

AEROELASTIC TAILORING IN WIND-TURBINE BLADE APPLICATIONS¹

Paul Veers
Sandia National Laboratories
Wind Energy Technology Department
Albuquerque, New Mexico, 87185-0708

Gunjit Bir
National Renewable Energy Laboratory
National Wind Technology Center
Golden, Colorado, 80401-3393

Donald Lobitz
Sandia National Laboratories
Structural Dynamics Department
Albuquerque, New Mexico, 87185-0439

Abstract

This paper reviews issues related to the use of aeroelastic tailoring as a cost-effective, passive means to shape the power curve and reduce loads. Wind turbine blades bend and twist during operation, effectively altering the angle of attack, which in turn affects loads and energy production. There are blades now in use that have significant aeroelastic couplings, either on purpose or because of flexible and light-weight designs. Since aeroelastic effects are almost unavoidable in flexible blade designs, it may be desirable to tailor these effects to our advantage. Efforts have been directed at adding flexible devices to a blade, or blade tip, to passively regulate power (or speed) in high winds. It is also possible to build a small amount of desirable twisting into the load response of a blade with proper asymmetric fiber lay up in the blade skin. (Such coupling is akin to distributed δ_3 without mechanical hinges.) The tailored twisting can create an aeroelastic effect that has payoff in either better power production or in vibration alleviation, or both. Several research efforts have addressed different parts of this issue. Research and development in the use of aeroelastic tailoring on helicopter rotors is reviewed. Potential energy gains as a function of twist coupling are reviewed. The effects of such coupling on rotor stability have been studied and are presented here. The ability to design in twist coupling with either stretching or bending loads is examined also.

Background

Whenever wind turbine blades twist, there is a direct influence on the angle of attack, changing loads and affecting output power. This is directly exploited in classic pitch control used in not only wind turbines but in rotors of all types. When the pitch changes are rapid enough, they can affect not only average loads and power, but vibratory loads as well, influencing fatigue life throughout the system. Even quite small angles of twist can have significant impact.

The concept of building blades that passively adapt to the incident wind loading is not new. Mechanisms that adjusted blade angle of attack in response to the thrust loading were quite popular in the early days of the modern wind energy push. Approaches and objectives were quite varied. Cheney and Speirings (1978) regulated power with a centrifugally loaded mass on an elastic arm. Bottrell (1981) has a system for cyclically adjusting pitch for per rev load balancing. The North Wind 4KW (Currin, 1981) had a system for passively adjusting pitch for both power and load control. Hohenemser and Swift (1981) studied alleviating yaw loads with cyclic pitch adjustments.

A Garrad-Hassan report (Corbet and Morgan, 1992) evaluates the use of all available blade loads to effect pitch changes that would regulate the power output of a turbine, aiming at a flat power curve in high winds.

¹ This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corp., a Lockheed Martin Company, for the United States Department of Energy.

Only pitching to feather is evaluated to avoid the vagaries of predicting power output in the post-stall regime. They report that several manufacturers were already using some form of passive power control in their designs (Lagerwey, NPS, Berewoud, Flexhat, Swedewind, Carter). The conclusion is that perfect regulation is very difficult to achieve, and that even less than perfect regulation is a challenge. These approaches also depend on quite substantial blade rotations to achieve perfect regulation.

Karaolis et al. (1988, 1989) introduced the concept of using biased lay-ups in blade skins to achieve different types of twist coupling for wind turbine applications. Figure 1 shows how different fiber orientations in a blade skin can be used to achieve bend-twist or stretch-twist coupling. By changing the blade skin from an orthotropic to a biased fiber lay-up, the blade can be aeroelastically tailored with minimal disturbance to the beam stiffness properties or manufacturing costs. Karaolis suggests that in addition to using the flapwise or centrifugal loading to twist a blade, it might be useful to internally pressurize a spar and use changes in the pressure to actively control the angle of blade twist. (Interestingly, Corbet and Morgan (1992) mention aeroelastic tailoring as a possible method for improved power control, but dismiss it because of the perceived inability of current manufacturing processes to produce blades with sufficient repeatability to make the concept reliable.)

A Kooijman (1996) report on aeroelastic tailoring concludes that “the use of aeroelastic tailoring of the Fibre Reinforced Plastics to control limited torsional deformation is a promising way to improve rotor blade design.” Kooijman evaluates building the elastic coupling into the blade skin. Some of his conclusions for blades designed for the “Smart Rotor” are that:

1. Bending-twist coupling gives the potential for a few percentages of energy yield improvement for constant-speed pitch-controlled turbines and improves starting torque by 10%.
2. Optimal constant-speed pitch-controlled rotor production is obtained with the inboard span twisting to feather and the outboard 60% of the span twisting toward stall as wind speed increases.
3. The coupling is best achieved with hybrid carbon/glass reinforcement in the cross ply direction.
4. Bending-torsion flexibility is about 10% less than a standard construction.

