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ACTIVE AERODYNAMIC LOAD CONTROL OF WIND TURBINE BLADES*

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ABSTRACT
The cost of wind-generated electricity can be reduced by mitigating fatigue loads acting on the rotor blades of wind turbines. One way to accomplish this is with active aerodynamic load control devices that supplement the load control obtainable with current full-span pitch control. Thin airfoil theory suggests that such devices will be more effective if they are located near the blade trailing edge. While considerable effort in Europe is concentrating on the capability of conventional trailing edge flaps to control these loads, our effort is concentrating on very small devices, called microtabs, that produce similar effects. This paper discusses the work we have done on microtabs, including a recent simulation that illustrates the large impact these small devices can exert on a blade. Although microtabs show promise for this application, significant challenges must be overcome before they can be demonstrated to be a viable, cost-effective technology.

INTRODUCTION
Wind energy is the fastest growing source of energy in the world today, with an average growth rate for the past 10 years of nearly 30% per year [1]. Although the contribution of wind to the world electrical energy consumption is currently less than 1%, the contribution is substantial in some individual countries. In Demark, for instance, approximately 22% of electricity comes from wind, in Spain, approximately 8%, and in Germany, approximately 5% [1]. For many utility companies in the U.S., wind energy has become not only the renewable energy of choice, but the least-cost option for new generation. However, there are numerous reasons to continue to further reduce the wind-energy cost of energy (COE). Two of these reasons are 1) increases in raw material costs are driving up the cost of turbines (and thus increasing COE) and 2) wind-generated COE is currently competitive only at the higher-wind sites that tend to be far from population centers (thus requiring the building of costly transmission lines to get the electricity to market).

One way to reduce the COE is to limit the fatigue or

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oscillating loads (rapid changes in loads caused by interaction of the blades with the wind) that a turbine rotor must withstand. These fatigue loads are often a primary consideration in turbine design. If the level of these loads can be reduced, some of the material can be removed from the rotor, tower, and drive train, reducing the capital cost of the turbine and the COE. Alternatively, a larger diameter rotor can be placed on the existing tower and drivetrain, resulting in additional energy capture and reducing the COE.

Oscillating or fatigue loads occur as a result of rotor yaw errors, wind shear, wind upflow, shaft tilt, wind gusts, and turbulence in the wind flow. Methods to control these loads include blade pitch control, blade twist control, and active aerodynamic devices (including, but not limited to, active trailing-edge flaps or ailerons and microtabs).

On most modern, large scale wind turbines, such as the GE 1.5 MW machines shown in Fig. 1, pitch control (pitching each blade around its longitudinal axis to change the effective angle of attack with respect to the wind) is used to limit peak power and average loads. Traditionally, pitch control has been used in a collective mode (i.e., in a programmed sequence, including phase shifts to account for timing on the individual blades) to relieve the fatigue loads due to yaw errors, wind shear, up flow and shaft tilt. However, as pointed out by Bossanyi [2] this mode of control is not able to address the loads due to wind gusts and turbulence. Significant research effort is now being focused on individual blade pitch control to further reduce loads. Here each blade pitches more or less independently as necessary to control gust loading, etc. on that particular blade. Use of individual pitch has been shown by Larsen, Madsen and Thomsen [3] and Bossanyi [2] to result in reductions in loads, compared with collective pitch. According to Larson et al [3], the use of cyclic pitch can reduce the blade flap fatigue loads at the hub by 15%, while the use of individual pitch can reduce them by 28%. They also show that the extreme load for the blade flap at the hub can be reduced 22% when using cyclic pitch and 14% when using individual pitch. Bossanyi [2] concludes that use of individual pitch control can result in a reduction of fatigue loads at the blade hub of 30 – 40%.

