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WIND TURBINE PASSIVE CONTROL USING AEROELASTIC TAILORING: STATE OF THE ART

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Abstract: *This work intends to be a historic review of the passive control of Wind turbines employing the aeroelastic tailoring concept. This concept demands to use the flap and torsion deformations coupling of the structural elements made with composite materials. Such couplings could be achieved and predetermined, using an adequate distribution and orientation of the layers of the composite materials that the structural element is made, in this case, the wind turbine blade. The flap deformations of the wind turbine blade are caused by the aerodynamic load that is applied over the blade. The torsion deformations can make a mitigation of these loads. Because of this such concept could be employed to improve the aerodynamic efficiency of the turbine, and even advance the mitigation of loads that are applied over the structure of the turbine blade. This mitigation of the aerodynamic loads could enlarge the fatigue life of the wind turbine blade and enable a substantial improvement in its structural efficiency.*

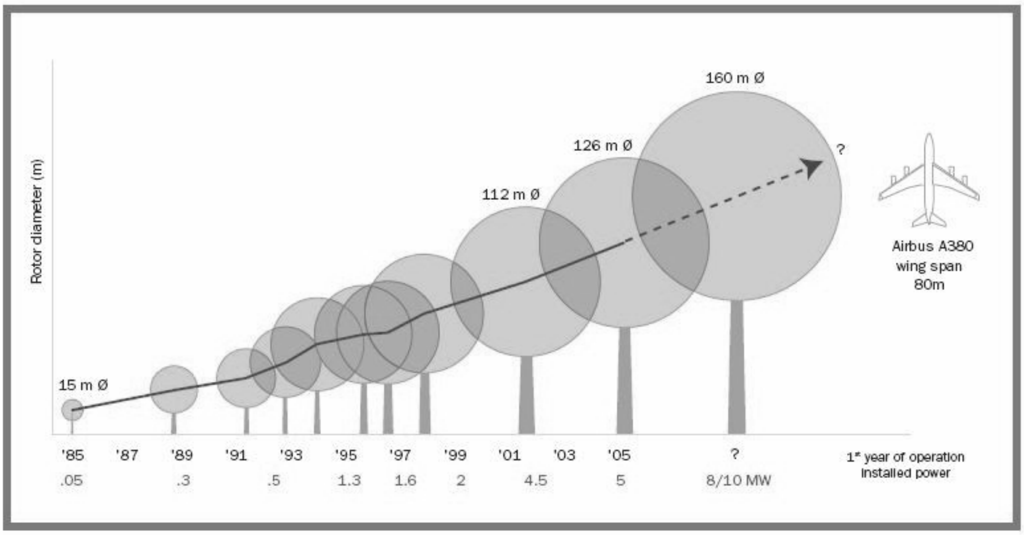
Keywords: *wind turbine; aeroelastic tailoring; passive control.*

1. INTRODUCTION

Discordant speculations from some authors point the wind mills origins. The first evidences indicate stone mills at Egypt near Alexandria three thousand years ago. But there is no conclusive proof that the Egyptians, Phoenicians, Greeks or Romans really used wind stone mills. The development of a lot of types of wind mills date from medieval times until the seventeenth century and can be considered result of a systematic research and development.

The first attempts to generate electrical energy with the advantage of the wind energy probably occurred at Denmark with a systematic development. Encouraged by the government a professor of an educational center of Askov, Poul La Cour, manufactured an experimental wind turbine that driven a dynamo, in 1891.

The size of the commercial wind turbines have grew dramatically in the last 25 years. From rotors of 10 to 15 meters in diameter and output power of 50 kW in 80´s to the actual power around 5 to 8 MW and rotors of 120 to 160 meters as shown in Figure (1). This accelerated development have forced the design tools to change from simple static calculus assuming constant wind to dynamic simulations with transient aerodynamic loads models and aeroelastic responses for the entire wind turbine structure, including tower, generator and control system.



