Active Aerodynamic Blade Load Control Impacts on Utility-Scale Wind Turbines*

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Abstract
The effect of implementing Active Aerodynamic Load Control on the trailing edge of the blade tip for 1.5MW and 5MW wind turbines has been investigated. These results are based on time-series simulations performed with the NREL FAST/AeroDyn code. An increase in blade length of 10% was found to result in 10-15% increase in energy capture and a corresponding 9-5% decrease in Cost of Energy for the 1.5MW turbine. Two different configurations of trailing edge flaps were investigated and found to be equally effective at controlling fatigue damage accumulation. The impact of neglecting the blade torsional mode in this work has been found to have a minor impact on the results.

Introduction
One prevailing trend in wind turbine technology throughout the past couple of decades has been growth in the size of the rotor to realize advantages of scale and the generally higher winds available at greater heights. Advancement of the current state of the art has been achieved through both efficient structural design and optimal material usage to produce the necessary structural efficiency for blades up to 60 meters in length.

Future designs for even larger machines will continue to push the extremes of the design envelope, primarily limited by the penalty of weight growth, available to the structural design team. Designers now must consider new and innovative solutions to enable larger blades because the design issues for larger blades differ from those which have been encountered in modern blade designs. For example, geometrically consistent upscaling of blade length shows that the edge stresses at the blade root due to gravitational loads grow in proportion to the length blade, while the flap stresses due to aerodynamic loads are independent of the size of the blade. Thus, at some blade length scale, edge stresses will replace the flap stresses as the blade design driver. This will lead to modifications to the current blade architecture. In addition, the blades will likely become increasingly flexible in the flap direction and softer in torsion.

Large wind turbines must operate under very turbulent and unpredictable environmental conditions where efficiency and reliability are highly dependent upon well-designed control strategies. The loads along the blade vary quickly in time and space due to the impact of gusts that are significantly smaller in size than the length of the blades. The resulting oscillating (or fatigue) loads frequently are the design drivers for the blades and some components of the drive train. Numerous studies [1-5] have shown that these fatigue loads can be significantly reduced with the use of distributed, fast-response, active aerodynamic load control (AALC) devices, typically small devices such as trailing edge flaps or tabs. Exploitation of these devices requires the development of appropriate control systems. The conventional turbine controllers operate at low frequency to control blade pitch. The relatively small size and short response time of AALC devices permits the development of an associated control system to achieve fatigue load reduction as a supplement or retrofit to the existing pitch control. Earlier work by the authors (6-8) has investigated the addition of microtabs to the blades of the National Renewable Energy Laboratory (NREL) Controls Advanced Research

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Turbine (CART) 600kW turbine [6] and the addition of morphing trailing edge flaps to the blades of the WindPACT 1.5MW turbine [8]. The integration of the AALC controller with the existing blade collective pitch and generator torque control has been seamless, with no observed impact of either control on the other.

The accurate evaluation of the impact of AALC fatigue load reductions on the Cost of Energy (COE) of a wind turbine will require a complete new turbine design that fully integrates this new technology. The cost estimates for this new turbine design are subject to very large errors, so the COE for the new turbine will be very hard to determine accurately. An alternative approach is to work with an existing turbine design and determine how much larger a rotor incorporating active aerodynamic load control can be made without exceeding the fatigue loading experienced by the original rotor. Adding AALC to a rotor results in reductions in the fatigue damage accumulation for the blade-root flap location, the design driver for many turbines in low wind speed sites. The rotor with AALC can then be grown to where the blade-root flap fatigue damage accumulation approaches the original level for the baseline rotor. With appropriate control logic and AALC hardware, the fatigue damage accumulation on the tower and drive train with the larger rotor can be kept nearly the same as on the original rotor, so the original equipment can be retained. This grow-the-rotor (GTR) approach is illustrated in Figure 1. This increase in rotor size moves the turbine power curve in control Region II to the left and results in additional energy capture. Since the wind-speed distribution at low wind sites is predominantly in Region II, this increased energy capture can be significant. The only additional costs involved in this evaluation are those associated with the actual cost of the AALC hardware (devices, actuators, sensors, control systems and mountings), including the incremental cost of increasing the length of the blades, costs associated with integrating the AALC hardware into the blades, and the increase in turbine Operating and Maintenance (O&M) costs due to the additional AALC hardware on the turbine. The GTR approach should permit us to more accurately estimate the impact of AALC on COE. Additional details on this GTR approach may be found in Berg, et al [7].