Individual pitch control is subject to two major limitations. First, the entire blade must be pitched – with the larger wind turbines being built today, the conditions along the blade are not uniform. Thus, it is impossible to relieve fatigue loads due to wind gusts and turbulence over the entire blade with individual pitch. Second, the blade cannot pitch rapidly enough to relieve the oscillating loads due to wind gusts that have rise times on the order of a couple of seconds and last for 5 – 10 seconds. (The International Electrotechnical Commission wind turbine design standard calls for consideration of an extreme gust that lasts for 10 seconds where the wind speed increases by 35% from the mean wind in a period of just over two seconds [4]). In addition, use of individual pitch on turbines already in the field and not designed with this type of rapid control in mind will lead to premature wear-out of the pitch mechanism, as that mechanism was never designed for the heavy use it will see in this scenario. Challenges in implementing individual pitch control include response time requirements to respond to load perturbations, the impact of these requirements on pitch motor size, and the power required to drive this system.

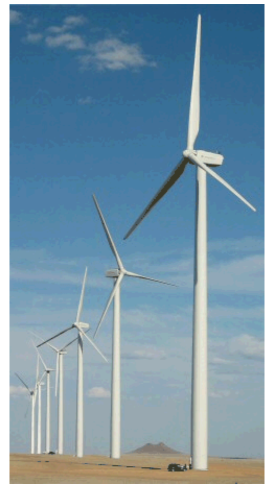


Figure 1. GE 1.5 MW Wind Turbines in the Colorado Green wind farm near Lamar, Colorado. The item at the base of the closest turbine is a minivan.

Passive blade bend-twist control is another concept for controlling the fatigue loads on a wind turbine blade [5-9]. Here, the twist distribution of the blade changes as the blade bends under the influence of the aerodynamic loads. According to Lobitz, Veers, Eisler, Laino, Migliore and Bir [6], bend-twist coupling can lead to a 20 – 70% decrease in fatigue damage (corresponding to a 20 – 30% decrease in fatigue loads) to the turbine. Passive bend-twist coupling is an integrated effect and is totally dependent upon the design of the blade – its response cannot be tailored on site to suit local conditions.

Active blade twist control can conceptually be achieved by embedding active laminates such as piezoelectric material in the spar caps of the blade. Hurdles faced by active blade twist control include blade structural integrity concerns, the cost of the active materials, and actuation power requirements.

ACTIVE AERODYNAMIC LOAD CONTROL DEVICES

The only way to reduce fatigue loads that are random and that vary along a blade is with active local load control devices that can respond quickly to changes in local flow conditions. Numerous investigations [10-18] suggest that significant further load reduction is possible through the use of active load control devices responding to local conditions on each blade. Investigation of the lift curve characteristics of active load control devices reveals that these devices affect the lift curve of an airfoil in one of two ways; those that modify the flow field by extending the lift curve of the airfoil to stall at a higher angle of attack as illustrated in Fig. 2(a), and those that effectively change the camber of the blade by shifting the entire lift curve slope up or down, as illustrated in Fig. 2(b). While either type may be effective in increasing the lift generated by an airfoil, only the latter type is effective in decreasing the lift and thus mitigating the loads.

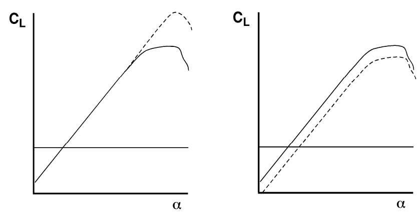


Figure 2: Effect of active aerodynamic devices on airfoil lift curve. Solid line is original airfoil, dashed line is airfoil with device. (a): Flow modification devices, (b): Effective camber modification devices

Perhaps the central question for active load control design is: "Is there a preferred chord location on the airfoil where these devices are most effective?" From thin airfoil theory [19][†]

$$C_\ell = 2\pi\left(\alpha + \frac{2}{\pi}\int_{x/c=0}^{+1} \frac{d(y_c/c)}{d(x/c)} \frac{\sqrt{\frac{x}{c}(1-\frac{x}{c})}}{\frac{x}{c}-1} d(x/c)\right) \quad (1)$$

where

α is the angle of attack of the chord line
$y_c(x)$ is the camber line of the airfoil
$\frac{d(y_c/c)}{d(x/c)}$ is the slope of the camber line
x/c is the non-dimensional distance from the leading edge
c is the chord length