Source: Jos Beurskens, ECN

Figure 1. Wind Turbine grow (Jos Beurskens, ECN)

This grow has even improved other systems requirements. One of these is the control system. Responsible for the generation performance of the wind turbine, now it is also the structural integrity keeper of the turbine rotor, and other systems, and even the turbine structural life.

2. WIND TURBINE CONTROL

Especially at large-scale wind turbines, high speed winds, fluctuations and gusts produce loads that can eventually exceed structural limits. There is a power limit imposed by the generator too. In some cases it is necessary to keep the rotor speed inside pre-defined limits, with the objective to generate the maximum of energy possible and not exceed these limits. In other hand, during distribution energy black outs, the resistant torque of the generator vanishes and the speed of the rotor can accelerate rapidly, leading the turbine to collapse. Because of these, during the wind turbine operation, it is necessary a system control to limit its speed operation.

Basically, the involved aerodynamic forces, shown in Figure (2), can be modified changing the angle of attack, the projected area of the rotor or the effective flow speed. The most effective way to control these aerodynamic forces is changing the angle of attack, adjusting the pitch of the blade. In general, the rotor blades are rotated around his longitudinal axis.

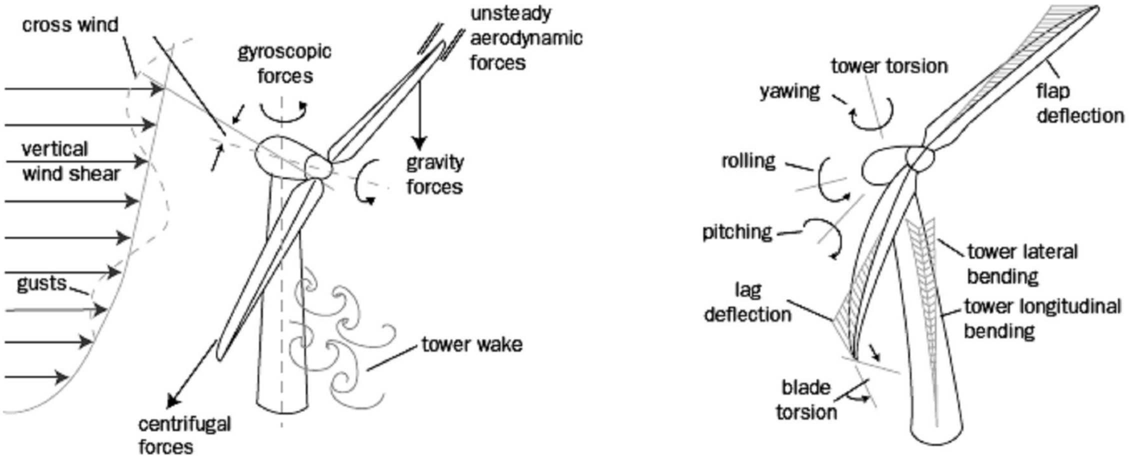


Figure 2. Wind Turbine aeroelastic loads and deflections (source: DFVLR).

Reducing the angle of attack the power extracted will be reduced too. The power can be increased moving the angle on the opposite direction. Other possibility is to increase de angle of attack to values greater than the critical angle of the airfoil. The effect produced is the stall of the airfoil and the reduction of the power. See Figure (3). This method has the advantage to need smaller angle modifications.

