thrust loads, allowing for an extremely light and thereby cheap construction of the turbine (Corbet and Morgan, 1992). The torsional flexibility was kept at bay under normal operating conditions with the use of an electromagnetic clutch, which was released under overspeed conditions to stall the blade (Fig. 11). Since the blade was allowed extreme flapwise bending it worked well for both fatigue and extreme loads as long as tower strikes were avoided for upwind machines.

There are many other ingenious passive control techniques mostly as a combination of or improvement upon some of the solutions mentioned above. An important drawback of passive control systems as mentioned in the report is that the natural frequency cannot be increased beyond 3P (P being the Pth harmonic of blade passage frequency, in other words P is used to represent an integral multiple of the rotor's rotational frequency). This has mostly to do with the fact that the stiffness of the control system and the inertia of the pitching motion depend on the location of the pitch axis. This causes a peak in dynamic response of power and load characteristics within the range of disturbances faced by a wind turbine. This is however somewhat mitigated in the case of variable speed turbines owing to a drive train with a natural frequency approaching zero (Corbet and Morgan, 1991). It seems that passive control by mechanical pitching alone cannot be the answer to power control and other methods need to be looked into. Nevertheless, a suitable combination of this technique with the modern concept of adaptiveness to take care of the oscillatory frequency problems could offer a viable solution, and it would be worth to explore.

### Structural adaptiveness

Even though wind turbine blades are slender structures that, at first sight, may look as beams, they are usually much more complex structural members due to the inhomogeneous distribution of material properties and the complexity of their cross sections (see for example Fig. 12). In a simple homogeneous prismatic beam with its reference line located at the barycenter of the sections, the stiffness matrix that relates strain and stress measures is a diagonal matrix. This means that the strain measures (i.e. the ways of deformation) are not related to one another. In more complex beams, with non-homogeneous sections or complex section geometries, this matrix is not diagonal any more, and coupling between the different modes of deformation appears. These are regarded as non-conventional couplings. Fiber reinforced laminates, which form most of the structures of modern wind turbine blades, are naturally prone to exhibit non-conventional couplings among deformation modes due to the anisotropy of their stiffness properties. Thus, blades made up of anisotropic materials (typically orthotropic laminated reinforced plastics) can be built in such a way that they behave as a beam with non-conventional couplings. In this case the adaptiveness

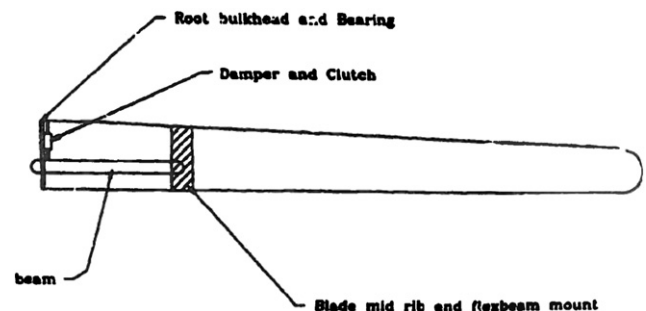
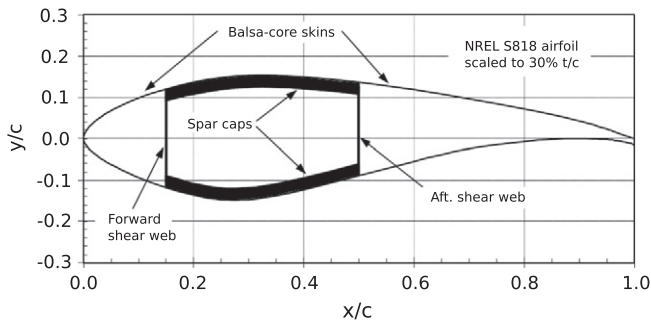


Fig. 11. Layout of the 300 kW Carter Wind Systems turbine (Corbet and Morgan, 1991).



**Fig. 12.** An example of a wind turbine blade internal structure representative of current commercial designs. The primary structural member is a box-spar, with a substantial build-up of spar cap material between the webs. The exterior skins and internal shear webs are both sandwich construction with triaxial fiberglass laminate separated by balsa core (Griffin, 2002a).

comes from the orthotropic stiffness of the skew laminated materials and their distribution over the blade sections. In a typical box-beam-spar blade structure (like the one depicted in Fig. 12) comprising two shear webs and two spar caps plus two skin shells, the skew laminate can be located in the spar caps or the skin only or in both of them in order to control the desired coupling level (Griffin, 2002b).

