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SAND2014-1802C

SMART Rotor Test & Data Analysis

Advanced Rotor Technology Development

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Purpose & Objectives

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Problem Statement:

Validation of Active Aerodynamic Load Control (AALC) modeling is needed. The simulations have shown how the technology can reduce damaging loads from wind gusts, wind shear, and yaw misalignment.

This project demonstrates the practical use of flaps and progresses the engineering methods needed for successful technology transfer to industry.

Impact of Project:

- Improved simulation accuracy can be used to assess load control approach and reduce commercialization risk
- Rotor balancing by active control can reduce wear-and-tear on entire machine
- A larger rotor, enabled by AALC, improves capacity factor for a given turbine size

This project aligns with the following DOE Program objectives and priorities:

- **Optimize Wind Plant Performance:** Reduce Wind Plant Levelized Cost of Energy (LCOE)
- **Accelerate Technology Transfer:** Lead the way for new high-tech U.S. industries
- **Modeling & Analysis:** Conduct wind techno-economic and life-cycle assessments to help program focus its technology development priorities and identify key drivers and hurdles for wind energy technology commercialization

Technical Approach

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Design & Build (FY10-11)

- Three research scale blades
- Integrated trailing edge flaps

Field Test (FY12)

- Demonstrate the control capability of the trailing-edge flaps at Bushland test site
- Evaluate the accuracy of simulation tools in predicting results of active rotor control
- Develop procedures for characterizing an operating wind turbine with active rotor control

Data Analysis (FY13)

- Ensure the time-accuracy and alignment of signals
- Translate observed load responses to fundamental aerodynamic blade and wake time scale for future engineering models

Process	Time Scale Definition	Time Scale
AALC Device Actuation	Actuation Period	0.09 – 1.1 sec
Response to Rotationally Sampled Wind	1P,2P,3P periods	0.3 - 1.1 sec
Dynamic Structural Response	Period of First Two Blade Flap Modes	0.09 - 0.22 sec
Local Section Flow	Chord / Relative Flow Velocity	0.004 sec
Local Section Flow Adjustment	5-10x Section Flow Time Scale	0.02 - 0.04 sec
Wake Response	Rotor Radius / Wind Speed	1.2 sec

Estimated time scales for test turbine at Bushland site.

Technical Approach

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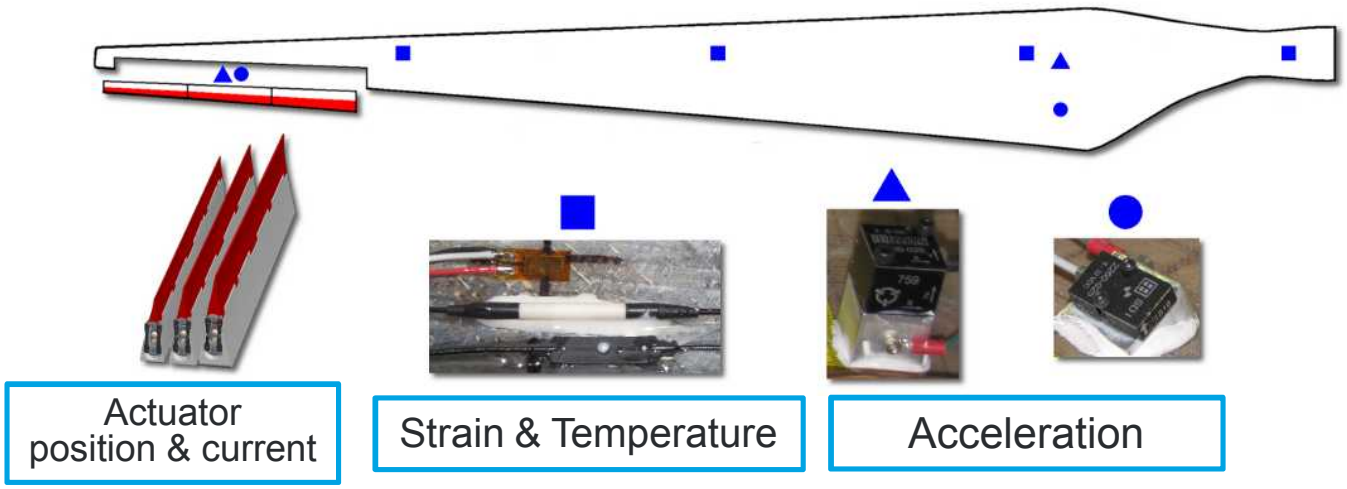
- Leverage Sandia's previous experience integrating sensors in blades
- Optimize number and location of sensors to enable estimation of other quantities not measured directly
- Work with partners to integrate state-of-the-art sensors