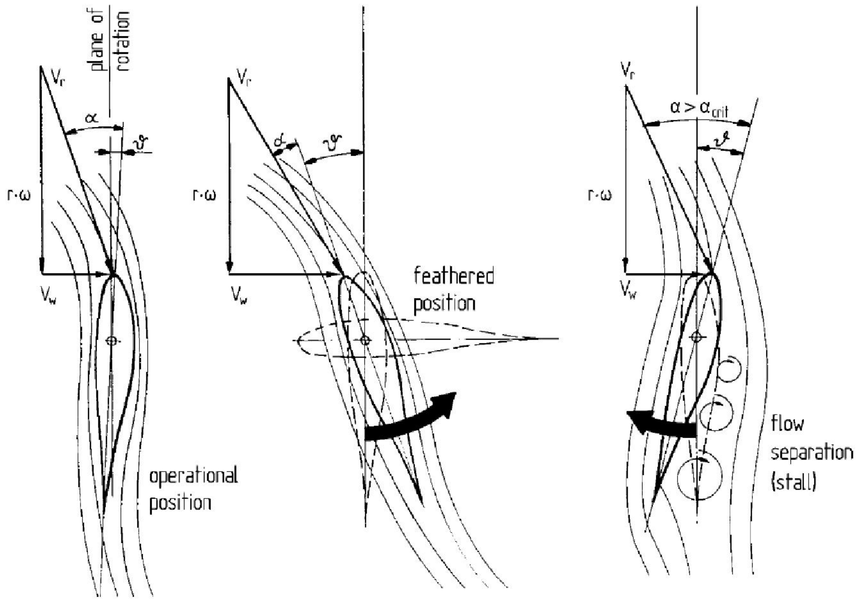


Figure 3. Controlling the rotor input power changing the blade pitch angle. (Hau, 2005)

Hulskamp, et al. (2009) states that the horizontal axis wind turbine (HAWT) manufactures aim challenges related with the market grow and the turbines sizes. For large wind turbines the design challenge is still the fatigue. The aerodynamic loads over the blade have a great number of perturbations that produces dynamic deflections and thereafter fluctuations on the stresses distribution. These perturbations are caused by flow field modifications and by the blade rotation over this field. Examples of these fluctuations are: wind shear, yaw misalignment, tower shadow and inflow fluctuations. The blade mass effects are also uneasinesses of the design. According to Hulskamp, historically, the wind turbines blades mass have grown with its diameters at an exponential rate of 2.4 a 2.65. The blades rotate on gravitational fields and the cyclic loads produced also add fatigue. So, to reach a large fatigue life for the wind turbines it is necessary mitigate this fluctuations amplitudes.

The wind turbine control has two categories: active and passive, like shown in Figure (4). The passive techniques are able to improve the energetic performance and reduce the loads over wind turbine without any external energy dispended. Examples of this kind of control used at wind turbines include yaw movement and aeroelastic torsion of the rotor blade. Active techniques need external or auxiliary energy. Some traditional active controls are yaw control and blade pitch. Advanced active controls explored actually are flow control using trailing edge flaps, microtabs and synthetic jets.

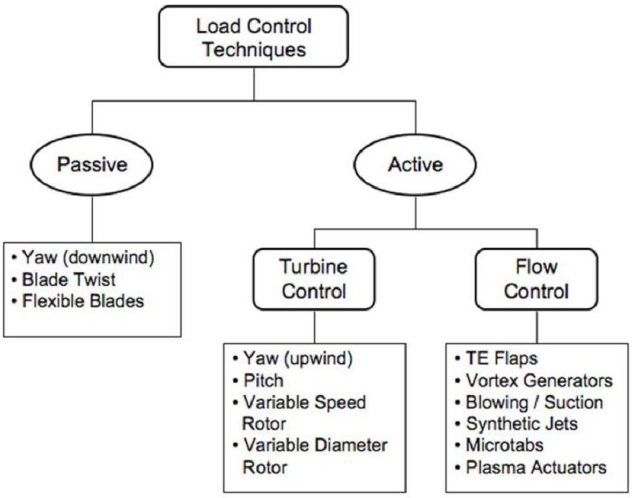


Figure 4. Control categories. (Johnson, van Dam e Berg, 2008)

3. PASSIVE CONTROL AND AEROELASTIC TAILORING

In the first years of the modern wind energy, the mechanisms of passive control that adjusted the blades angle of attack in response to the load were very popular. Cheney and Speiring (1978) controlled the power using inertial masses placed on an elastic arm, driven by the centrifuge force on the rotor. Bottrell (1981) made a system that set the blade pitch in response to the misbalanced moments on the rotor disc. Currin (1981) also developed a power and load control mechanism adjusting the pitch. Corbet and Morgan (1992) evaluated the use of all incident loads on the blade in purpose to change the pitch blade and regulate power output. Only angles to feathering were evaluated. They had concluded that a perfect control was very difficult to achieve. Even an imperfect control was a challenge.