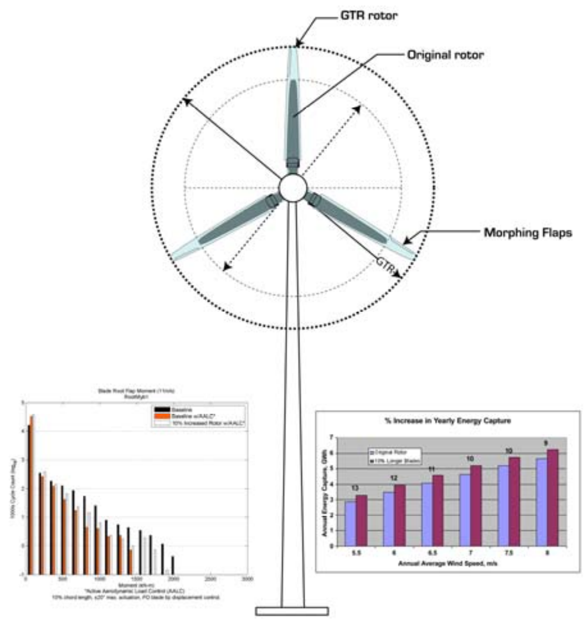

Figure 1. The Grow-the-Rotor Concept.

While incorporating active-aerodynamic load control on a wind turbine rotor may yield many benefits, including decreased fatigue damage accumulation on many components and increased energy capture, one primary criterion for determining whether to add AALC on a given turbine is the financial impact; does the decrease in capital costs or increase in energy capture resulting from adding AALC more than offset the additional costs due to the AALC? That is, does the addition of AALC yield a lower cost of energy (COE)? This paper addresses this question by investigating the COE impacts due to adding one type of AALC system (morphing trailing edge flaps) to the WindPACT 1.5MW turbine [9] blades. It also examines the impact of the above-mentioned trends toward larger rotors on the ability of AALC systems to reduce fatigue loads and enable increased rotor size.

Simulation Procedure

Turbine component fatigue accumulation calculations require time-series load histories at the turbine locations of interest at a number of mean wind speeds spanning the entire operating range of the turbine. For this work, these load histories were generated with structural dynamic simulations of the turbine of interest performed with the NREL FAST structural dynamics code [10], utilizing the NREL AeroDyn aerodynamic code [11] to compute the aerodynamic forces on the blades. FAST utilizes a modal representation of the turbine to determine its response to applied forces. AeroDyn utilizes the Blade Element

Momentum (BEM) representation of aerodynamic loads, relying on airfoil characteristic lookup tables to determine the load at any angle of attack. A dynamic wake model within Aerodyn incorporates the unsteady effects of the wake on the rotor inflow. The MatLab/Simulink [12] control simulation code was used to model both the standard Variable Speed Variable Pitch (VSVP) controller and the AALC control logic for these simulations. The version of AeroDyn that we used was modified to model the effects of blade trailing edge deflection by selecting appropriate alternate lift and drag curves in response to control input from Simulink. All turbine simulations were driven with 10-minute duration, 3-dimensional turbulent wind fields (IEC Normal Turbulence Model, Type A turbulence [13]) generated with the NREL TurbSim code [14].

Load Control Devices

The active aerodynamic load control devices investigated in this work consisted of morphing trailing edges and conventional flaps. The morphing trailing edge technology was developed by FlexSys Inc of Ann Arbor, MI to smoothly and quickly deflect the blade trailing edge toward either the pressure or suction surface of the blade to form an effective flap, while avoiding the surface discontinuities in the upper and lower surfaces, the hinge line and the attendant air gap that are associated with traditional flaps. Figure 2 contrasts conventional flaps and morphing trailing edges for a typical wind turbine airfoil (the NREL S825 scaled about the camber line to 21% t/c).

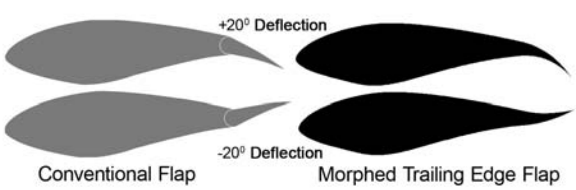

Figure 2. Conventional Flap and Morphing Trailing Edge Flap Shapes, 20% Chord Flap Length, +/-20° Deflection.

AALC Controllers

Simple PD controllers were developed to activate the trailing edge devices, in conjunction with conventional VSVP control, to provide effective fatigue load alleviation for these wind turbines. The controller performance index goal maintained maximum power output while minimizing blade-root bending moment oscillations about a mean value during turbulent wind conditions. In addition, the control algorithm minimized the flap bending and torsion coupling; these considerations may be neglected in small turbines, but they become more important as the turbines increase in size.

A more detailed description of the AALC controllers developed for the 1.5MW turbine may be found in a paper by Wilson, et al [8]. Wilson found that both tip deflection and tip-deflection rate controllers were effective in reducing the blade-root flap moment fatigue loading, while having little effect on the generator power, the rotor speed, the low speed shaft torque, the tower base side-to-side and fore-aft moments, and the tower-top yaw moment responses. The tip deflection rate controller was found to be less effective at reducing the blade-root flap fatigue loads, so the tip deflection controller is used for all the results reported in this paper. Figure 3 depicts the MatLab/Simulink model of the turbine with the conventional VSVP control and the new AALC PD controls, which operate independently of the standard VSVP control.

Wind Turbines Studied

The wind turbines investigated in this work were both upwind, 3-bladed machines, with variable speed, variable pitch industry-standard controllers. Turbine characteristics are listed in Table 1. When used, the AALC devices were added to the outer 25% of the blades on each turbine. No attempt was made to optimize the span-wise placement or extent of these devices.