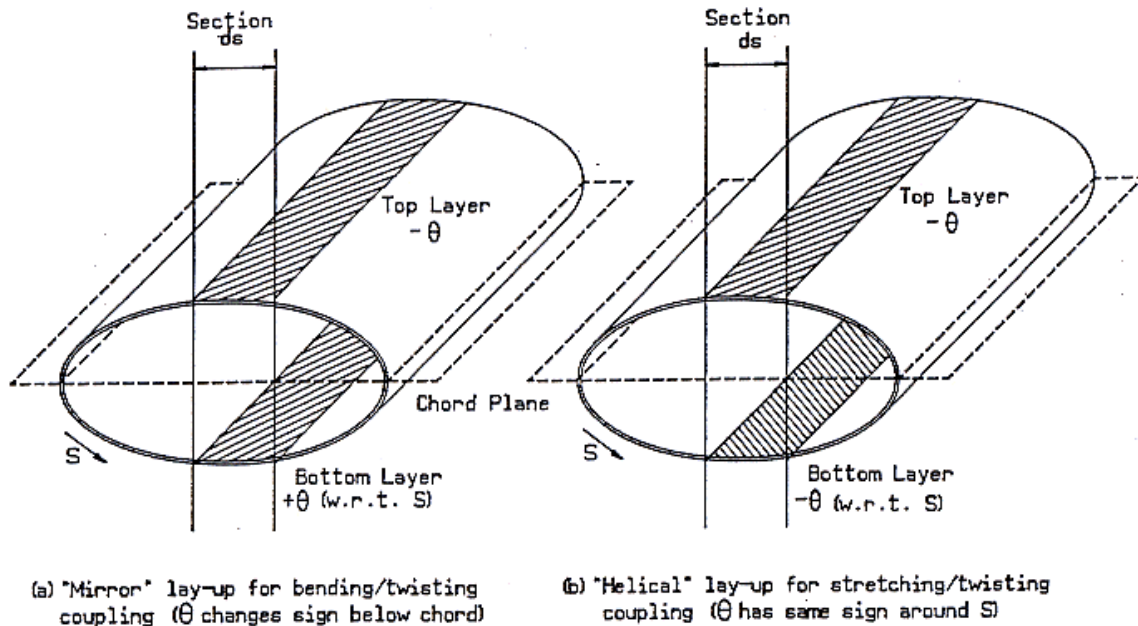


Figure 1: Type of asymmetric lay-ups required to produce (a) bending-twist and (b) tension-twist coupling (from Karaolis, et al., 1988).

A recent *Windpower Monthly* (Feb. 1998) reported that some Lagerwey turbines will include the “TenTorTube” device for passively controlling power and reducing run-away risk. This tube, shown in Figure 2, attaches a pitchable tip to the blade and twists in response to centrifugal loads caused by rotor-speed changes. The mechanism can be locked at low speeds and then used to produce a large change in power at higher rotor speeds. The aramid-epoxy device can be made as long as is needed to produce the desired magnitude of tip rotation. Therefore, large twist angles can be achieved, even with an entirely elastic device.

The ability to design in a few degrees of blade twist was encouraged by a report by Stoddard, et al. (1989) which found a few degrees of elastic twist in blades not intended to have any. They concluded that up to two and a half degrees of twist occur on the blades in the study group (UTRC – 2.6 deg., ESI – 0.4 deg., Carter – 2.0 deg.). Therefore, it should be possible to design in desirable elastic twist in response to rotor loads, either centrifugal or flap, that enhance energy capture performance.

The reorientation of the fiber directions *in the blade skin or spar* to achieve either flap-load or extension-load coupling with blade twist, has potential to be a cost effective and reliable aeroelastic tailoring approach. We seek here to investigate modest blade rotations produced by elastic twist of the blade itself without any additional mechanisms or devices. The helicopter industry has long ago seen the potential in aeroelastic tailoring. The next section includes a summary of helicopter experience. There are a number of possible uses of aeroelastic tailoring in wind turbine applications, each of which is discussed in subsequent sections. Stall enhancement to better regulate and permit larger diameter rotors and improved average energy capture are discussed first. Then dynamic effects including load alleviation and stability issues are reviewed. The manufacturing constraints and opportunities are just beginning to be addressed.

Helicopter Experience

Wind turbines and helicopters, though designed for different objectives, share similar aeroelastic problems. A sizeable rotor dominates behavior of both the systems. Its rotary blades elastically couple with surrounding air and other system components to influence overall performance, vibration, loads, and stability. Because of these similarities, the aeroelastic tailoring techniques developed for helicopter blades can be readily applied to wind turbine blades.

Earlier structural tailoring attempts in the helicopter field (Miller 1956, Hirsch 1956, McCarthy 1955, Daughaday 1957) were limited to tuning of blade chordwise and spanwise mass distributions with a single objective of blade vibration reduction. Later, as the art of blade manufacturing became more sophisticated, aerodynamic means such as blade twist and swept tips were introduced (Blackwell 1983) as a means for controlling vibration.

Most of the subsequent aeroelastic tailoring research is heavily linked with optimization techniques and understandably so. Aeroelastic tailoring is a multidisciplinary problem dealing with a strong coupling amongst blade elasticity, aerodynamics, dynamics, and controls. We cannot, for example, hope to enhance

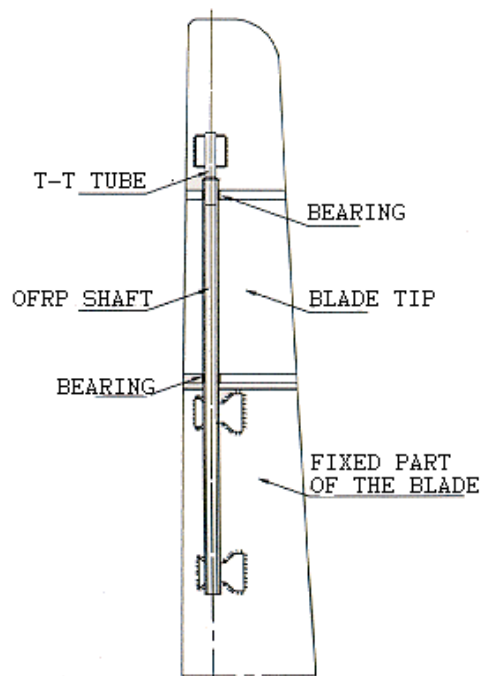


Figure 2: TenTorTube schematic (from Joose and van den Berg, 1996).

performance without influencing vibration or stability. We must use a multi-objective criterion encompassing conflicting demands such as performance enhancement, vibratory response, and load reduction subject to multidisciplinary constraints like aeroelastic stability, resonances, system weight, and aerodynamic shape. Friedman (1983, 1984) and Shanthakumaran (1982) present the first documented optimum structural tailoring efforts to reduce helicopter vibration subject to aeroelastic constraints. The studies considered a four-bladed hingeless rotor (much like most of the wind turbine rigid-blade rotors except that the helicopter blades are softer inplane). The design variables consisted of the blade box-spar geometric parameters, and the blade structural and non-structural masses. The constraints consisted of the flap, lag, and torsion frequencies, and the aeroelastic stability margins. The objective function contained peak-to-peak oscillatory hub shears and hub rolling moments. A general-purpose constrained optimization package (Miura 1979) was used to solve the optimization. Results showed a reduction of 38% in hub shear and a reduction of 25% in hub rolling moment. The blade mass decreased by 20%. Celi et al. (1988, 1987) extended these studies to include double-cell box sections and swept tips. Results indicated vibration reduction between 20-50%; tip sweep reduced vibration by an additional 10%.