Koraolis, Mussgrove and Jeronimidis (1988) introduced the passive adaptive blades concept. See Figure (5). Using different angles positioning of the composite materials layers on the blade skin, was possible to introduce a deformation coupling of the blade in response to the extension, flexural on bending and torsion loads. This technique was named aeroelastic tailoring.

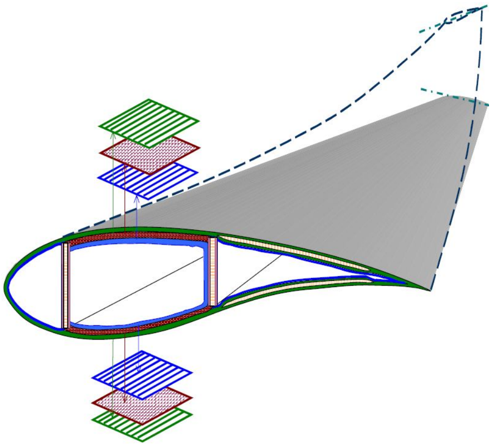


Figure 5. Aeroelastic Tailoring (Ashwill, 2006)

Due to Goeij, van Tooren and Beukers (1999), the Aeroelastic Tailoring term was defined by Weisshaar (1987): “the incorporation of directional stiffness in an aeronautic structure design to control the aeroelastic deformation, static and dynamic, in the way to influence its structural and aerodynamic performance in a benefic way”.

Kooijman (1996) said that the aeroelastic tailoring technique is promissory to the wind turbines rotor blade designs. On this work, he evaluated elastic couplings made using the blade skin. But also it is possible to get this coupling with the internal structure of the blade aeroelastic tailored.

Lobitz, Veers and Migliore (1996) verified that torsion coupling blades combined with larges rotors could increase the power extraction.

Middleton, Fitches, Jeronimidis and Feuchtwang (1998) designed, analyzed, manufactured and tested a blade with extension-torsion coupling. Made with composite material, it was manufactured using a helicoidally layer distribution of glass and carbon fibers. Studies that investigated the annual energy production grown due to annual average wind speed shown that one degree torsion angle increased around 5% the capture energy. Two degrees in torsion increased the energy in 10%.

When the wind turbine blade has an “active” aeroelastic behavior the dynamic structural stability is affected. The most common problems are the divergence and the classical flutter. Lobitz and Veers (1998) determinate the stability limits of the wind turbines rotor blades in function to the amount of coupling introduced. A coupling coefficient was defined to help in the evaluation of the produced effects. The results have shown the stability limits were not transposed even for coupling coefficients over 80% of the maximum.

Eggers, Ashley, Rock, Chaney and Digumarthi (1996) shown that the blade torsion to the feathering is great potential way to reduce the aerodynamic loads. It was shown that the flap response could be reduced to the half for a tree degrees variation on the pitch. The implications on the cyclic load was enormous, increasing the fatigue life and reducing the blade mass.

Lobitz and Laino (1999) investigated the effects of torsion bending coupling in for cycling loads using tree different control strategies: constant speed with stall control, variable speed with stall control and variable speed with pitch control. Also were investigated transient loads and coupling modifications. Like shown by Eggers (1996), an aeroelastic control is similar to a proportional control, and not an integral one.