Fatigue Damage Accumulation Calculations

The TurbSim-generated wind fields were created to yield the appropriate mean wind speed and turbulence levels and statistical behavior, but the actual fields depended upon a random seed number – different seed numbers resulted in different wind fields. Six 10-minute simulations were run at each mean wind speed (with different random seeds) to develop representative loads distributions. For this effort, simulations were run at mean wind speeds of 4, 6, 7, 8, 9, 10, 11, 12 and 18m/s. The critical turbine load locations that were monitored included blade root fore-aft (flap) and side-to-side (edge) bending moments, low-speed shaft torque, tower-base fore-aft and side-to-side moments and tower-top yaw bending moment.

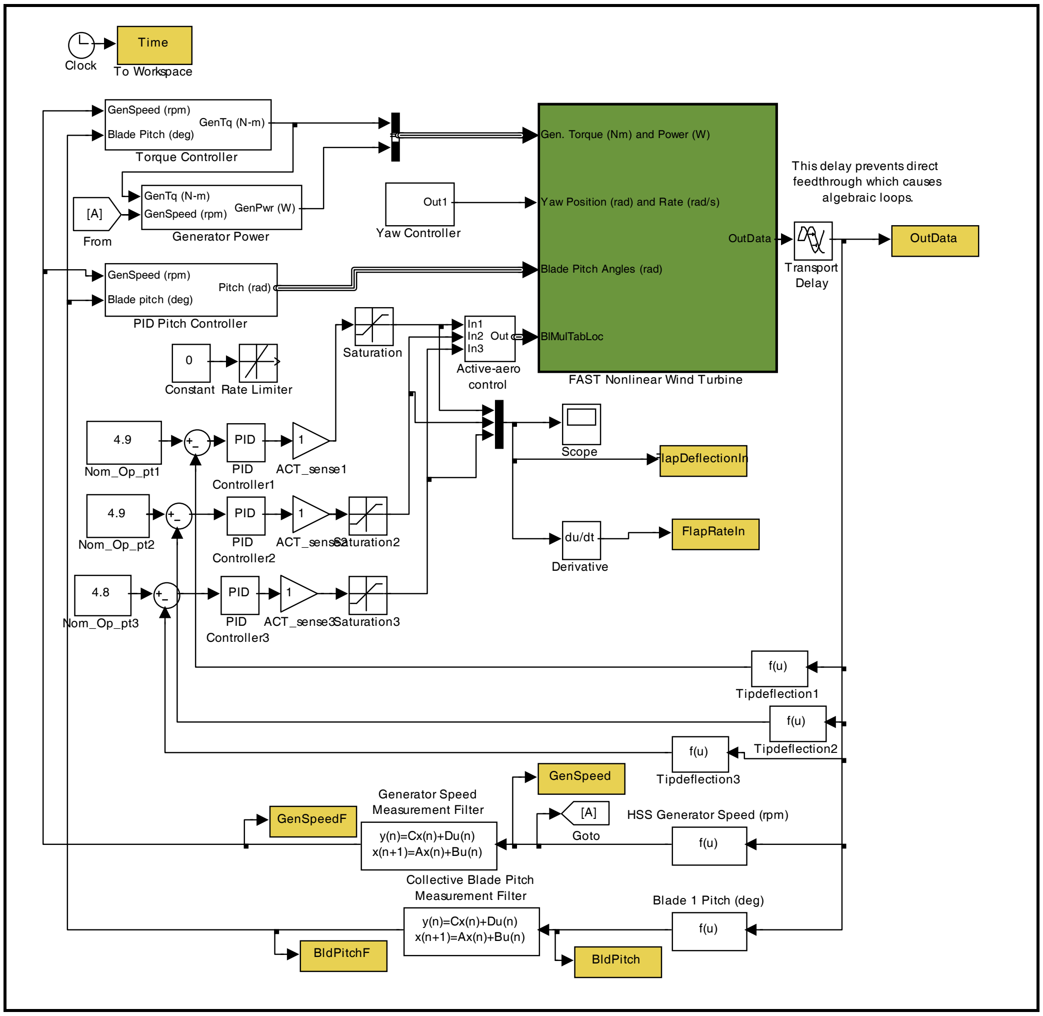

Figure 3. Active Aerodynamic Independent PD Flap Control with existing VSVP control for the NREL offshore 5-MW baseline wind turbine.

Figure 4 illustrates typical changes to the root flap bending moment resulting from this addition of the AALC at 12m/s mean wind speed. It is obvious that the moment oscillations that cause fatigue damage are somewhat reduced, but the impact on the fatigue load damage accumulation is not obvious. In order to assess this impact, the critical location load time histories resulting from the simulations were rain-flow cycle counted with the NREL Crunch code [17] and these results were used in linear damage calculations to determine the fatigue damage accumulation for each of the critical turbine locations at each mean wind speed. Combining those accumulations with a Rayleigh wind speed distribution for a mean wind speed of interest yielded an overall damage accumulation for each turbine location for that particular mean wind speed.