Thus the lift has two components:

$$C_{\ell\alpha} = 2\pi\alpha \quad (2)$$

is the lift due to airfoil angle of attack

$$C_{\ell c} = 4\int_{x/c=0}^{+1} \frac{d(y_c/c)}{d(x/c)} \frac{\sqrt{\frac{x}{c}(1-\frac{x}{c})}}{\frac{x}{c}-1} d(x/c) \quad (3)$$

is the lift due to airfoil camber

Inspection of Equation (3) reveals that the effect of camber disappears at the leading edge (*x/c* = 0) and is maximum at the trailing edge of the blade. If $\frac{d(y_c/c)}{d(x/c)}>0$, the largest reduction in lift due to camber occurs at the trailing edge; if $\frac{d(y_c/c)}{d(x/c)}<0$, the largest increase in lift due to camber occurs there. Thus, devices that effectively modify the airfoil camber near the trailing edge are particularly attractive candidates for load control. The fact that the aerodynamic forces are also low near the airfoil trailing edge is an added benefit for devices at this location. Active local load control devices that have been considered to date include trailing-edge flaps, microtabs and microflaps [10-18].

Trailing-edge flaps or ailerons are one type of device that shifts the entire lift curve. They have been utilized in the past for aerodynamic braking and wind turbine control and are now also being considered for load control. For this purpose, these devices can be configured in two different ways. On a torsionally stiff blade, deflection of the flap toward the pressure surface will generate an increase in aerodynamic load, whereas deflection of the flap toward the suction surface will generate a decrease in load. However, on a torsionally soft blade, deflection of the flap toward the pressure surface will create a pitching moment that will twist the nose of the blade toward the pressure surface and decrease the load, while a flap deflection toward the suction surface will create a pitching moment that will twist the nose of the blade toward the suction surface and increase the load on the blade. Figure 3 shows a wind turbine blade with a trailing edge flap being tested at the National Wind Technology Center in Boulder, Colorado. Hurdles faced by actively controlled flaps and ailerons include aero-acoustic noise generated by gaps between the device and the blade and by the edges of the device, the complexity of the actuation system needed to deflect the device and the actuation power requirements.

Figure 3: Wind turbine blade with trailing-edge flap in test stand (Courtesy of National Renewable Energy Laboratory)

[†] The authors are indebted to Christian Bak of Risø National Laboratory in Denmark for bringing this expression to their attention.

EUROPEAN EFFORTS

European researchers have made considerable progress in investigating the use of trailing edge flap-type of devices that can be deflected quickly and independently along the length of the blade. This work has been on-going for the past three years. Analytical studies by Basualdo [13], Troldborg [14], Buhl, Gaunaa, and Bak [15], Anderson, Gaunaa, Bak and Buhl [16] and Abdallah [17] show that significant reductions in fatigue loading are possible with a trailing edge flap active load control. In 2006 Bak, Gaunaa, Anderson, Buhl, Hansen, Clemmensen and Moeller [18] performed a wind tunnel test on a 16.4% thick 660mm (26.0 in) chord airfoil with 9% chord piezo-electric actuated flaps. They subjected the airfoil to a sinusoidal pitching motion and used the flaps to try to reduce the oscillating loads experienced by the airfoil. When they drove the flaps in a similar motion, but with a 30° phase lag, they measured about an 80% reduction in the airfoil unsteady loads.