They also demonstrated on the same work that the reduction of the angle of attack is more efficient in mitigating the fatigue damages. It was demonstrated that this strategy could reduce in 70% the damages. On the other hand, increasing the angle of attack in the stall direction augments the damages.

There are limits on the quantity of coupling that a superposition of asymmetric layers can achieve. Tsai and Ong (1998) established the limits to the coupling quantities that can be achieved with asymmetric composite materials layers depends on the matrix and fiber properties. They also established the most convenient angles for the layers with function of the properties.

Joose and van den Berg (1996 and 1994) worked with small turbines and shown they can improve its performance using aeroelastic coupling. In this case the extension torsion coupling is the most adequate to assist variable speed control systems looking limit speed and power.

Lobitz, Veers and Migliore (1996) demonstrated that even for small angles of torsion a control system can operate a large rotor to improve its energetic performance without increasing its maximum power.

4. HELICOPTERS FLIGHT DYNAMICS APPLIED TO WIND TURBINES

Despite of having designs to different objectives, wind turbines and helicopters share similar aeroelastic problems. Its rotating blades, aerolastically couples with the air, influencing the global performance, vibrations, loads and stability. Due to these similarities the aeroelastic tailoring technique developed for helicopters blades can be rapidly applied to wind turbines (Veers and Bir, 1998).

The first works have concentrated on the mass distribution over the chord and span with the objective to reduce vibrations (Miller, 1956; Hirch, 1956; McCarthy, 1955 and Daughaday, 1957). After that (Blackwell, 1983), aerodynamic solutions such as torsion and sweeping blades were used as mean to control vibrations too.

Friedman (1983 and 1984) and Shanthakumaran (1982) presented the firsts structural optimizations using aeroelastic tailoring on the effort to reduce vibrations on helicopters. Lim and Chopra (1988 and 1987) handled the vibration problems with a general formulation including numerous contributions with stand out analytical direct formulation in load derivatives calculations on the rotor hub and the blade stability. Other remarkable contributions was the natural frequencies positioning (Peters, 1986 and 1988), mass reduction (Bielawa, 1971), flight handle quality improvements (Celi, 1989) and vibration reduction using modal shaping (Taylor, 1982; Davis, 1988 and Weller, 1988 and 1989).

Hong (1985) and Panda (1987) shown that elastic coupling could have powerful influence on stability, blade tensions and loads. Smith and Chopra (1991) show limitations on these studies with respect to non classical phenomena such as blade shear and torsion.

Friedman et al. (1992) developed the aeroelastic tailoring techniques capabilities on influence vibrations and rotor stability. But Ganguli and Chopra (1992, 1993 and 1994) were the first ones to employ a systematic optimization on helicopters blades using aeroelastic tailoring.

Until there all efforts were concentrated in mitigating hub loads, what resulted in bigger bending moments and blade stresses, reducing the fatigue life. Ganguli and Chopra (1997) extended the aeroelastic tailoring research to reduce simultaneously the hub loads and blade bending moments.

5. RECENT WORKS ON WIND TURBINES

Recent works had shown that blade geometry also can be improved with aeroelastic tailoring increasing performance, mitigating loads and obtaining benefits on stability (Celi, 1988). Bir and Chopra (1994) developed an advanced geometry blade model that has variable sweep, positive dihedral, thickness reduction and torsion along span. Ganguli and Chopra (1997) integrated this advanced blade geometry with an aeroelastic optimization of the geometry and the anisotropy of the blade composite material, simultaneously, reducing blade stresses and vibration.

According Veers et al. (1998), there are potential advantages to the wind turbine blades designed employing aeroelastic tailoring. For stall control rotors, for constant speed as for variable speed, there is an annual potential gain in energy at about 25% that can be achieved improving the control system while the rotor diameter increases. On pitch control machines this gain is smaller, stay around 1 to 3%. On variable speed turbines with pitch control the best option is to substitute the pitch control by a passive bending torsion coupling. There is a large potential, but also a great amount of uncertain, on the mitigation of fatigue loads, using the aeroelastic tailoring. Researches on helicopters area point that there is an enormous potential of the technique. Improvements employing bending torsion coupling by aeroelastic tailoring must firstly be vastly evaluated using wind turbines aeroelastic models and equally on the control issue, before the benefits could be effectively proved.