Fatigue damage calculations are well known to vary widely. In an effort to minimize the impact of the particular fatigue calculation method used on these results, we evaluated the impact of modifications to the baseline rotor by examining the ratios of damage equivalent load (DEL) at the critical locations for the modified rotor to the DEL at those same locations for the baseline rotor. The DEL is the single cyclic load amplitude that would produce the equivalent amount of fatigue damage as the spectrum of loads that was actually experienced by the structure. An increase in DEL represents an increase in the overall fatigue damage in the structure.

Turbine	1.5MW WindPACT [9]	5MW NREL Offshore [16]
Rating	1.5MW	5.0MW
Rotor Size	65.9m	126m
Blade Length	31.3m	61.5m
Hub Height	85.7m	90m
V_{rated}	12.5m/s	11.4m/s
$V_{cut\text{-}out}$	22.5 m/s	25m/s
AALC Device	Morphing trailing edge (20% chord)	Morphing trailing edge (20% chord) Conventional flap (10% chord)
Extent of AALC	Outer 25% of blade	Outer 25% of blade
Deflection limits	+/- 10°	+/- 10°

Table 1. Wind Turbines Investigated in This Work

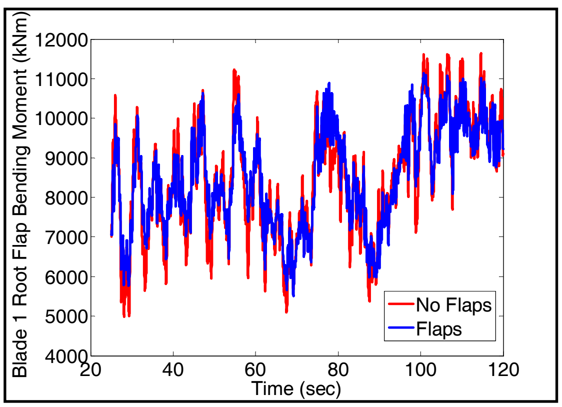

Figure 4. Impact of Morphing Trailing Edge Technology Control on Blade Root Flap Moment of 5MW NREL Offshore Turbine at 12m/s wind speed. Trailing Edge is 20% Chord, +/- 10° Maximum Deflection, 100°/sec Deflection Rate Limit.

Results for 1.5MW Turbine

A complete set of simulations, as described above, was run for the baseline 1.5MW turbine. The critical-location time histories were analyzed to determine fatigue load damage accumulations for each of the critical turbine locations.

The FlexSys morphing trailing edge load control hardware (20% chord flap length, +/-10°deflection, with 100°/sec maximum deflection rate) was added to the outer 25% of blade span in the turbine model. The appropriate control logic was implemented into the simulator, the simulations were rerun and the cycle counting and fatigue damage accumulations for each mean wind speed were recalculated. This was done for all of the critical locations; the results were then compared with the baseline results to evaluate the changes in fatigue damage accumulations at each of the critical locations. Table 2 and Figure 5 compare the one-million cycle DEL of the standard-size rotor with AALC to the baseline rotor. Adding AALC devices resulted in significant decreases in blade-root flap, blade-root pitch, tower-base fore-aft and tower-top yaw moment fatigue damage across all wind speeds, with essentially no effect on blade-root edge or tower-base side-side moment fatigue damage. The AALC devices caused a small decrease in the low-speed shaft torque fatigue damage at wind speeds in control region II below rated wind speed), but a very large decrease for control region III (above rated wind speed).

One-million Cycle Damage Equivalent Load (AALC/Baseline)					
	9m/s	11m/s	18m/s	Rayleigh Wind 5.5m/s	Rayleigh Wind 7m/s
Low Speed Shaft Torque	-1.7	-4.9	-33.5	-3.1	-7.3
Blade Root Edge Moment	1.7	1.9	-2.5	0.8	0.8
Blade Root Flap Moment	-31.2	-27.1	-30.4	-23.1	-26.3
Blade Root Pitch Moment	-11.4	-4.5	-14.1	-7.1	-7
Tower Base Side-Side Moment	-0.1	-8	-7.2	-0.9	-2.9
Tower Base Fore-Aft Moment	-18.6	-16.5	-13.8	-5	-8
Tower Top Yaw Moment	-53.2	-42.9	-43.4	-25.1	-32.2

Table 2. Changes to Fatigue Damage Accumulation Resulting from the Addition of FlexSys Morphing Trailing Edge Technology to 1.5MW WindPACT Turbine. Trailing Edge is 20% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit. All Damage is % Change from the Baseline Levels.