Lim and Chopra (1988, 1987) tackled the vibration reduction problem using a more comprehensive formulation. Though this study resembled the previous studies cited, it included a number of substantial contributions, in particular the formulation of a direct analytical approach (1987) for the calculation of the derivatives of hub loads and the blade stability with respect to the design variables. Studies using 25 design variables showed a 20-77% reduction in hub shear and moments. In addition to these fairly comprehensive studies, a number of less ambitious studies, too numerous to be cited, were conducted at universities and industry, wherein the main objective was to explore fundamental aspects of the optimal tailoring problem. Some notable contributions are the study of blade frequencies placement (Peters 1986, 1988), weight reduction (Bielawa 1971), improvement of handling qualities (Celi 1989), and vibration reduction using modal shaping or modal vibration indices (Taylor 1982, Davis 1988, Weller 1988, 1989).

As these optimal tailoring techniques were maturing, metallic blades were rapidly giving way to composite blades. Composites offer several advantages over metals such as superior fatigue characteristics, higher stiffness-to-weight ratio, fabricability of complex-geometry blades, and potential for aeroelastic tailoring. Composite-blade elastic anisotropy can not only be tightly controlled but also varied over the span by appropriate selection of ply angles, thickness, and spanwise lay-up. Resulting anisotropy provides direct bending-axial-torsion elastic couplings not possible with metallic blades.

Early studies on the aeroelastic behavior of composite blades (Hong 1985, Panda 1987) showed that the elastic couplings could have a powerful influence on aeroelastic stability, blade stresses, and loads. These studies, however, did not model precisely the nonclassical phenomena like shear and warping. Smith and Chopra (1991) addressed this limitation. Later, Chandra and Chopra (1991, 1992) used Vlasov theory to extend composite blade modeling to include composite beams of arbitrary sections, including open sections and closed multi-cell sections. These models were integrated into a comprehensive aeroelastic code (Bir, 1990) and used as a starting point for all the subsequent aeroelastic tailoring efforts carried out at the University of Maryland. Friedman et al (1992) were also involved in the development of an aeroelastic-tailoring capability for composite straight and swept-tip blades; results though have not yet been presented. While it had been amply demonstrated that composite couplings can significantly influence rotor vibration and stability, Ganguli and Chopra (1992, 93, 94) were the first to apply a systematic optimization approach to composite tailoring of helicopter blades. The analytical formulation of sensitivity derivatives, a key step in the optimal tailoring process, was extended to cover composite blades. Hitherto, aeroelastic tailoring efforts had been confined to minimization of hub loads only, which at times resulted in higher blade bending moments, leading to higher stresses and reduced blade fatigue life. Ganguli and Chopra (1997) extended aeroelastic-tailoring research to simultaneously minimize both hub loads and blade-

bending moments. Constraints were imposed on blade stability, rotating-blade frequency placement, and autorotational inertia. Results showed significant reductions in both hub and blade loads. Reductions resulted from elastically introduced couplings. Positive flap/torsion elastic coupling, equivalent to a δ_3 of about 35 degrees, reduced hub loads. Reduction of flap, lag, and torsion stiffness at the blade root decreased the blade dynamic stresses. Negative lag/torsion elastic coupling, equivalent to a δ_4 of about -10 degrees, enhanced the lag-mode stability (some readers may be aware that rotor-lag instability is a major issue for helicopters).

Recent research has shown that the blade geometry may also be tailored to gain performance, loads, and stability benefits (Celi 1988). Bir and Chopra (1994) developed a comprehensive model of an advanced geometry blade that involves variable sweep, anhedral, taper, and twist along the blade span. Ganguli and Chopra (1997) integrated this advanced geometry blade with aeroelastic optimization schemes, then simultaneously tailored blade geometry and composite anisotropy to minimize blade stresses and vibration. They performed the tailoring studies on a four-bladed, soft-inplane hingeless rotor with variable sweep, taper, and anhedral, and with a two-cell composite box spar. The tailored blade achieved a reduction of 40-60% in the 4/rev hub loads, and a reduction of 15-25% in the peak-to-peak vibratory blade flap and lag bending moments.

As noted earlier, the objective function for a helicopter rotor design differs somewhat from that for a wind turbine blade. For a mission-driven helicopter design, the emphasis is on maximizing rotor in-plane stability and minimizing vibration without deteriorating performance and fatigue life. For a cost-driven wind turbine design, the emphasis is on enhancing or regulating power without adversely affecting fatigue loads, blade response, and system stability. The general optimal aeroelastic tailoring approach however is similar for both systems. The nature of design variables is also the same for both helicopter and wind turbine blades. Wind turbine research can save substantial time and developmental cost by adapting well-established tailoring/optimization and code-integration techniques developed for helicopters over the last two decades.

Steady Effects on Average Power

Constant Speed Stall Control

Enhanced stall control of wind turbines has been used in the past to improve the energy capture of rotors by allowing the rotor size to grow while maintaining a low maximum rating on other components in the system. Tangler and Somers (1995) and Klimas (1984) have published families of airfoils that have since been used to stall regulate turbines at lower power levels with the associated reduced system cost of energy. An aeroelastically tailored blade that twists to stall in response to flap loads has a similar effect.

Lobitz and Veers (1996) examined generic coupling effects on annual energy production of a stall regulated HAWT. The blades were assumed to twist to stall, reducing maximum power. The rotor diameter was then increased to bring maximum power back up to the initial level. Twist levels were specified in maximum amplitude and spanwise variation and allowed to vary with wind speed in linear and quadratic manners. A twist proportional to power was also used. It was discovered that the details of spanwise variation or how the twist varied with wind speed (or power) had only minor impacts. The twist-coupled blades combined with larger rotors increase power in the important middle-range of wind speeds while power in high winds remains the same. Figure 3 shows the increase in annual energy as a function of the annual average wind speed. The three lower curves are for a maximum twist angle of one degree (increasing energy by about 5%) and the top curves are for a maximum twist of two degrees (resulting in energy gains of about 10%). The improvements are not overly sensitive to the wind resource.

