Optimized Active Aerodynamic Blade Control for Load Alleviation on Large Wind Turbines

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Problem Statement and Goal

- With Wind Turbines Blades Getting Larger and Heavier, Can the Rotor Weight be Reduced by Adding Active Devices?
- Can Active Control be Used to Reduce Fatigue Loads?
- Can Energy Capture in Low Wind Conditions be Improved?

Initial Research Goal:
Understand the Implications and Benefits: Embedded Active Blade Control: Alleviate High Frequency Dynamics
Research Objectives

- Define the active aero control problem (critical path /drivers, analysis/simulation scenario, performance index: maximize energy capture, minimize root moment, other)
- Proof-of-concept (i.e., microtab control to reduce fatigue loads/cycling)
- Preliminary Technical Approach:
  - Optimization for tab on/off sequencing
  - Conventional feedback control for reducing load/fatigue in turbulent case
  - Dynamic stall flutter problem analysis w/ nonlinear power flow limit cycle control proof-of-concept
Microtab Concept
Background

- Evolutionary Development of Gurney flap
- Tab Near Trailing Edge Deploys Normal to Surface
- Deployment Height on the Order of the Boundary Layer Thickness
- Effectively Changes Sectional Camber and Modifies Trailing Edge Flow Development (so-called Kutta condition)

Collaboration: Case van Dam at UC Davis
Microtab Concept

- Small, Simple, Fast Response
- Retractable and Controllabe
- Lightweight, Inexpensive
- Two-Position “ON-OFF” Actuation (option)
- Low Power Consumption
- No Hinge Moments
- Expansion Possibilities (scalability)
- Do Not Require Significant Changes to Conventional Lifting Surface Design (i.e., manufacturing or materials)

Collaboration:
Case van Dam
UC Davis
MicroTab Profiles
AeroDyn Inputs

![Graphs showing lift and drag coefficients vs. angle of attack.](image)
Modified Control System Design

- **Hybrid Controller:** Proportional-Integral (PI) Blade Pitch Control with Proportional-Derivative (PD) Microtab Control for above rated wind speed conditions, Region III

- **Microtab PD Control:** Uses tip deflection feedback and nominal reference tip deflection as set point

- **Optimize** controller gains based on Performance Index for constant power output while minimize cyclic loads (root flapwise bending moment) in Region III
System Modeling and Analysis
Augmented w/ Microtab Control

Dynamic Simulation Environment: FAST (Fatigue, Aerodynamics, Structures, and Turbulence) run within Matlab/Simulink

This delay prevents direct feedthrough which causes algebraic loops.
CART Model Investigated

Controls
Advanced Research Turbine (CART): utilized as simulation testbed with 600kW rated power @ 42 RPM

WindPACT Virtual Turbine Calculated Static System Frequencies [2]

<table>
<thead>
<tr>
<th>Wavelet Detail Band</th>
<th>Frequency Range (Hz)</th>
<th>Vibrational Modes Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>D9</td>
<td>0.234 – 0.469</td>
<td>1-P, Tower bending</td>
</tr>
<tr>
<td>D8</td>
<td>0.469-0.938</td>
<td>2-P</td>
</tr>
<tr>
<td>D7</td>
<td>0.938-1.875</td>
<td>Blade 1st bending</td>
</tr>
<tr>
<td>D6</td>
<td>1.875 – 3.75</td>
<td>Blade 2nd bending</td>
</tr>
<tr>
<td>D5</td>
<td>3.75 – 7.5</td>
<td>Blade, blade/tower</td>
</tr>
<tr>
<td>D4</td>
<td>7.5 – 15</td>
<td>Blade, blade/tower</td>
</tr>
<tr>
<td>D3</td>
<td>15 – 30</td>
<td>Blade, blade/tower</td>
</tr>
</tbody>
</table>

Turbulent Intensity [1]

- Derived from model: virtual variable-speed 1.5-MW, 3-bladed upwind turbine: 85-m hub height, 70.5-m rotor DIA. Examine time-varying turbulence/loading response
- Root Flapwise Bending Loads, Band D6-D7
- Time-frequency spectral decomposition of root flapwise load encountering coherent turbulent structure
- Red color signifies occurrence: highest level of dynamic stress energy - dark blue least
- While peak amplitudes of load time histories in Bands D6 - D7 decreases, number of stress reversals increase as rotor passes through coherent turbulent structures
- Due to nature of load application and existence small values of structural damping – potential significant transient storage of vibrational energy that must be dissipated
- Potential modal dynamic amplification may exist, could contribute to lower than designed component service lifetimes
- Microtabs good candidate to reduce high frequency dynamics and fatigue loads
Turbulent Wind Input
(Specific Case Explored)

23.2 m/s Mean Wind Speed, IEC Type A Turbulence
Time Domain - FAST/Simulink

Simulation Results

- Blade 1 Tip Deflection (m)
  - No MicroTabs
  - MicroTabs

- Blade 1 Root Flap Bending Moment (kNm)
  - No MicroTabs
  - MicroTabs

Graphs showing time-domain simulation results with comparison between 'No MicroTabs' and 'MicroTabs' conditions.
Time Domain - FAST/Simulink Simulation Results

![Graph showing blade pitch angle over time with and without microtabs. The x-axis represents time in seconds, ranging from 0 to 20. The y-axis represents blade pitch angle in degrees, ranging from 13 to 18. Two lines are shown: red for 'No MicroTabs' and blue for 'MicroTabs'.](image)

![Graph showing blade microtab sequencing. The x-axis represents time in seconds, ranging from 0 to 20. The y-axis represents blade 1 microtab sequencing values, ranging from -1 to 1.](image)
Time Domain - FAST/Simulink
Simulation Results

- Generator Power (kW)
- Rotor Speed (RPM)

No MicroTabs vs MicroTabs
Time Domain - FAST/Simulink Simulation Results

- **Time (sec)**
- **Tower Base Side-Side Moment (kNm)**
  - No MicroTabs
  - MicroTabs

- **Time (sec)**
- **Tower Base Fore-Aft Moment (kNm)**
  - No MicroTabs
  - MicroTabs
Visualization: MicroTab Control

(Click on image below to play video)
Observations - Summary

- Potential Benefits to Designer:
  - Increase Effective Rotor Size
  - Extend Potential Life Expectancy and Reliability
  - Ultimately Reduce Cost-Of-Energy of Future Large Wind Turbine Machines

- Active Aero Devices may Provide Substantial Benefit for Future Wind Turbine Designs
Future Control Design: Reduce Load/Fatigue: Increase Energy Capture

- Lightweight adaptive blade design with embedded sensors and actuators utilizing integrated hybrid pitch/distributed flap control system
- Combined blade pitch/flap control system: reduced loading above rated speed (may increase energy capture below rated speed)
- Nonlinear flutter control system based on nonlinear power flow design: identifies stability boundary, improved performance by promoting lightweight/high strength blade design
- Smart structures technology to be investigated to facilitate implementation of smart blade concept