Fedorov, Dimitrov, Berggreen, Krenk, Branner and Berring (2009) investigated the structural behavior of a wind turbine blade with bending torsion coupling. The experimental analysis of the study was implemented on a real 23 meter wind turbine blade section. Only an 8.4 meters section was used for the testes. With the intentional objective to introduce a measurable bending torsion coupling additional unidirectional layers was laminated on upper and the lower surfaces of the test section using a vacuum infusion process. The direction of lamination was 25^0 based on a finite element analysis as it is shown in Figures (6) and (7).

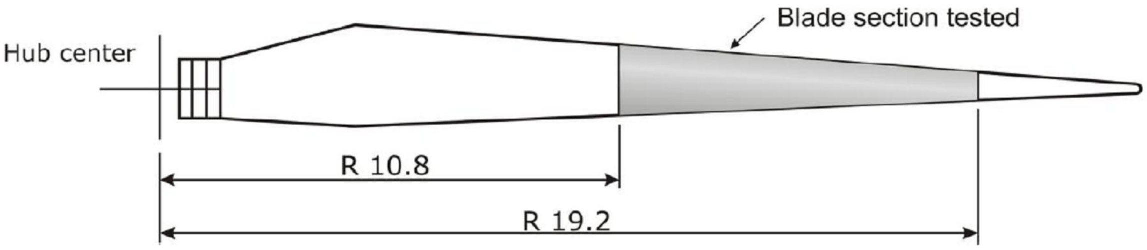


Figure 6. 23 meters wind turbine blade (Fedorov et al., 2009)

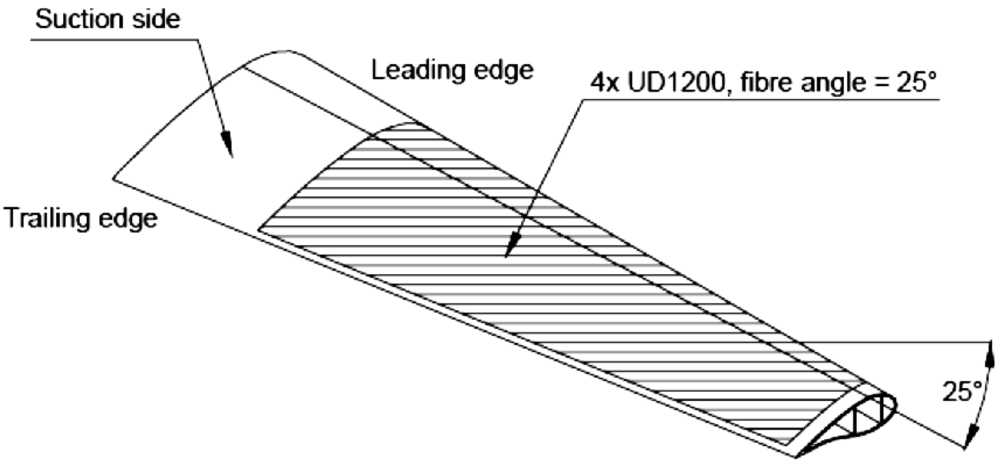


Figure 7. Coupling introduction (Fedorov et al., 2009)

Five different finite element models using tree different shell elements and two other finite elements named shell-solid were deployed and validated with experiments. On the bending loads all models had good displacement predictions while the torsion stiffness was generally underestimated by all models. On the case of the bending torsion combined load again the displacement prediction was good for all models and the torsion stiffness was underestimated too. On the pure torsion load all models underestimated the bending stiffness over the blade span but had good results on the tip region. See Figures (8), (9) and (10).