In terms of their structural design and calculation, the ad hoc kinematic assumptions made in classical beam theories (like the Bernoulli or the standard Timoshenko approaches) give results that may differ significantly from the real deformation that occurs when even standard (rather stiff) blades are subjected to aerodynamic loads in operational conditions. These differences become much more acute in the case of adaptive blades, where the internal structure is specifically designed to promote deformational-mode coupling, to the point that, in some cases, the aeroelastic response becomes unstable and dangerously unpredictable. This is the reason why practical examples of adaptive blades are relatively rare, and fully-commercial designs are still to come. Nevertheless, there had been some attempts in the past to develop adaptive blades. Karaolis et al. (1988) identified three possible ways of coupling deformations with the aim of achieving particular adaptive behaviors:

**Bending/twist coupling:** The main load contributing to the bending of the blade is the flapwise aerodynamic load component. This principally depends on the wind and rotation speeds, so it is ideal as a sensor of the working condition and to control the power output. Fig. 13(a) shows the way this kind of coupling can be obtained by a particular layup of the laminate.

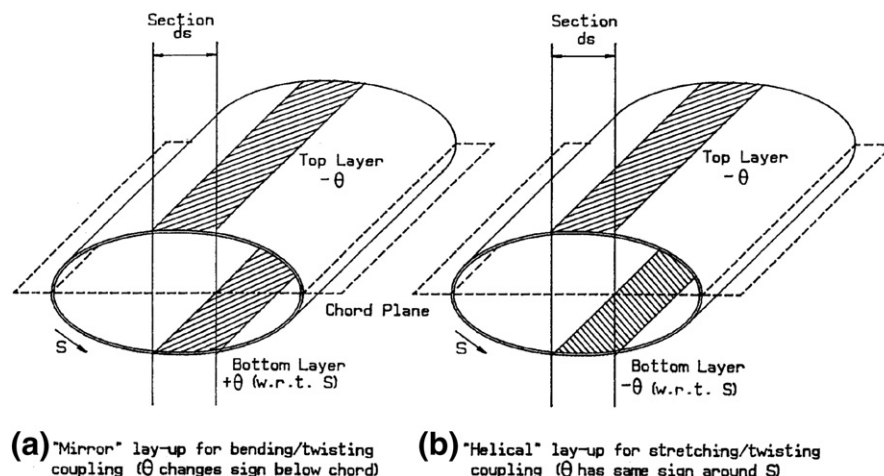
**Stretching/twist coupling** The main contributing load to the stretching of a blade is the centrifugal force. In the case of a blade in which the stretch and the twist are coupled the rotor speed can be used to modify the twist angle and consequently the angle of attack, ultimately controlling the aerodynamic load. This was proposed as a mean of control for variable speed rotors or as an emergency system for both, fixed and variable speed ones. Fig. 13(b) shows the way this kind of coupling can be obtained by a particular layup of the laminate.

**Pressure/twist coupling** Karaolis et al. (1988) also proposed to pressurize the interior of the blade as a mean of controlling the twist angle. As the controlling action in this case, i.e. increasing or lowering the internal pressure, needs to be externally commanded this type of control does not fit into the adaptive or smart blade concept.

The most promising from the three strategies mentioned above is the bending/twist coupling and most of the efforts were aimed to its development. Twist sense is also another factor to be considered. The twist under increasing load can be in the sense of stall (increasing the angle of attack) or in the sense of feather (decreasing the angle of attack). Each of them becomes more appropriate depending on the desired control behavior and the variables to be optimized. Also, there are some characteristic instabilities associated with each twist sense.

Lobitz et al. (2001) reviews issues related to the use of aeroelastic tailoring as a cost-effective, passive means to shape the power curve and reduce loads. Their major findings could be summarized as follows:

- By moderately twisting the blade toward stall through twist-coupling and simultaneously growing the rotor diameter, significant increases in annual energy that can be achieved.
- By optimally selecting blade pitch and twist-coupling parameters, energy capture for a variable speed stall-controlled rotor can approach that of a variable speed variable-speed-controlled rotor.
- Twist-coupled blades tend to be less stable with regard to divergence (twist to stall) and classical flutter (twist to feather), but not prohibitively so.
- Twist-coupling to stall significantly increases fatigue damage and can promote stall flutter.
- Twist-coupling to feather significantly decreases fatigue damage without reducing power output (especially at the lower wind speeds).
- For variable speed pitch-controlled rotors, twist-coupling to feather substantially decreases fatigue damage without reducing power output (for all wind speeds).