MICROTABS

There are a large number of other devices that shift the entire lift curve and have the potential to effect similar load reductions. Trying to study all of these devices to determine relative advantages and disadvantages would be a very daunting and expensive effort. One particularly promising concept is the microtab proposed in 2000 by Yen, van Dam, Brãeuchle, Smith and Collins [20]. The concept involves small tabs (deployment height on the order of the boundary layer thickness) that are placed near the trailing edge of an airfoil and deploy approximately normal to the airfoil surface. The presence of the tabs changes the effective camber and the trailing-edge flow conditions as depicted in Fig. 4 (for the pressure surface of the airfoil), thereby affecting the aerodynamic characteristics of the airfoil, as shown in Fig. 5. Of particular interest is the fact that these very small devices create changes in airfoil lift comparable to the changes that are created by much larger flaps, but their small size means they can potentially be activated much more quickly. The mechanical simplicity, small size, fast response time and anticipated small amount of energy required for deployment of these microtabs are very attractive features. Further information on microtabs may be found in References 10, 21 and 22.

The Wind Energy Technology Department at Sandia Laboratories has decided to focus our attention and the work of our partners on these fast acting small aerodynamic devices, exploring in detail their time-dependent effect on sectional lift, drag, and pitching moment, and their effectiveness in mitigating high frequency loads on the wind turbine. Although microtabs may not be the optimum active aerodynamic load control devices for wind turbine load alleviation, what we learn in investigating this particular configuration should apply to most of the other configurations as well. Thus our work with this technology will not be wasted, even if we later decide that another technology is more effective.

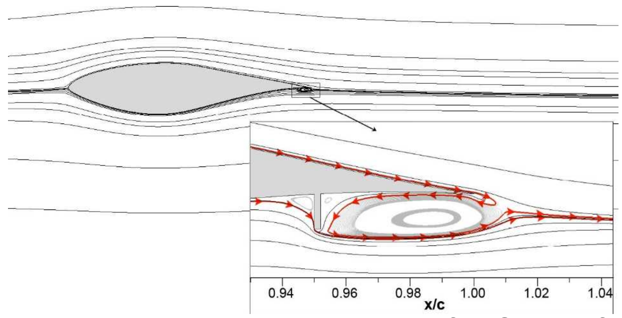
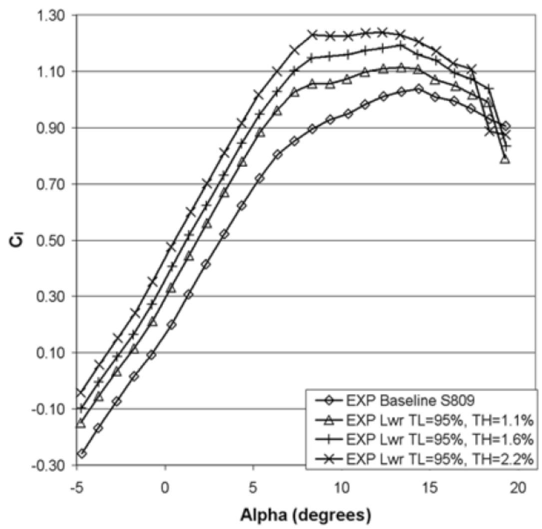


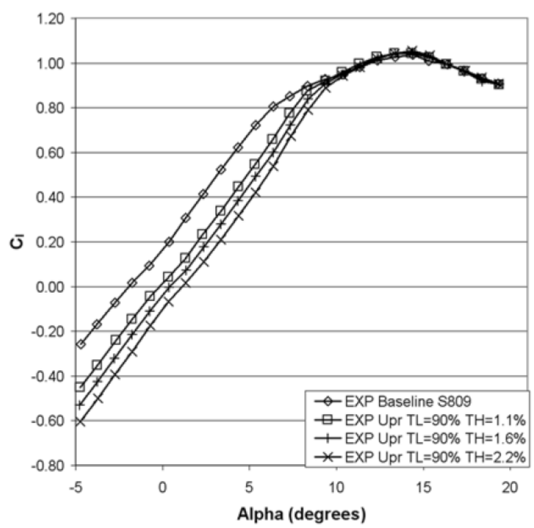
Figure 4: Instantaneous streamlines of an S-809 airfoil surface with a 1.1%*c* pressure surface microtab at 0.95*x/c*. Inset: Tab region with critical instantaneous streamlines denoted by arrows (*Ma* = 0.25, *Re* = 1 X 10^6, a= 0°).