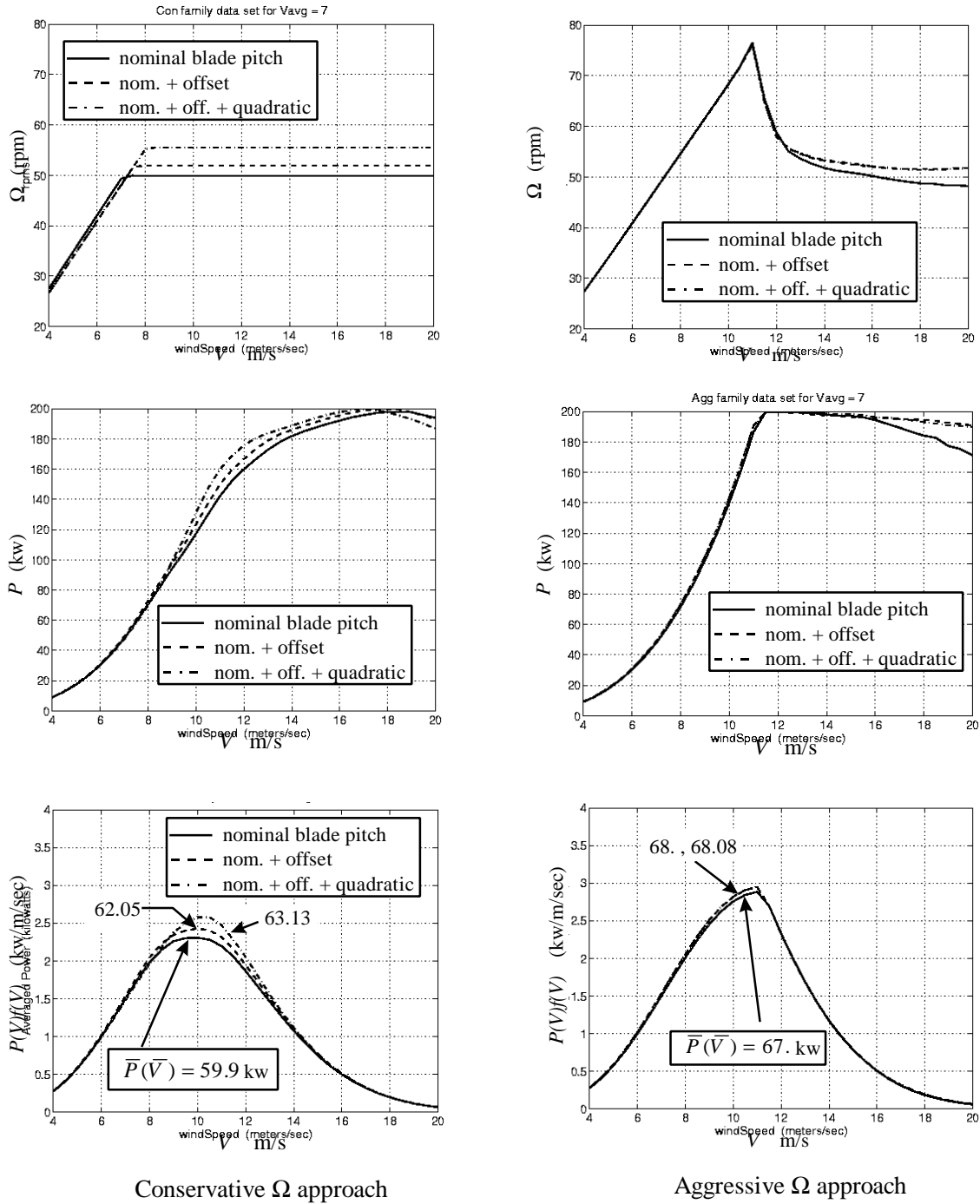


Figure 5: Summary of twist-tension coupling on variable speed systems. The left side are the (conservative) realistic speed control options while the right show the (aggressive) theoretical best case (Eisler and Veers, 1998).

Large angles of twist and large rotor diameter changes were also investigated. Figure 4 shows how the energy capture increases with maximum angle of twist averaged over a range of mean wind speeds. The increase in rotor radius and rotor area are plotted on the same scale. Notice that for twist angles less than seven degrees the energy increase exceeds the growth in swept area. For larger twist angles the benefits drop off substantially.

Care needs to be used, however, when predicting performance enhancements based on fine tuning a stall-controlled rotor. Predicting power output in deep-stall has a very high uncertainty. Field data is required to prove that aeroelastic enhancement of stall control can be reliably achieved.

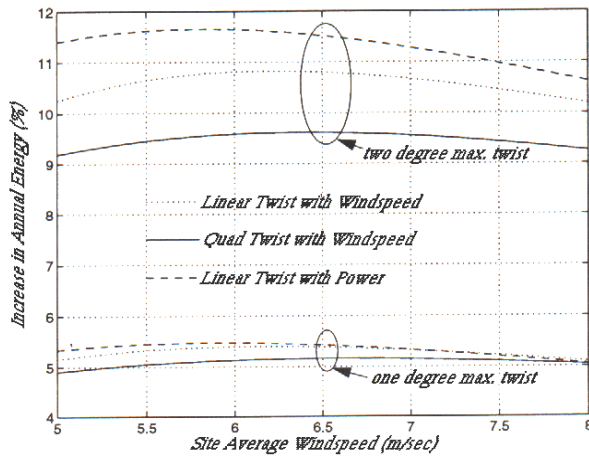


Figure 3: Annual Energy increase for different amounts and types of twist coupling at different sites (Lobitz and Veers, 1996).

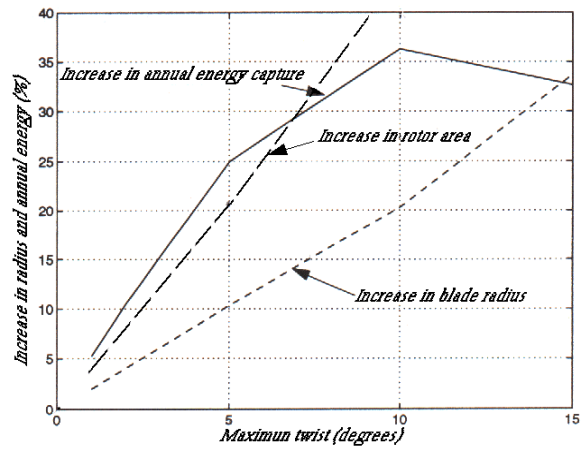


Figure 4: Increase in rotor size and annual energy from enhanced stall as a function of twist angle (Lobitz and Veers, 1996).

Variable Speed with Stall Control

It can be argued that with variable speed and pitch control, there is no need for additional power control from any other source. Even stall-controlled variable-speed systems can theoretically control power by slowing the rotor down to achieve a flat power regulation. The question is whether the twist-coupled blade can be used to achieve enough of the functionality of an active control device (pitch control, for example) with a more reliable and inexpensive passive approach.