**Fig. 13.** Lay-ups for bending/twist and stretching/twist couplings (Karaolis et al., 1988).

Two of the most common aerodynamic stability constraints, divergence and classical flutter, were analyzed by Lobitz and his colleagues (Lobitz and Veers, 1998; Lobitz et al., 2001). If the blade twists due to increasing load in a sense that the load increases even further, divergence may occur. That happens when the rotational speed produces a situation where the blade is not able to resist the load increase that is caused by the corresponding state of deformation. In classical flutter, a resonant condition is achieved for a particular phasing between the aerodynamic load and the fluctuations in elastic deformation. For each wing there is a specific speed where it will start to flutter, i.e. a flutter boundary. For wind turbine blades, that boundary is defined as the rotational speed at which the blade will flutter assuming zero wind flow (i.e. still air). The difference between normal operating speed and flutter speed is called the *stability margin*.

Lobitz and Veers (1998) developed their analysis by simply increasing the rotor speed until the system became unstable neglecting the incoming wind (i.e. turbine assumed turning in still air). Based on linear aerodynamic theory (i.e. assuming no blade stall) they investigated divergence and classical flutter instabilities for the bending-twist coupled blade. Divergence involves the destabilization of blades that twist toward stall, while flutter occurs in the case of blades that twist toward feather, the flutter end of the spectrum being significantly less critical than the divergence end as shown in Fig. 14. Stall flutter, which imposes another important stability constraint, was not yet studied deeply for blades exhibiting twist-bending coupling (Lobitz et al., 2001). We are going to revisit this topic in the final section.

### Geometrical adaptiveness

Flexo-torsional coupling can also be achieved by modifying blade geometry. One such concept, extensively studied in aeronautics, is that of *swept wings*. Serious research on swept wings was initiated by Germany during 1930s and continued during World War II while working on jet powered aircrafts (Anderson, 1997; Meirer, 2010). Wing sweep is related to the relative position of the torsional center of the section structure and the aerodynamic center of the airfoil sections along the wing. The wing can be of a backward-sweeping configuration or of a forward-sweeping one. For the backward-sweeping wing, the aerodynamic center of the airfoil is located behind the torsional center of the section structure, in such a way that the upward lift results in a pitching moment which reduces the angle of attack. This arrangement helps avoid structural divergence, making it a preferred configuration for most aircrafts flying at high-subsonic and transonic regimes. One of the earliest examples of a swept back wing can be seen on the German Messerschmitt Me-262 jet fighter of World War II (see Fig. 15). The success of which prompted a similar approach on a number of post-war aircraft such as the F-86 Sabre (see Fig. 16) and the Boeing B-47 Stratojet (Blair,

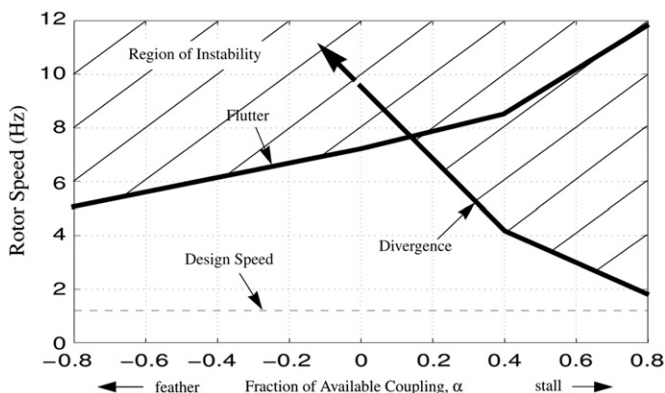


**Fig. 15.** A well-preserved captured example of the Messerschmitt Me 262, seen here during a test flight in the USA in post-war times. This was the first Me-262 to fall intact into Allied hands on March 31st 1945. Source: Photo archives of the National Museum of the U.S. Air Force (NM-USAF).

1980; Foreman and Harvey, 1990; O'Connell, 2006), and it is a typical feature found in most modern commercial jets.

In the forward sweeping configuration the aerodynamic center is located forward of the torsional center, resulting in an increase in the angle of attack with an upward lift inducing a natural nose-up motion. The experimental swept-forward wing aircraft Grumman X-29 (see Fig. 17) used this principle to induce aerodynamic instability on the wing to increase agility. But this also requires computerized pilot controls to compensate this inherent instability. The increase in angle of attack with increasing lift also leads to structural divergence. In the X-29 this is solved by tailoring the anisotropic properties of the composite materials on the wing structure to counteract the effects caused by the structural divergence (Thruelsen, 1976; Winchester, 2005). Hence, the X-29 wings could be considered as a particular example of geometrical and structural adaptiveness acting simultaneously to mutually cancel each other. Besides the adaptiveness effects, swept wings contribute to delay the increase in drag caused by fluid compressibility at high Mach numbers (Barmby et al., 1951; Hilton et al., 1952). Within the scope of this work we will only focus on the structural-adaptiveness aspect of the swept-wing concept, which is the relevant one in terms of wind turbine applications.