Two examples of the effectiveness of microtabs for two-dimensional and three-dimensional flows are highlighted here. Figure 6 illustrates the computed transient flow behavior for a tab deployment on the pressure side of the S-809 airfoil [23]. As the tab initially deploys, a low pressure region and counterclockwise vortex forms immediately downstream of the tab. Up to nondimensional deployment time of T=0.8 (Fig. 6f), the growing tab vortex behaves like a separation bubble. Once the counterclockwise vortex and its low pressure region extend beyond the trailing edge, an interesting phenomenon occurs; the suction-surface flow leaving the trailing edge is now entrained into this pressure surface vortex. At this point, the suction surface flow is pulled down around the trailing edge and driven upstream along the pressure surface by the main vortex (Fig. 6g). This flow continues upstream along the pressure surface, driven by the vortex, and travels along the downstream side of the tab to the lower tip of the tab where it meets the pressure surface flow that has traveled along the upstream side of the tab. Here, at this new stagnation point, the two flows leave the airfoil/tab surface. This shift in the separation point from the trailing edge to the tip of the tab changes the so-called Kutta condition of the airfoil. This change effectively increases the camber and circulation generation of the aerodynamic profile (Fig. 6h).

Figure 5(b) presents wind-tunnel measured data for tabs deployed on the suction side of a 3-D blade tip model with an S-809 section shape (Figures 7 and 8). Rather than the constant tab-effectiveness demonstrated by pressure surface tabs shown in Fig. 5(a), suction surface tabs cause lift mitigation in the linear regime that slowly decreases to zero at an angle of attack of about 12° (in this case). This is because the tabs cause the mitigation by forcing the boundary layer to separate from the airfoil surface at the tab location. Once the flow has separated forward of the tabs, the tabs have lost their effectiveness, regardless of tab height.



(a)



(b)

Figure 5: Wind-tunnel measured tab effectiveness for S-809 airfoil at Re = 1 X 10^6; (a): Effect of tab height at 95%c on pressure side, (b): Effect of tab height at 90%c on suction side.

In order to implement these devices and to develop a functioning control system, the unsteady behavior and any potential nonlinearities must first be understood. However, until recently, most of the work focused on the steady state behavior of the microtabs. Recent work has studied the transient behavior of deploying microtabs. The CFD methodology applied for this study has been extensively validated in the past and has been proven successful in simulating microtab deployment for airfoils [24].