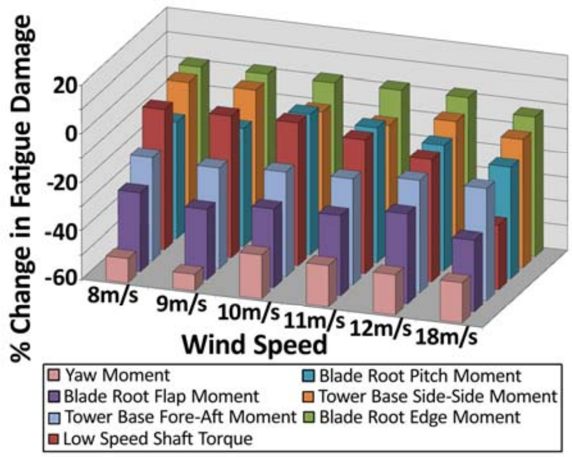

Figure 5. Changes to Fatigue Damage Accumulation Resulting from the Addition of FlexSys Morphing Trailing Edge Technology to 1.5MW WindPACT Turbine. Trailing Edge is 20% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit. All Damage is % Change from the Baseline Levels.

The length of the AALC-equipped blades was then increased by 10% (by scaling up the dimensions and properties of the blades in the FAST code, as required) and the simulations and fatigue calculations were rerun. This approach to increasing the length of the blades is quick, but very approximate. In general, a complete blade redesign would be required to provide an accurate model of the larger blade. Table 3 and Figure 6 summarize the impact of this larger rotor on the turbine fatigue damage accumulations. The increase in blade length resulted in small increases in fatigue damage accumulation for the low-speed shaft torque, the tower-base side-side and fore-aft moment and the tower-top yaw moment locations. Thus, the tower base and drive train of the turbine should be adequate to support this rotor. The fatigue damage accumulation for the blade-root flap decreased slightly from the baseline level at low wind speeds and high wind speeds, but it increased significantly at 11m/s, near the rated wind speed of 12.5m/s. The reason for this increase is not understood at this time, but it is very probable that the magnitude of the increase can be reduced or eliminated by appropriate tuning of the control algorithm. The cumulative fatigue damage accumulation for both Rayleigh wind speeds for the blade-root flap moment was changed little from the baseline level. The increase in blade length did result in a very large increase in fatigue damage accumulation for the blade-root edge location (44-50% above the baseline level), largely due to the increased periodic gravitational loads resulting from the added weight, and the blade-root pitching moment (about 30% above the baseline level). We do not consider these increases to be a severe problem, as the increase has resulted in the blade-root edge moment fatigue accumulation rising only to the level where it is comparable to the original blade-root flap moment fatigue accumulation. A redesign of the blade (which would be necessary to refine the longer blade model) should be able to significantly reduce both the edge moments and the pitching moments.

One-million Cycle Damage Equivalent Load (10% GTR-AALC/Baseline)					
	9m/s	11m/s	18m/s	Rayleigh Wind 5.5m/s	Rayleigh Wind 7m/s
Low Speed Shaft Torque	-12	-40.6	-39.1	2.5	-6.7
Blade Root Edge Moment	46.9	49.5	44	46.1	46.4
Blade Root Flap Moment	-5	20.9	-1.5	6.5	4.3
Blade Root Pitch Moment	28.6	33	24.8	33.2	33.3
Tower Base Side-Side Moment	20.4	8.3	2.8	43.2	31.3
Tower Base Fore-Aft Moment	-0.7	17.2	7.1	22.2	18.6
Tower Top Yaw Moment	-37.6	-17.9	-16.1	-0.9	-8.2

Table 3. Changes to Fatigue Damage Accumulation Resulting from the Addition of FlexSys Morphing Trailing Edge Technology and 10% Increase in Blade Length to 1.5MW WindPACT Turbine. Trailing Edge is 20% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit. All Damage is % Change from the Baseline Levels.

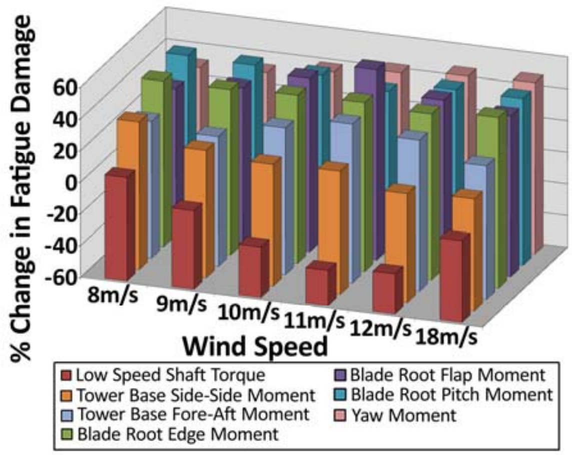

Figure 6. Changes to Fatigue Damage Accumulation Resulting from the Addition of FlexSys Morphing Trailing Edge Technology and 10% Increase in Blade Length to 1.5MW WindPACT Turbine. Trailing Edge is 20% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit. All Damage is % Change from the Baseline Levels.

Impact of Adding AALC on Turbine Energy Capture and Cost of Energy for 1.5MW Turbine

Berg, et al [7] examined the impact on turbine energy capture of increasing the rotor blade length for the 1.5MW turbine by 10%. The increase in energy capture ranged from 15% at a 5.5m/s Rayleigh distribution wind site to 10% at an 8m/s Rayleigh distribution wind site. Those results are summarized in Figure 7. Use of AALC in control region II resulted in some loss of energy capture. The fatigue damage contribution at low wind speeds is very low, so the AALC was turned off at wind speeds below 8m/s for these calculations. Operating in this manner will both reduce the wear and tear on the devices and maximize energy capture.