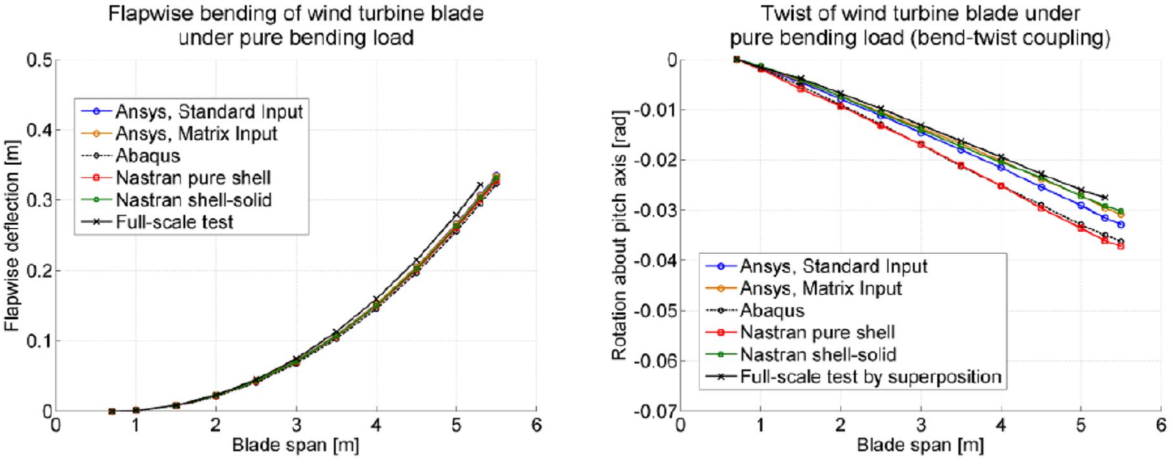


Figure 8. Pure bending loads. (Fedorov et. al., 2009)

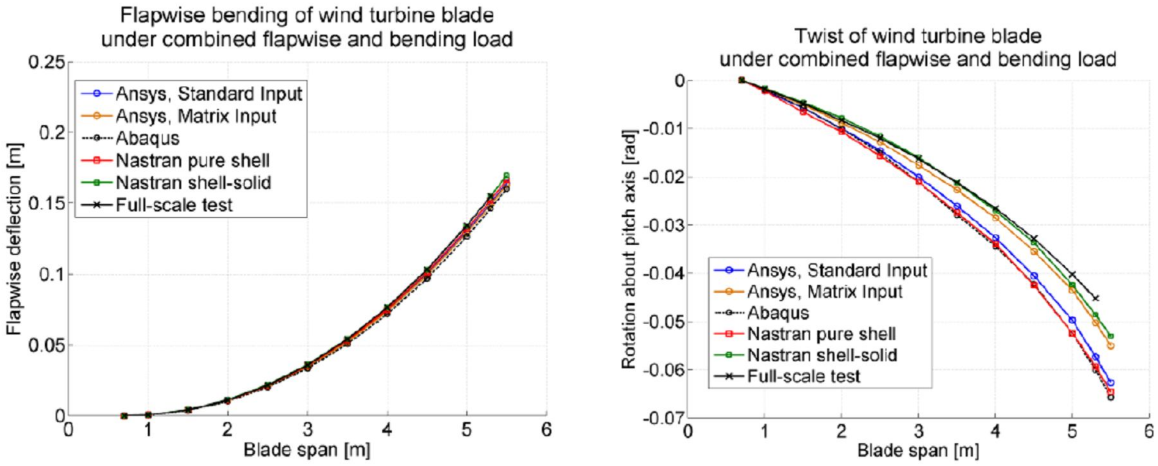


Figure 9. Combined load. (Fedorov et. al., 2009)