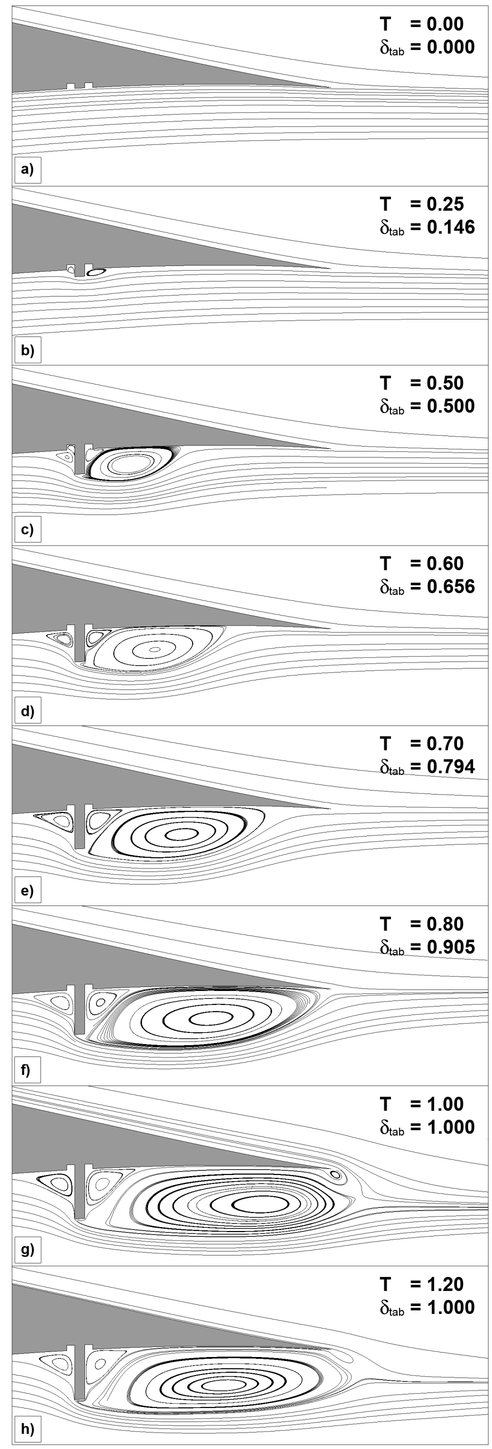


Figure 6: Instantaneous streamlines in trailing-edge region of S-809 airfoil during tab deployment. Tab height is 1%c, tab deployment time T = $U_\infty t_{deployment}/c$ = 1.0, fully turbulent flow (*Ma* = 0.25, *Re* = 1 X 10^6, a= 0°).

CONTROLS

Active load control devices on a wind turbine blade become truly effective only when they are used in conjunction with sensors to determine the loads acting on the blade and a control system to deploy and retract individual devices at appropriate times. Development of such a system will require the ability to accurately simulate the time accurate response of the entire system, including the sensors, control system, device actuators, flow response to device deployment and retraction, and the aeroelastic behavior of the entire turbine. Bak et al [19] found that activating trailing edge flaps at the wrong time resulted in increasing blade loads by as much as 70%, rather than reducing them by as much as 80%.

Figure 7: Blade tip model mounted in wind tunnel test section. Flow from right to left. Model span is 24.7 inches.

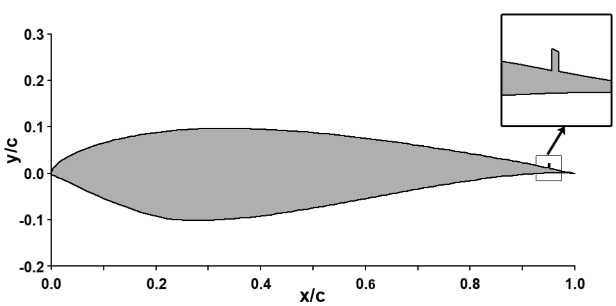


Figure 8: Airfoil section with a suction surface microtab at 95% chord.

Aeroelastic simulations of the effect of microtabs operating in conjunction with a simple control program have been conducted using the FAST/AeroDyn software [25, 26] in conjunction with MATLAB's Simulink [27]. The National Renewable Energy Laboratory (NREL)-developed Simulink/FAST interface has been modified to simulate independent control of several radial sections of microtabs on each blade, and to provide the necessary inputs to model the time dependence of the section lift and drag changes as the devices are deployed and retracted.

In a simple demonstration of the impact that microtabs can exert on blade loading, the NREL Controls Advanced Research Turbine (CART), a 600 kW, two-bladed, upwind turbine, has been modeled in FAST. Earlier simulations have shown that the control effectiveness of the microtabs is greatest if they are installed only on the outer 25% of the blade span [28]. Therefore, the current model assumes that only the outer 25% of the blade span is fitted with microtabs near the trailing edge on the suction side of the blade, as shown in Fig. 8. A simple control system simulation has been implemented to deploy the microtabs on one blade every time it passes in front of the tower, attenuating the load on that one blade. Once the blade has passed the tower, the microtabs are retracted, and the load attenuation disappears. Obviously, this is not a situation that would be deliberately created for actual turbine operation, but it provides a graphic demonstration of the impact of the microtab deployment. The results for a 15 m/s steady wind (no turbulence- or gust-induced loading) are shown in Fig. 9, and for an 18.2 m/s turbulent wind in Fig. 10. In both figures, a positive tip displacement indicates movement toward the tower (smaller displacement means more tower clearance). The microtab-equipped blade passes upwind of the tower at an azimuth angle of 180°. For either wind condition, the deployment of the tabs reduces the blade tip displacement (and thus increases the tower clearance of the tip) of that blade by about 0.25m. For the steady wind case (Fig. 9), this is nearly 1/3 of the normal tip displacement of 0.84m experienced by the second, non microtab equipped, blade. For the turbulent wind case (Fig. 10), blade root fatigue damage is increased as a result of tab deployment. The potential negative impact of this on turbine COE will receive additional in-depth attention in future work.