The same notion of the swept-wind concept can be applied to the design of wind turbine blades by means of geometric modifications of the blade planform, for example curving the blade axis forward or



**Fig. 14.** Aeroelastic stability boundaries for the bending-twist coupled CEB (Lobitz et al., 2001).



**Fig. 16.** A historic photo of a North American F-86F Sabre jet, taken circa 1953. Source: Photo archives of the U.S. Air Force (USAF).





**Fig. 17.** An image of the X-29 advanced technology demonstrator aircraft flying over desert terrain near NASA's Dryden Flight Research Facility in California. It was flown in a joint NASA-Air Force research program between 1984 and 1988 to investigate handling qualities, performance, and systems integration on the forward-swept-wing configuration. Source: Photo collection of NASA Dryden Flight Research Center (Nasa).

backward in the direction lying on the rotor plane (ie. the direction of advance of the blade in its rotational motion). This way, with the same internal layout of the blade (sections, material properties and distribution) a conventional blade can be transformed in an adaptive one. Fig. 18 shows two images of the STAR-Rotor wind turbine reported by Knight et al. Group KCW, (2009), and Fig. 19 shows its blade plan-form, designed to provide bend-twist coupling.

If a suitable magnitude of bend-twist coupling can be achieved using this approach at utility-scale turbines, the structure of typical commercial blades might be fabricated much as it is now (Zuteck, 2002) without the need to modify the internal structure or, in combination with a structural-adaptive construction, it might maximize the benefits of the two techniques used together.



**Fig. 18.** Two images of the STAR-Rotor prototype turbine using a swept-back adaptive blade configuration Group KCW, (2009).

## Final remarks

We have presented a historical background and a review of the perspectives and trends in the development of the adaptive-blade concept for wind-power applications. Here we may add a few concluding remarks with respect to the future lines of research that would be worthwhile to explore in order to face the challenges presented by this innovative concept:

Regarding structural adaptiveness, it is argued that it is difficult to control the design and construction so the blade is fine tuned for that behavior. Thus, two challenges are posed to the manufacturing process Zuteck (2002):

- The first is that off-axis fiber for the major structure is difficult to fabricate.
- The second category of challenges is in the area of possible fatigue limits due to ending or curving angled fibers.

Regarding geometrical adaptiveness, this technique has proven to give good results in experimental investigations. Knight et al. Group KCW, (2009) presents results from field testing of a wind rotor modified to exhibit some amount of geometrical adaptiveness (see Fig. 20). Among many interesting conclusions it can be highlighted that the modified rotor increased average energy capture by 10–12% as compared to baseline turbines.

In terms of aeroelastic instability Stoddard et al. (Stoddard et al., 2006) states that the primary cause of flutter and divergence in certain wind turbine rotors, that have demonstrated aeroelastic instabilities and blade flexibility problems in operation, is blade torsional flexibility. In stall-regulated (fixed pitch) rotor systems an added potential flexibility problem is stall flutter. In pitch-regulated (controlled pitch) rotor systems, blade elastic twist in operation can lead to major increases in pitching moment and the attendant pitching system power required. Other possible risks identified in the report are:

- Elastic blade twist near rated conditions, if nose-down or toward feather, causes delay of stall and negates the desired load alleviation, thereby causing potential rotor overloading.
- Elastic blade twist if nose-up, or toward stall, causes premature blade stall, the potential for stall flutter, and loss of power.
- At operating conditions below rated or stalled conditions, the same arguments, though less significant, apply.

Several studies have been conducted trying to optimize different variables representing the turbine overall behavior ((Maheri et al., 2006)) such as improving the annual energy capture (Eisler and Veers, 1998; Lobitz et al., 2001), reducing the fatigue loading Lobitz and Laino, 1999; Lobitz et al., 2000 and material configuration, design and manufacturing (Locke and Contreras Hidalgo, 2002; Ong and Tsai, 1999; Ong and Tsai, 2000; Valencia and Locke, 2004). As a final reflection: The dynamics of high deformable blades, as the proposed adaptive blade concept, is very sensitive to the fluid–structure interaction process. The improvement of the accuracy of numerical simulations will allow to reduce the uncertainties related to blade dynamics and to better understand the physics involved. When analyzing the fluid–structure interaction phenomena at the blades, it becomes difficult to extrapolate experimental data from wind-tunnel due to the big size differences between the model and the real scale wind turbine and the complex mixture of unsteady loads in a typical turbine operational state. Hence, the wind turbine industry is relying more and more on computer models for the design and optimization of the blade structure and aerodynamics. Nevertheless, as can be inferred from this work, there are several features of the coupled aeroelastic problem that go beyond the capacities of current commercial codes, mostly, the complex interaction of physical processes that result in the abovementioned aeroelastic instabilities.