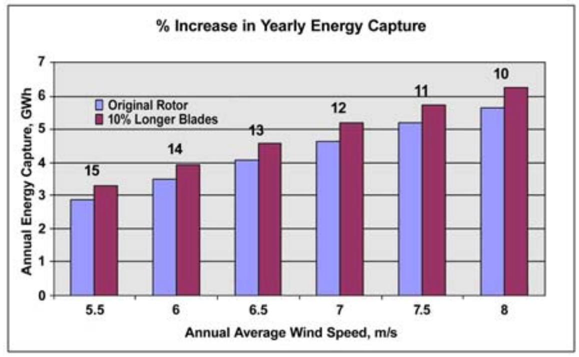

Figure 7. Impact of 10% Growth in Blade Length on the Energy Capture of the WindPACT 1.5MW Turbine with AALC. Morphing Trailing Edge with 20% Chord Flap Length, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit.

The formula commonly used by NREL to compute turbine COE is [18]

$$COE = \frac{FCR * ICC + LRC}{AEP} + (O\,\&\,M) + LL$$

Where

FCR is fixed charge rate (=0.1158)
ICC is initial capital cost
O&M is operating and maintenance cost (=$0.007/kWh) (2002 $)
LRC is levelized replacement cost (=$10.70/kW - $16,050 for 1.5MW) (2002 $)
AEP is annual energy production
LL is land lease (=$0.00108/kWh) (2002 $)

The cost of a 1.5MW machine today is approximately $2,250,000. Using the figures given above (no effort was made to update the 2002 values to present day values):

$$COE_{Orig} = \frac{(0.1158)(\$2{,}250{,}000) + \$16{,}050}{AEP} + \$0.00108 + \$0.0007$$

FlexSys estimates the cost of their morphing trailing edge hardware, including installation, for the 1.5MW as $70,000 and the associated increase in combined (O&M) and LRC as $1750 per year. This figure includes the cost of anticipated hardware repair/replacement. The cost of growing the blade by 10% is approximately 3% of the original blade cost, and the original blade cost is 10% of the turbine cost. Given that the cost of a 1.5MW turbine is $2,250,000 today, the cost of growing the blade by 10% is approximately $6,750. Therefore, for the 10%

larger rotor with the addition of active aerodynamic load control

$$COE_{AALC} = \frac{(0.1158)(\$2.25M + \$70{,}000 + \$6{,}750)}{AEP_{AALC}} + \frac{\$16{,}050 + \$1{,}750}{AEP_{AALC}} + \$0.00108 + \$0.007$$

COE calculations for a baseline 1.5MW WindPACT turbine and for one with 10% longer AALC blades at Rayleigh wind speed distributions for mean wind speeds ranging from 5.5m/s to 8m/s are listed in Table 4 and summarized in Figure 8. The impact on COE of increasing the size of the rotor is clearly highest at the lowest wind sites and decreases as the mean wind speed increases.

Wind, m/s	AEP, GWh	COE, ¢/kWh	AEP (AALC), GWh	COE (AALC) ¢/kWh	Decrease in COE, %
5.5	2.87	10.45	3.29	9.54	8.7
6.0	3.47	8.78	3.95	8.08	8.0
6.5	4.07	7.60	4.59	7.07	7.1
7.0	4.65	6.76	5.18	6.35	6.0
7.5	5.18	6.15	5.74	5.81	5.5
8.0	5.66	5.69	6.23	5.42	4.9

Table 4. Impact of 10% Increase in Blade Length on the Cost of Energy for the 1.5MW WindPACT Turbine at Rayleigh Wind-Speed Distribution Sites. Turbine is Equipped with Morphing Trailing Edge Technology. Trailing Edge is 20% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit.

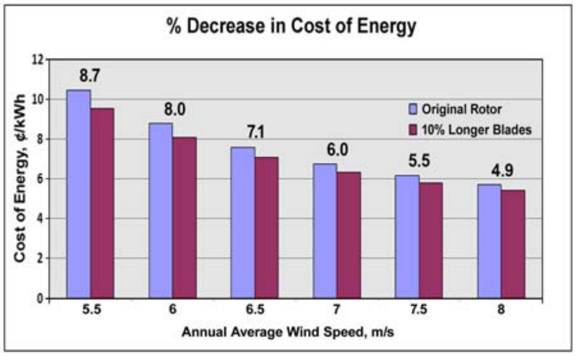

Figure 8. Impact of 10% Growth in Blade Length on the Cost of Energy for the WindPACT 1.5MW Turbine with AALC. MorphingTrailing Edge with 20% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit.

Results for 5MW Turbine

A complete set of simulations was run for the baseline 5MW turbine and the standard fatigue analysis summarized above was used to determine fatigue load damage accumulations for each of the critical turbine locations.