The Simulink/FAST software, together with the MSC/ADAMS code [29] (a flexible, multi-body dynamic simulation code with virtually unlimited degrees of freedom) will presently be used to investigate the potential load mitigation capability of various microtab configurations and control strategies on a complete variable-speed, pitch-controlled wind turbine.

SENSORS, ACTUATORS AND OTHER CONCERNS

The only way to accurately determine fatigue loads that are random and that vary along each wind turbine blade is to have a multitude of sensors that are also dispersed along each blade. These sensors must be durable) and quite cheap to make the active load control concept feasible. Fiber optic fiber-Bragg gratings (FBG) used as strain gauges or accelerometers are promising technologies that we are investigating. The fiber optic sensing material can be easily integrated in a fiberglass blade, effectively protecting the sensors from the environment. However, with current technology, the opto-electronic equipment needed to determine loads information from FBG sensors (the interrogator) is very expensive. Technology advances in this area bring the potential of significant decreases in interrogator price, but that potential has not yet been realized. This technology and others will receive continued attention.

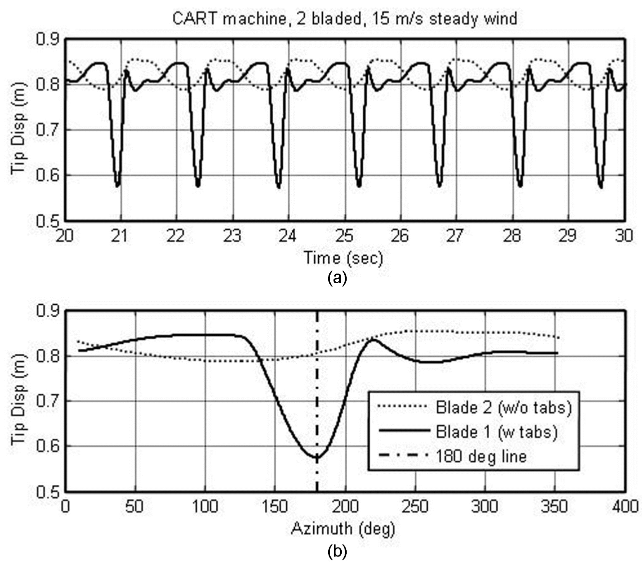


Figure 9: Effect of microtabs on tip displacement of CART turbine. (a): Time series of tip displacements, (b): Tip displacements as a function of rotor azimuth angle.

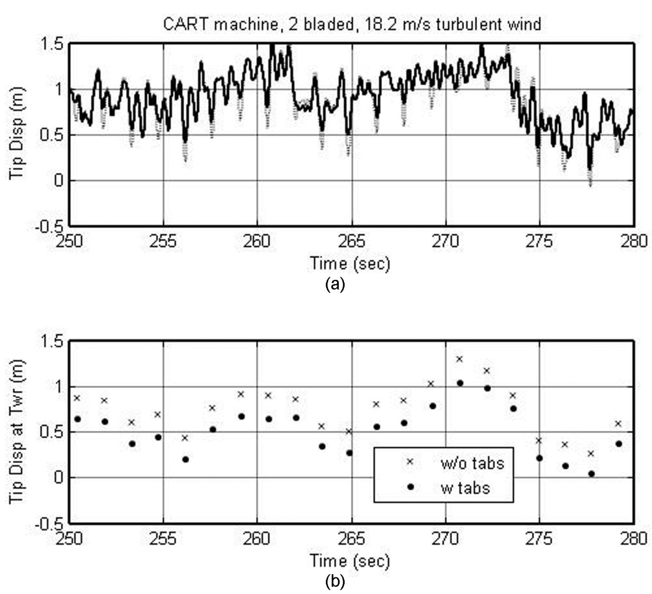


Figure 10 Effect of microtabs on tip displacement of CART turbine. (a): Time series of tip displacements, (b): Tip displacements as a function of rotor azimuth angle.