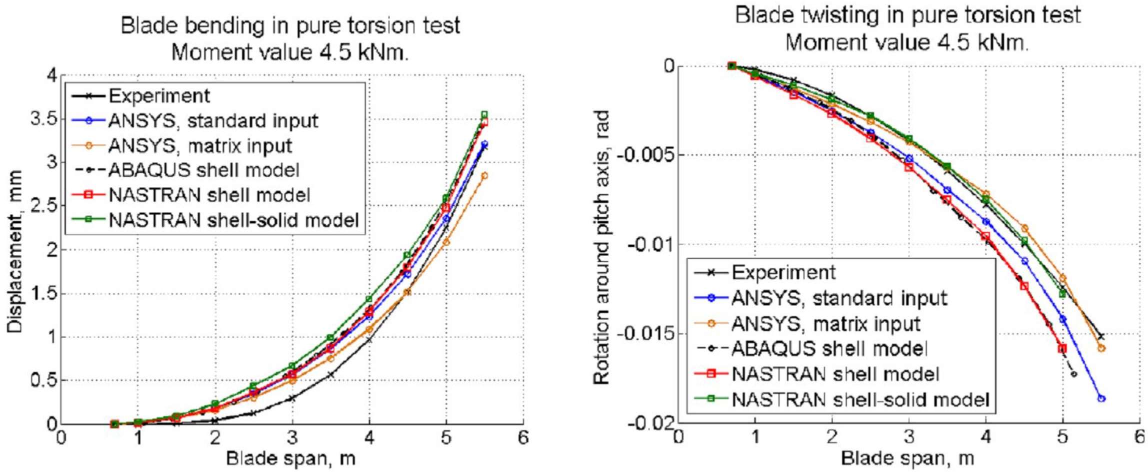


Figure 10. Pure torsion load. (Fedorov et. al., 2009)

In agreement with Fedorov et al. (2009), the finite element model foremost representative of the bending torsion coupling for the aeroelastic tailoring studies is the shell solid, with maximum error of the order of 6.5%. On other hand large error of 31% was found in shell finite element models, on the torsion angle predictions. According the authors, these errors probably are due to erroneous shear flow distribution round transversal section. This leads to an underestimation of torcional stiffness and consequently the torsion angles.

The smart rotors concept actually is largely employed and studied on the wind turbines research. Hulskamp, Champliaud and Bersee (2009) developed a scaled experiment to test this smart rotor concept. Aeroelastic tailoring was used to design and manufacture the dynamic model used. The tests were designed in order to verify the blade dynamic behavior including the sensors performance and its fatigue life. The results were compared with numerical simulations using finite element models.

6. CONCLUSIONS AND PERPECTIVES

The use of the wind energy to generate electricity is now well accepted for a large number of equipment manufactures. This manufactures install hundreds of Megawatts every year. Despite the existence of innumerous new developments, especially for large wind turbines, still have lots of challenges. There is a considerable space for development with respect to the science and technology of the wind turbines.

The aeroelastic tailoring technique could be used to produce a passive control system for the actual large scale wind turbines that are been designed and manufactured nowadays, with a future extremely practicable and promising. Meanwhile the most recent works show that the analysis techniques must be refined to make viable a consistent prediction of the aeroelastic behavior of the wind turbine blades, looking for a control system design really effective and robust.

After the study of passive controlled wind turbine blades, it could be conclude that: a passive pitch control system enlarges on an significant manner the power output of the wind turbine on its operating range; blades designed using the aeroelastic tailoring technique can twist and extends under aerodynamic and gravitational loads; it is possible to affect the pitch angle with the wind speed in order to obtain optimum performance; there is a quasi linear relation between flap bending moments and required pitch angle variation; and a passive pitch control system has minimal maintenance and inspection costs.

Due to the fact the passive control is advantageous from the economic point of view, especially for large wind turbines, the aeroelastic tailoring, together with the smart rotors new concepts, can became complementary techniques, making possible optimum designs for the twenty first century wind turbines.

7. ACKNOWLEDGEMENTS

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