Eisler and Veers examine the performance gains from adaptive blades on a variable speed machine when compared to the perfect performance of a system that runs at peak C_p below rated power and at maximum power at all higher wind speeds. Converging on this theoretical limit without a pitching system is the goal. A 300 KW baseline turbine (the AWT-26) was required to regulate at 200 KW in the study to insure that the speed control or aeroelastic tailoring would play a large role in regulating the power. The blade design (choice of airfoils, unstressed twist, chord length, blade length, etc.) was held constant in the study.

Competing speed-control approaches are compared. An “aggressive” approach assumes that you can achieve the perfect power curve by operating at any speed required to produce the desired power. The end result is the same power curve as for variable speed with pitch control and matches the theoretical limit (Carlin, 1997). A “conservative” approach assumes that peak efficiency is tracked up to some point, but that the rotor speed needs to be limited to the speed that produces maximum power at any higher wind speed, with the result that the generator is never relied upon to slow down the rotor in high winds. The plots in Fig. 5 illustrate the approach and results. The top two plots show rotor speed versus wind speed for the conservative (left) and aggressive (right) approaches. The middle plots show the resulting power curves. The perfect power curve has a sharp corner at the rated power while the conservative approach has a rounded corner coming up to rated power. The bottom curves show energy density (power multiplied by the wind speed distribution) for a 7 m/s Rayleigh site.

Speed control alone could not be used to produce the perfect power curve shown in Fig. 5; the speed changes are much too rapid over a very small wind speed range. In addition, the rotor is required to slow down quickly as the wind speed increases just at the point when the rotor is producing rated power. The generator in such a system would require a large excess capacity, or “headroom” (Muljadi, et al., 1996).

The results were produced using an optimization procedure to drive the PROP-PC code (Tangler, 1987). It estimated the best choices for rotor speed, pitch offset, and coefficient on a quadratic twist to rotor speed relationship meant to model centrifugally driven twist coupling. The rotor size was not allowed to change. If the aggressive approach were possible without pitch control, there is no room to improve the power curve with twist coupling. The conservative approach resulted in a 9-12% loss in annual energy. An adaptive blade can be used to get closer to the theoretical maximum. The centrifugal-coupled twist brings back some of the performance in the mid range, making up between 1/3 and 1/2 of the difference between the conservative speed control and the theoretical maximum. The total improvement is 4-5%, although up to 3% could be regained with an optimized pitch offset. In low wind sites, the optimum pitch offset was almost as good as aeroelastic coupling. Results for flap-twist coupling were almost identical to centrifugal-twist coupling in this application.

The variable-speed, stall-regulated concept is now in use. The Wind World turbines being installed offshore of Sweden use this control approach (*Windpower Monthly*, 1998). These turbines use variable speed with a power converter rated at one third of the maximum, and then switch to constant speed operation in winds above about 8 m/s. This is one example of a configuration that might benefit from adaptively enhanced stall control based on centrifugally coupled twist.

Dynamic Effects

Dynamic Stability

Whenever the wind turbine blade becomes aeroelastically “active,” that is, the elastic deformations play a role in the aerodynamic loading, dynamic stability will be affected. Lobitz and Veers (1998) address two of the most common stability constraints, namely flutter and divergence. Flutter is the condition where the phasing between the aerodynamic load fluctuations and elastic deformations are such that a resonant condition is achieved. Every wing will have a flutter boundary at some speed; for wind turbines the boundary is defined at the rotational speed (typically determined in still air) at which the blade will flutter. The stability margin is the difference between the flutter speed and normal operating speed. Divergence is a quasi-static condition where the blade twists in response to increasing load in a direction that further increases the load. If this condition exists on a blade there will be an operating speed at which the increase in loads caused by the deformation exceeds the ability of the blade to resist the load, called divergence.

The stability boundaries were determined with respect to the amount of twist coupling built into the blade. A coupling coefficient, α , was defined to facilitate the generic examination of stability effects. For a blade with bending-twist coupling, the matrix equation for blade bending and twisting strains \mathbf{e}_b and \mathbf{e}_t due to bending and twisting loads M_b and M_t are

$$\begin{bmatrix} EI & -g \\ -g & GK \end{bmatrix} \begin{Bmatrix} \mathbf{e}_b \\ \mathbf{e}_t \end{Bmatrix} = \begin{Bmatrix} M_b \\ M_t \end{Bmatrix}, \quad (1)$$

where EI and GK are the beam bending and torsional stiffness, respectively. The coupling coefficient, g , is constrained to values that keep the system positive definite. The range of realizable g values is limited to

$$g = a\sqrt{EIGK}; \quad -1 < a < 1. \quad (2)$$

Using the NREL Combined Experiment Blade properties, the flutter and divergence stability boundaries were mapped over the range of possible α 's. Results are shown in Figure 6. The stability boundaries are not exceeded even with coupling levels up to 80% of the theoretical maximum. The stability margin decreases toward the extreme values of the coupling coefficient. For positive α , the blade bends downwind and twists toward stall, increasing angle of attack and also increasing loads. The divergence constraint comes closest to the operating speed at high positive α values. Conversely, for negative α , the blade twists toward feather reducing aeroloads. In this region it is increasingly difficult to get the blade to diverge, but the flutter boundary moves closer to the operating speed.

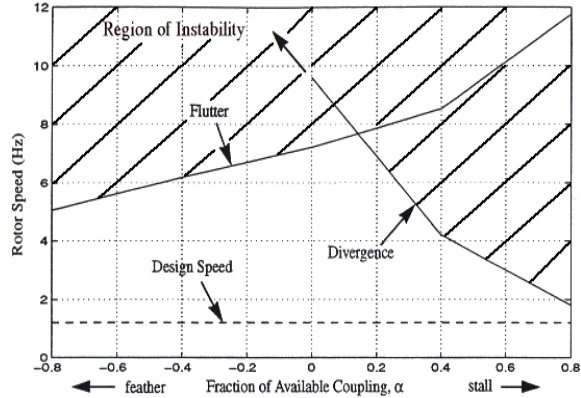


Figure 6: Regions of instability due to twist coupling in the blade (Lobitz and Veers, 1998).

Another important stability constraint, stall flutter, is yet to be investigated for twist-coupled blades. Efforts are underway at NREL to adapt the *umarc* analysis code for rotor dynamics to wind turbine applications. Among the many benefits of this development will be a stall-flutter analysis capability.