The same configuration of FlexSys morphing trailing edge load control hardware (20% chord, +/-10°deflection, with 100°/sec deflection rate limitation) was added to the outer 25% of blade span in the 5MW turbine model. The appropriate control logic was implemented into the simulator logic, the simulations were rerun and the cycle counting and fatigue damage accumulations for each mean wind speed were recalculated. This was done for all the critical locations; the results were then compared with the baseline results to evaluate the changes in fatigue damage accumulations at each of the critical locations. Table 5 and Figure 9 compare the one-million cycle DEL of the baseline rotor with AALC to the baseline rotor. Adding the AALC devices resulted in significant decreases in blade-root flap and tower-top yaw moment fatigue damage across all wind speeds, with some increase in low-speed shaft torque and blade-root pitch moment and essentially no change to the blade-root edge or tower-base side-side or fore-aft moment fatigue damage accumulations. The large increase in the low-speed shaft torque fatigue accumulation at 11 and 18m/s is in distinct contrast to the reduction that occurred for the 1.5MW turbine (Table 2). Again, the reason for this increase is not understood at this point, but it is very probable that that the magnitude of the increase can be reduced or eliminated by tuning of the controller algorithm.

One-million Cycle Damage Equivalent Load (AALC/Baseline)					
	9m/s	11m/s	18m/s	Rayleigh Wind 5.5m/s	Rayleigh Wind 7m/s
Low Speed Shaft Torque	2.1	17.7	27.0	7.5	14.5
Blade Root Edge Moment	2.3	3.0	-0.1	1.5	1.6
Blade Root Flap Moment	-34.0	-14.2	-13.6	-15.3	-14.3
Blade Root Pitch Moment	-0.8	7.9	27.6	7.7	12.0
Tower Base Side-Side Moment	3.9	0.5	-5.5	-0.6	-3.3
Tower Base Fore-Aft Moment	-24.3	-12.7	0.1	-4.9	-6.2
Tower Top Yaw Moment	-32.4	-10.5	-17.4	-13.8	-15.9

Table 5. Changes to Fatigue Damage Accumulation Resulting from the Addition of FlexSys Morphing Trailing Edge Technology to 5MW NREL Offshore Turbine. Trailing Edge is 20% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit. All Damage is % Change from the Baseline Levels.

Comparison of these results with those for the 1.5MW turbine reveals that the impact on the critical blade-root flap moment location damage accumulation of adding AALC is roughly half as much reduction for the 5MW as for the 1.5MW. In addition, the AALC on the 5MW is far less effective at reducing loads than the AALC on the 1.5MW turbine.

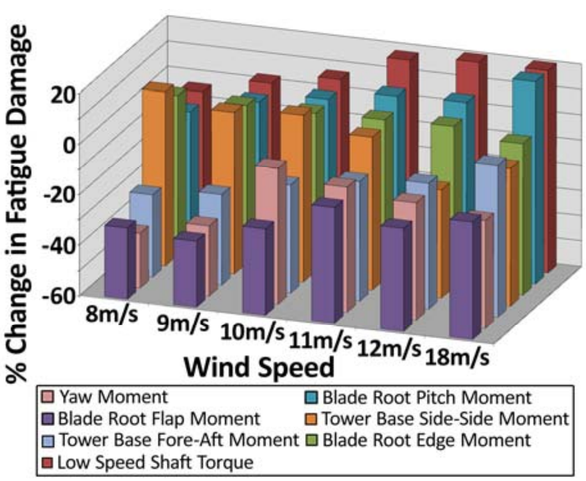

Figure 9. Changes to Fatigue Damage Accumulation Resulting from the Addition of FlexSys Morphing Trailing Edge Technology to 5MW NREL Offshore Turbine. Trailing Edge is 20% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit. All Damage is % Change from the Baseline Levels.

The use of conventional flaps, rather than the FlexSys morphing trailing edge, as the AALC devices for the 5MW turbine was also investigated. The conventional flap configuration was 10% chord with +/-10° maximum deflection angle and 100°/sec maximum deflection rate. These results are presented in Table 6 and Figure 10 and are seen to be roughly comparable to the results presented in Table 5 and Figure 9 for the morphing trailing edge devices. Keep in mind that a direct comparison between these two sets of results is not appropriate, as the chord-wise extent of the devices are different.

One-million Cycle Damage Equivalent Load (AALC/Baseline)					
	9m/s	11m/s	18m/s	Rayleigh Wind 5.5m/s	Rayleigh Wind 7m/s
Low Speed Shaft Torque	-1.9	6.3	12	2	5.1
Blade Root Edge Moment	1.1	1.5	-0.3	0.6	0.7
Blade Root Flap Moment	-23.8	-11.9	-12.6	-13.4	-12.9
Blade Root Pitch Moment	-2.8	1.7	14.9	1.9	4.2
Tower Base Side-Side Moment	0.3	1.8	-5.3	-0.5	-2.7
Tower Base Fore-Aft Moment	-16	-12.3	-3	-3.8	-5
Tower Top Yaw Moment	-29.2	-19	-21.3	-14.1	-17.2

Table 6. Changes to Fatigue Damage Accumulation Resulting from the Addition of Conventional Flaps to 5MW NREL Offshore Turbine. Flap is 10% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit. All Damage is % Change from the Baseline Levels.