Deployment and retraction of the microtabs requires simple, durable actuators. During a 20-year turbine lifetime, an actuator will be cycled somewhere in the vicinity of 10^9 times. It will be exposed to the elements and must function reliably in heavy icing conditions, sand storms, rain storms, extreme heat, and the corrosive atmosphere typical of marine environments. Such an actuation device has not yet been identified.

Mounting considerations for the devices are very important. The current wind turbine blade manufacturing methods result in blades that are very cheap – finished blades cost on the order of $3/lb [30]. Any active aero load control devices must be integrated into the blade in such a way that the blade manufacturing techniques are not significantly changed. The trailing edge location of these devices simplifies the design process considerably – loads there are quite low (in contrast to main structural elements near the blade maximum thickness). One design concept under consideration is integrating the devices into a trailing edge section that is manufactured separately from the main blade, as shown in Fig. 11. An added benefit of this type of configuration is ease with which malfunctioning devices could be replaced. The sharp trailing edges on current blades are frequently damaged during transportation and assemble of the turbine, so field installation of such a trailing edge component after assembly would result in a reduction in the costs of repairing such damage, partially offsetting the added cost of attaching the component.

Assuming that inexpensive, durable sensors and actuators will be available and can be integrated into the blade at a reasonable cost, there are still several other questions that must be addressed. Much of the future work on control simulation will be focused on understanding the response speed requirements for sensors and actuators. Will sensors on the blade sense loads quickly enough that the microtabs can be deployed in time to alleviate loads? Or will successful load alleviation be possible only with sensors that sense turbulent winds before they impact the wind turbine blade? How quickly must the microtab actuators deploy the devices in order to realize the load reduction potential? Are these actuation speeds possible at reasonable power levels? These are some of the issues that will be addressed in the near term future with the simulation software described in the preceding section.

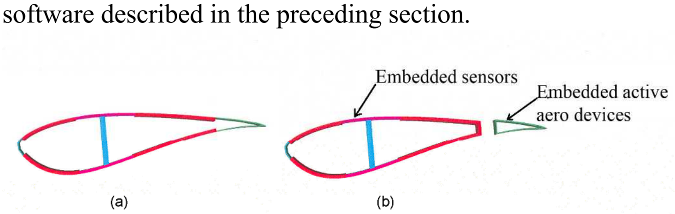


Figure 11: Traditional blade design and conceptual design for active aero device in trailing edge. (a): Traditional Blade Design, (b) Conceptual Active Device Blade Design

SUMMARY

Active aerodynamic load control devices have the potential to reduce the wind-induced fatigue loads on wind turbine blades to levels far below what can be achieved with the current collective blade pitch control technology. The degree to which individual blade pitch control and passive/active blade twist control can mitigate these loads is limited because load conditions vary along each blade and these controls can not respond to those local conditions. Distributed control devices that can respond to local loads offer the best potential for fatigue load reduction. The active aerodynamic control devices that will be most effective in controlling loads are found to be those that alter the effective camber of the blade. Thin airfoil theory shows that these devices are most effective when they are installed at the blade trailing edge. While trailing edge flaps have been the subject of European research in this area for the past several years, the research work of Sandia National Laboratories and its university contractors has focused on the small devices known as microtabs. Microtabs are particularly attractive because of their simple shape, low loads and potentially quick response. Simulations have shown they exert significant control authority, but many challenges must be solved before the economic feasibility of such a device can be conclusively demonstrated.

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