Unsteady Aerodynamic Performance

Fingersh and Carlin (1998) report that the losses in variable speed systems due to the inability of the rotor to run exactly at the desired tip speed ratio to maintain peak efficiency, “tracking losses,” might be as high as 10% in the region of peak efficiency, leading to about a 5% loss of annual energy. It can be shown that these losses are proportional to the turbulence intensity of the winds and the curvature at the peak of the C_p curve. Therefore, a good way to reduce these losses is by reducing the curvature in the C_p curve. A flat top on the curve would allow a variable speed turbine to operate at maximum efficiency over a range of tip speed ratios making the turbine less sensitive to fluctuating wind speed. A blade that twists in response to varying flap loads could have a passive mechanism to produce a broader peak in the C_p curve. However, detailed studies on this topic have not been done to date. Because of the relatively small range of wind speed over which the changes in blade configuration are required, it may be difficult to achieve a substantial benefit.

Fatigue Load Reduction

Twisting to feather in response to increasing winds is a potential means to reduce the dynamic loading on the blades, and hence the rest of the system. Eggers et al. (1996) demonstrated load reductions by linking a pitch control system to flapwise blade loads using simple integral control. The results shown in Figure 7 indicate that they could reduce the rms blade bending response to turbulent winds by about half. And this was accomplished with rms pitching angles of 3 degrees if 1/3 span ailerons are used and substantially less with full-span pitch control. The fatigue implications of such a substantial decrease in cyclic loading are enormous, measured in increased lifetime or reduced blade weight. Their calculations omit some important factors, most notably spatial variation in the wind and therefore the per rev contribution to loading so important to wind turbines. However, the load reductions are dramatic enough that it would be hard to imagine that some significant portion would not remain when the full dynamics of the loading are considered.

An aeroelastically twisting blade is similar to the control system investigated by Eggers in that the blade pitch angle would respond to bending loads in a way similar to a proportional, rather than an integral, controller. The low frequency response of the two would be quite similar; the aeroelastically tailored blade would attenuate loads out to the frequency of the first combined bending/torsion mode of the blade, typically above the first few per rev frequencies.

The ability of bending-twist coupled blades to attenuate (or exacerbate) the cyclic loading is being investigated in a Sandia National Laboratories contract with the University of Utah. The Utah researchers will use ADAMS/WT simulations of a generic constant-speed, stall-controlled wind turbine to evaluate the fatigue loading influence of various levels and directions of twist coupling.

Design and Manufacturing

Just because there are potential benefits from aeroelastic tailoring does not mean that the blades can be manufactured to produce the necessary coupling. There are limits to the amount of coupling that can be achieved with asymmetric fiber lay-ups. The best direction and the maximum coupling are a function of the fiber and matrix properties. Tsai and Ong (1998) indicate that stiffer fiber materials result in the higher coupling levels, with maximum α for flat plates just below 0.8 for a graphite-epoxy system and 0.6 for a glass-epoxy system. The carbon system achieves maximum coupling with all the fibers at about 20 degrees to the axis of bending while the glass maximum is at about 25 degrees. These theoretical maxima, however, do not account for the need for off-axis strength and toughness, nor do they apply directly to cross sections other than flat plates.

Karaolis (1988) has mapped out the best combinations of two direction lay-ups to maintain strength and produce twist coupling in an airfoil shape. The results indicate that the best coupling can be achieved with the off-axis fibers oriented at about 20 degrees to the spanwise axis of the blade. Tsai and Ong (1998) find the same result for the D-spar shape. Karaolis predicts that with this configuration twists on the order of just under one degree per meter of span can be achieved based upon limits to maximum strain in the blade. The Tsai and Ong results indicate that graphite-epoxy D-spars have maximum couplings around $\alpha = 0.55$ while glass-epoxy D-spars max out at around $\alpha = 0.4$. Interestingly, hybrid glass and graphite lay-ups, using the graphite to get the coupling and the glass to provide the off-axis strength, do just as well as all graphite. The major reasons for the reduction from the flat plate α 's are the need for fibers in other orientations (to provide robust, omnidirectional strength and panel buckling resistance) and the vertical "rib" on the spar. Kooijman, who also recommends 20 degree reinforcement, suggests that the coupling is maximized by avoiding 45 degree lay-ups in the rib.

The manufacturing process will depend on the type of coupling to be produced. Fiber winding is well suited to producing stretch-twist coupling in a spar, while clam-shell construction with the top and bottom skins manufactured separately is best suited to bend-twist coupling (see Fig. 1).

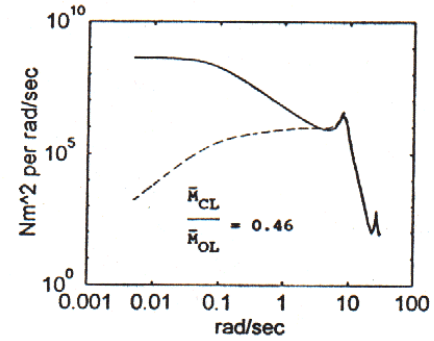


Fig. 11(a) 20 m/s

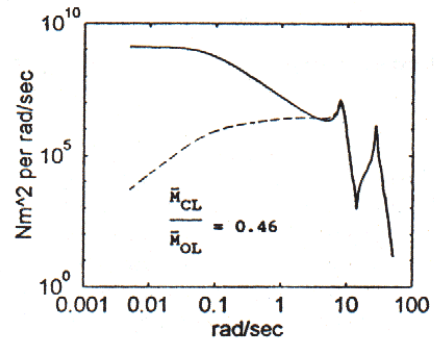


Figure 7: PSDs of loads with (dashed) and without (solid) bending load feedback control at wind speeds of 20 m/s (top) and 30 m/s (bottom) (Eggers et al., 1996).

Conclusions

There are several potential advantages of aeroelastically tailored wind-turbine blades. For stall-controlled rotors, both constant and variable speed, there are large annual energy gains (around 25%) to be made by enhancing the stall regulation while growing rotor diameter. On pitch-controlled machines, there are much smaller gains (1-3%) to be had by optimizing the aeroelastic blade design over the operating range. On variable-speed, pitch-controlled machines, the best opportunity is to replace the pitch mechanism with a passive twist coupling that replaces some of the lost energy production (1/3 to 1/2) while improving reliability and lowering installed cost.