Especially, the correct prediction of the flexo-torsional modes of deformation is of capital importance for the analysis of adaptive-blade



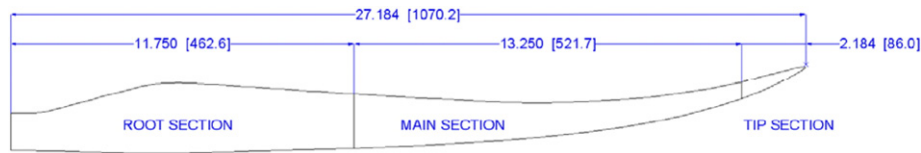


Fig. 19. Plan-form shape of a geometrically modified blade for the STAR-Rotor turbine Group KCW, (2009).

prototypes. A good example of this is reported by Knight et al. Group KCW, (2009) where the shape of the blades of a commercial turbine was modified in order to achieve some degree of geometrical adaptiveness. The power curve of the modified rotor (see Fig. 20) outperformed the prediction of the simulation code used during the design stage for wind speeds lower than nominal. In this case the lack of proper simulation tools, resulted in an under-prediction of the energy yield, but more dangerous consequences can occur in other cases.

The state-of-the-art to simulate the aeroelastic dynamics of wind turbine blades, is to solve both problems in a coupled manner: the structure modeled as a Bernoulli or Timoshenko beam, and the flow by means of a classical implementation of the well-known Blade-Element Momentum (BEM) aerodynamic model. This leads to a fully non-linear coupled scheme (see (Hansen et al., 2006), where a thorough coverage of the topic is presented). Traditional aeroelastic codes like the FAST-Aerodyn suite (Jonkman and Buhl, 2005; Moriarty and Hansen, 2005; Laino and Hansen, 2002) are based on this approach. The accuracy of these models is limited by the fact that both the flow and the structural models cannot reflect the effects of the feedback of the deformation modes on the aerodynamic loads exerted on the blade sections. Hence, the important role played by the flexo-torsional deformation is missed, which makes them unable to properly simulate the behavior of adaptive blades. Therefore, it is necessary to supply the industry with innovative models that may predict the behavior of new designs in the adaptive-blade field, avoiding the risk of compromising reliability. These models should be capable of capturing the complex features of innovative blades, which will allow new prototypes to be tested at realistic full-scale situations with an affordable computational effort (see (Lago et al., 2013; Otero et al., 2012)).

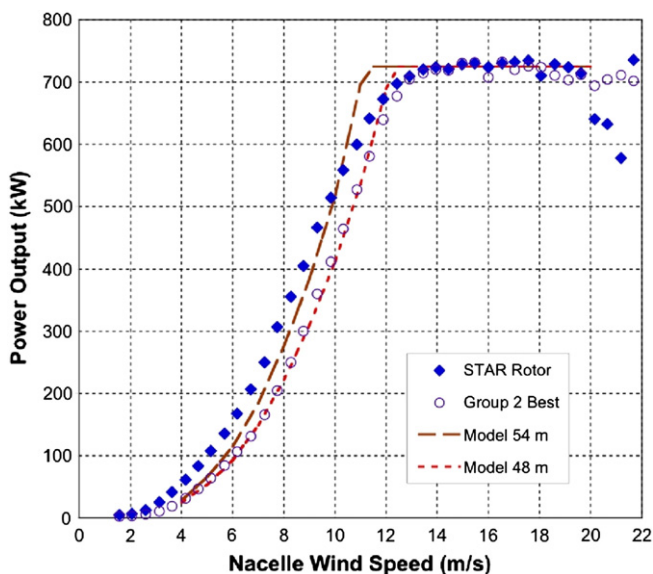


Fig. 20. Power curve of a geometrical modified blade, the STAR-Rotor compared with measurements for the baseline rotors (Group-2Best), results for the baseline rotor given by the numerical model (Model 48 m), and results for the modified rotor given by the numerical model (Model 54 m) Group KCW, (2009).

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