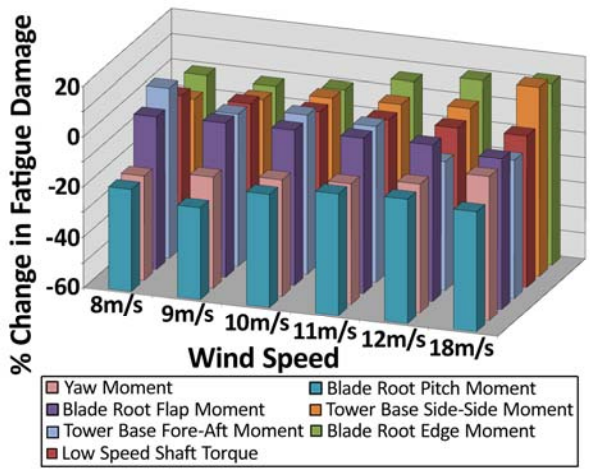

Figure 10. Changes to Fatigue Damage Accumulation Resulting from the Addition of Conventional Flaps to 5MW NREL Offshore Turbine. Flap is 10% Chord, +/-10° Maximum Deflection, 100°/sec Deflection Rate Limit. All Damage is % Change from the Baseline Levels.

Impact of Neglecting Blade Torsional Flexibility

The work discussed above utilized the standard FAST structural dynamics code, which assumes that blades are infinitely stiff in torsion. In reality, activating an AALC devices will exert a pitching moment on the blade that will tend to twist it, and this twist will attenuate the effect that the AALC device exerts on the flow field. This can lead to serious instability problems, as reported by Gaunaa and Andersen [19]. The CurveFAST code [20], based on the FAST code, but enhanced to model the blade torsion modes, was used to investigate the effect on the results presented here of neglecting this structural response. The analysis results for the CurveFAST code with the 1.5MW WindPACT model described above at 8m/s and 12m/s wind speeds are compared with the FAST results for exactly the same conditions in Table 7. With the exception of the blade-root pitch moment, the differences between the FAST and CurveFAST results are very small – the differences are less than 8%, indicating that the results presented in Tables 2, 3, 5 and 6 are not heavily affected by ignoring the AALC-induced twisting of the blade. The predicted blade-root pitching moment DEL is very different between the two codes, especially at the higher wind speed. This simply reflects the fact that the AALC devices are, indeed, inducing twist on the blade. The much higher fatigue accumulation at the higher wind speed simply reflects the heavier usage of the devices at the higher wind speed (together with the dependence of the magnitude of the moment on the square of the wind speed).

	8m/s FAST	8m/s CurveFAST	8m/s Difference	12m/s FAST	12m/s CurveFAST	12m/s Difference
Low Speed Shaft Torque	-2.3	-4.2	1.9	-9.7	-6.4	-3.3
Blade Root Edge Moment	1.3	-3.2	4.5	2.2	-5.4	7.6
Blade Root Flap Moment	-27.6	-21.9	-5.7	-23.1	-23.2	0.1
Blade Root Pitch Moment	-12	-23.9	11.9	-8.4	208.9	-217.3
Tower Base Side-Side Moment	-0.3	-1.1	0.8	-3.1	-8.8	5.7
Tower Base Fore-Aft Moment	-17.6	-13.6	-4	-13.8	-14.5	0.7
Tower Top Yaw Moment	-50	-43.1	-6.9	-43.4	-43.3	-0.1

Table 7. Comparison of Fatigue Damage Accumulation for FAST and CurveFAST Codes. FlexSys Morphing Trailing Edge Technology on 1.5MW WindPACT Turbine. Trailing Edge is 20% Chord, +/- 10° Maximum Deflection, 100°/sec Deflection Rate Limit. All Damage is % Change from the Baseline Levels.

Conclusions and Future Work

Addition of AALC (with a simple PD controller) to the blades of either the 1.5MW WindPACT turbine or the 5MW NREL Offshore turbine resulted in large decreases in the blade-root edge moment fatigue damage accumulation, with the 5MW turbine seeing only about half the reduction in DEL fatigue load accumulation as that seen by the 1.5MW. Growing the rotor of the 1.5MW turbine by 10% resulted in decreases in COE ranging from about 5% at an 8m/s site to nearly 9% at a 5.5m/s wind site. The conventional flap AALC configuration was found approximately as effective as the morphing trailing edge AALC configuration at controlling the fatigue damage accumulation on the rotor blade-root flap moment location. These results are not heavily influenced by the inability of the FAST code to analyze the AALC-induced twisting of the blade.

No attempt was made to optimize the AALC PD controller. Efforts to tune the controller would potentially result in improved fatigue damage reductions.

Future work will investigate the impact of the AALC-induced twisting on the results presented here for the 5MW wind turbine, examination of the use of 20% chord conventional flaps on the 1.5 and 5MW turbines. Other AALC device configurations will also be studied, and the impact of the various devices on wind-turbine energy capture will be investigated.

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