There is great potential, but just as great uncertainty, about the ability to attenuate fatigue loads. Research in the helicopter field indicates that the potential is certainly there. Stability margins are likely to be reduced, but not necessarily to dangerous levels. Stall flutter is yet to be evaluated. Twist coupling designed into the blade skin is likely to be limited to coupling coefficients (α) of about 0.5. The ability to attenuate loads in the dynamic environment of wind turbine blades has been suggested with active feedback control. Realizing similar improvements with passive aeroelastic coupling must be first evaluated with fully capable aeroelastic models of the wind turbine system and must then be evaluated in controlled field experiments before the benefits can be considered proven. Work on these areas is already in progress.

References

- Bielawa, R. L. (1971) "Techniques for Stability Analysis and Design Optimization with Dynamic Constraints of Nonconservative Linear Systems," AIAA Paper 71-388.
- Bir, G., Chopra, I., Nguyen, K. (1990) "Development of UMARC (University of Maryland Advanced Rotor Code)," *Proc. of the 46th Annual National Forum of the AHS*, Washington, D.C., May 1990.
- Bir, G., and Chopra, I. (1994) "Aeroelastic Stability of Rotorcraft with Advanced Geometry Blades," *Mathematical and Comp. Modeling*, Vol. 19, No. 34, Feb. 1994.
- Blackwell, R. H. (1983) "Blade Design for Reduced Helicopter Vibration," *Journal of the American Helicopter Society*, Vol. 28, No. 3, pp. 33-41.
- Bottrell, G. W. (1981) "Passive Cyclic Pitch Control for Horizontal Axis Wind Turbines," Proceedings of Wind Turbine Dynamics, NASA Conf. Pub. 2185, DOE Pub. CONF-810226, Cleveland, OH.
- Carlin, P. (1997) "Analytical Expressions for Maximum Wind Turbine Average Power in a Rayleigh Wind Regime," *1997 ASME Wind Energy Symposium* held at 35th AIAA Aerospace Sciences Meeting and Exhibition, Reno, NV, Jan. 6-9, 1997.
- Celi, R. (1987) "Aeroelasticity and Structural Optimization of Helicopter Rotor Blades with Swept Tips," *Ph.D. Dissertation*, Mechanical, Aerospace and Nuclear Engineering Dept., UCLA.
- Celi, R., and Friedman, P. P. (1988) "Structural Optimization with Aeroelastic Constraints of Rotor Blades with Straight and Swept Tips," *AIAA Paper 88-2297*; also, *AIAA Journal*, Vol. 28, No.5.
- Celi, R. (1989) "Optimum Design of Helicopter Rotors for Longitudinal Handling Qualities Improvement in Forward Flight," AIAA Paper 89-1270.
- Chandra, R., and Chopra, I. (1991) "Experimental and Theoretical Analysis of Composite I-Beams with Elastic Couplings," *AIAA Journal*, Vol. 29, No. 12.
- Chandra, R., and Chopra, I. (1992) "Structural Behavior of Two-Cell Composite Rotor Blades with Elastic Couplings," *AIAA Journal*, Vol. 30, No. 12.
- Cheney, M. C. and Speirings, P. S. M. (1978) "Self Regulating Composite Bearingless Wind Turbine," *Solar Energy*, Vol. 20.
- Corbet, D. C. and Morgan, C. A. (1992) "Report on the Passive Control of Horizontal Axis Wind Turbines," ETSU WN 6043, Garrad Hassan and Partners, Bristol, UK.
- Currin, H. (1981) "North Wind 4kW 'Passive' Control System Design," *Proc. Wind Turbine Dynamics*, NASA Pub. 2185, DOE Pub. CONF-810226, Cleveland, OH.

- Daughaday, H., DuWaldt, F., and Gates, C. (1957) "Investigation of Helicopter Blade Flutter and Load Amplification Problem," *J. of the American Helicopter Soc.*, Vol. 2, No. 3, pp. 27-45.
- Davis, M. W., and Weller, W. H. (1988) "Application of Design Optimization Techniques to Rotor Dynamics Problems," *J. of the AHS*, Vol. 33, No. 3, July, pp. 42-50.
- Eggers, A. J. Jr., Ashley, H., Rock, S. M., Chaney, K., and Digumarthi, R. (1996) "Effects of Blade Bending on Aerodynamic Control of Fluctuating Loads on Teetered HAWT Rotors," *J. of Solar Energy Engr.*, Vol. 118, No. 4, Nov. 1996.
- Eisler, G. R. and Veers, P. S. (1998) "Optimization Applied to Adaptive Blade Use on a Variable-Speed Wind Turbine," Sandia National Laboratories, to be published.
- Fingersh, L. and Carlin, P. (1998) "Results from the NREL Variable-Speed Test Bed," AIAA-98-0050, Proc. 1998 ASME Wind Energy Symposium held at 36th AIAA Aerospace Sciences Meeting and Exhibition, Reno, NV, Jan. 12-15, 1998.
- Friedmann, P. P., and Shanthakumaran, P. (1983) "Aeroelastic Tailoring of Rotor Blades for Vibration Reduction in Forward Flight," *AIAA Paper 83-0916*,.
- Friedmann, P. P., and Shanthakumaran, P. (1984) "Optimum Design of Rotor Blades for Vibration Reduction in Forward Flight," *Journal of the AHS*, Vol. 29, No. 4, pp. 70-80.
- Friedmann, P.P., Venkatesan, C., and Yuan, K. (1992) "Development of a Structural Optimization Capability for the Aeroelastic Tailoring of Composite Rotor Blades with Straight and Swept Tips," 4th AIAA Symp. on Multidisciplinary Analysis and Optimizations, Cleveland, Ohio, Sept. 1992.
- Ganguli, R., and Chopra, I. (1992) "Aeroelastic Optimization of a Composite Helicopter Rotor," *Fourth AIAA Symposium on Multidisciplinary Analysis and Optimizations*, Cleveland, Ohio, Sept. 1992.
- Ganguli, R., and Chopra, I. (1993) "Aeroelastic Optimization a Helicopter Rotor with Composite Tailoring," *Proceedings of the 49th Annual Forum and Technology Display of the American Helicopter Society*, St. Louis, Missouri, May 19-21, 1993.
- Ganguli, R., and Chopra, I. (1994) "Multi-Objective Optimization of a Composite Helicopter Rotor," Presented at the 35th Structures, Structural Dynamics and Materials Conference and Adaptive Structures Forum, April 1994.
- Ganguli, R., and Chopra, I. (1997) "Aeroelastic Tailoring of Composite Couplings and Blade Geometry of a Helicopter Rotor Using Optimization Methods," *Journal of the AHS*, Vol. 42, No. 3.
- Hirsch, H., Dutton, R. E., and Rasamoff, A. (1956) "Effects of Spanwise and Chordwise Mass Distribution on Rotor Blade Cyclic Stresses," *Journal of the AHS*, Vol. 1, No. 2, pp. 37-45.
- Hohenemser, K. H. and Swift, A. H. P. (1981) "Dynamics of an Experimental Two Bladed Horizontal Axis Wind Turbine with Blade Cyclic Pitch Variation," *Wind Turbine Dynamics*, NASA Pub. 2185, DOE Pub. CONF-810226, Cleveland, OH.
- Hong, C.H., and Chopra, I. (1985) "Aeroelastic Stability of a Composite Blade," *Journal of the AHS*, Vol. 30, No. 2.
- Joose, P. A. and van den Berg, R. M. (1996) "Development of a TenTorTube for Blade Tip Mechanisms," P7.17, Proc., 1996 European Union Wind Energy Conf. and Exhib., Göteborg, May 20-24, 1996.
- Karaolis, N. M., Mussgrove, P. J., and Jeronimidis, G. (1988) "Active and Passive Aeroelastic Power Control using Asymmetric Fibre Reinforced Laminates for Wind Turbine Blades," Proc. 10th British Wind Energy Conf., D. J. Milbrow Ed., London, March 22-24, 1988.
- Karaolis, N. M., Jeronimidis, G., and Mussgrove, P. J. (1989) "Composite Wind Turbine Blades: Coupling Effects and Rotor Aerodynamic Performance," Proc., EWEC'89, European Wind Energy Conf., Glasgow, Scotland, 1989.
- Klimas, P. C. (1984) "Tailored Airfoils for Vertical Axis Wind Turbines," SAND84-1062, Sandia National Laboratories, Albuquerque, NM.
- Lim, J., and Chopra, I. (1987) "Design Sensitivity Analysis for an Aeroelastic Optimization of a Helicopter Rotor," AIAA Paper 87-0923.

- Lim, J., and Chopra, I. (1988) "Aeroelastic Optimization of a Helicopter Rotor," *Proc., 44th Annual Forum of the AHS*, Washington DC, June 1988, pp. 545-558.
- Lobitz, D. L., Veers, P. S., and Migliore, P. G. (1996) "Enhanced Performance of HAWTs Using Adaptive Blades," *Proc. Wind Energy '96, ASME Wind Energy Symposium*, Houston, Jan. 29 - Feb. 2, 1996.
- Lobitz, D. L. and Veers, P. S. (1998) "Aeroelastic Behavior of Twist-Coupled HAWT Blades," AIAA-98-0029, *Proc. 1998 ASME Wind Energy Symposium* held at 36th AIAA Aerospace Sciences Meeting and Exhibition, Reno, NV, Jan. 12-15, 1998.
- McCarthy, J. L., and Brooks, G. W. (1955) "A Dynamic Model Study of the Effect of Added Weights and Other Structural Variations on the Blade Bending Strains of an Experimental Two-Blade Jet-Driven Helicopter in Hovering and Forward Flight," *NACA TN-3367*.
- Miller, R.H., and Ellis, C.W. (1956) "Helicopter Blade Vibration and Flutter," *Journal of the American Helicopter Society*, Vol. 1, No. 3, pp. 19-38.
- Miura, H., and Schmit, L. A. (1979) "NEWSUMT- A Fortran Program for Inequality Constrained Function Minimization- User's Guide." *NASA CR- 159070*.
- Panda, B., and Chopra, I. (1987) "Dynamics of Composite Rotor Blades in Forward Flight," *Vertica*, Vol. 11, No. 1-2.
- Peters, D. A., Rossow, M. P., Korn, A., and Ko, T. (1986) "Design of Helicopter Rotor Blades for Optimum Characteristics," *Computers and Mathematics with Appls.*, Vol. 12A, No.1, pp. 85-109.
- Peters, D. A., and Cheng, Y. P. (1988) "Optimization of Rotor Blades for Combined Structural Performance and Aeroelastic Constraints," *Proc., Recent Advances in Multidisciplinary Analysis and Optimization*, NASA CP-3031, Pt. 1, pp. 163-180.
- Shanthakumaran, P. (1982) "Optimum Design of Rotor Blades for Vibration Reduction in Forward Flight," *Ph.D. Dissertation*, Mechanics and Structures Dept. UCLA.
- Smith, E. C., and Chopra, I. (1991) "Formulation and Evaluation of an Analytical Model for Composite Box Beams," *Journal of the American Helicopter Society*.
- Stoddard, F., Nelson, V., Starcher, K., Andrews, B. (1989) "Determination of Elastic Twist in Horizontal Axis Wind Turbines," AEI, West Texas State Univ., SERI Cntr. RL-6-06013, NREL, Golden, CO.
- Tangler, J. (1987) "A Horizontal Axis Wind Turbine Performance Prediction Code for Personal Computers," Solar Energy Research Institute, Golden, CO.
- Tangler, J. and Somers, D. (1995) "NREL Airfoil Families for HAWTs," *Proc. Windpower '95*, American Wind Energy Association, Washington D. C.
- Taylor, R. B. (1982) "Helicopter Vibration by Rotor Blade Modal Shaping," *Proc., 38th Annual Forum of American Helicopter Society*, Anaheim, CA, May, pp. 90-101.
- Tsai, S. and Ong, C-H. (1998) , "D-Spar Blade Design and Manufacture," unpublished contractor reports, Sandia National Laboratories contract BB-6066 Stanford University.
- Weller, W. H., Davis, M. W. (1988) "Experimental Verification of Helicopter Blade Design Optimized for Minimum Vibration," *Proc., 44th Annual National Forum of the American Helicopter Society* , Washington, DC, June 1988, pp. 263-279.
- Weller, W. H., Davis, M. W. (1989) "Wind Tunnel Tests of Helicopter Blade Design Optimized for Minimum Vibration," *Journal of the AHS*, Vol. 34, No. 3, July 1989, pp. 40-50.
- Windpower Monthly* (1998) February Windtech Notes, compiled by D. Milborrow, pp. 42-43.