Sandia has 9 years of experience with in-blade sensing systems

Field Tests, State-of-the-Art

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	DTU, Vestas	DTU, Vestas	SNL
Year Published	2010[1]	2013[2]	2013[3]
Turbine	V27	V27	Micon 65/13M
rotor diameter	27 meter	27 meter	19 meter
pitch	variable	variable	fixed
Number of Active Blades	1	1	3
Device (TEF = Trailing Edge Flap)	flexible TEF	hinged TEF	hinged TEF
percent of span, installed	15%	15%	20%
percent of span, functional during test	15%	5%	20%
Structural Sensors	strain, accel	strain, accel	strain, accel
Aerodynamic Sensors	Pitot tubes (3)	Pitot tubes (3)	no
Achieved closed-loop control?	no	yes	no

1. D. Castaignet, et al., "Results from the first full scale wind turbine equipped with trailing edge flap", 2010 AIAA Applied Aerodynamics Conference
2. D. Castaignet, et al., "Full-scale test of trailing edge flaps on a Vestas V27 wind turbine: active load reduction and system identification", 2013 Wind Energy Journal
3. J. Berg, et al., "Field Test Results from the Sandia SMART Rotor", 2013 ASME Wind Energy Symposium / AIAA Aerospace Sciences Meeting

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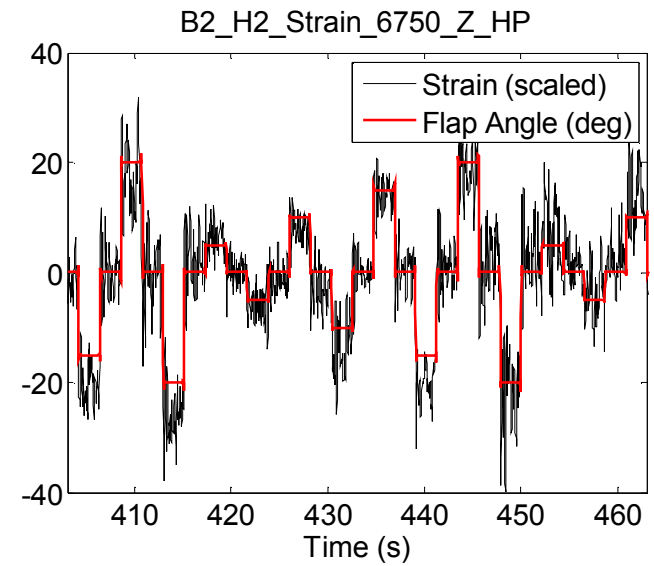
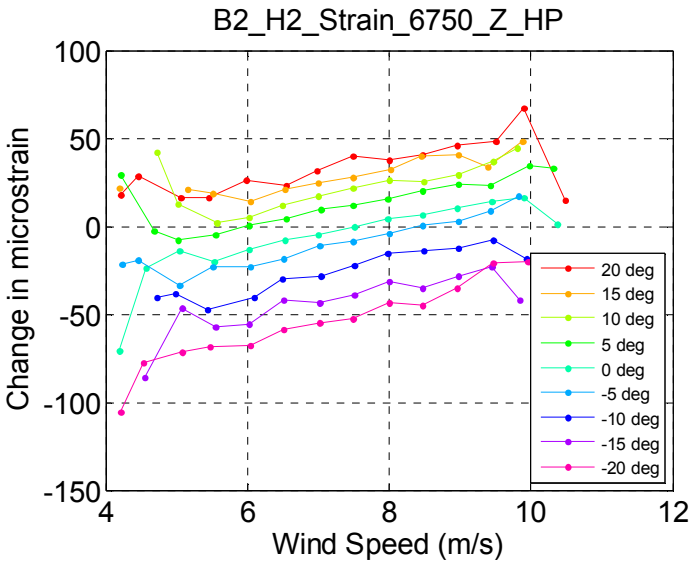
Control Capability Demonstrated

- Response captured over a range of flap angles and wind speed
- At 3/4 span with -20 and 20 degree flap, strain magnitude changed by 50 and 33 microstrain
- These changes are 114% of the strain induced by normal power production

The flap control authority ranged from completely unloading to doubling the load on the flapped section of the blade

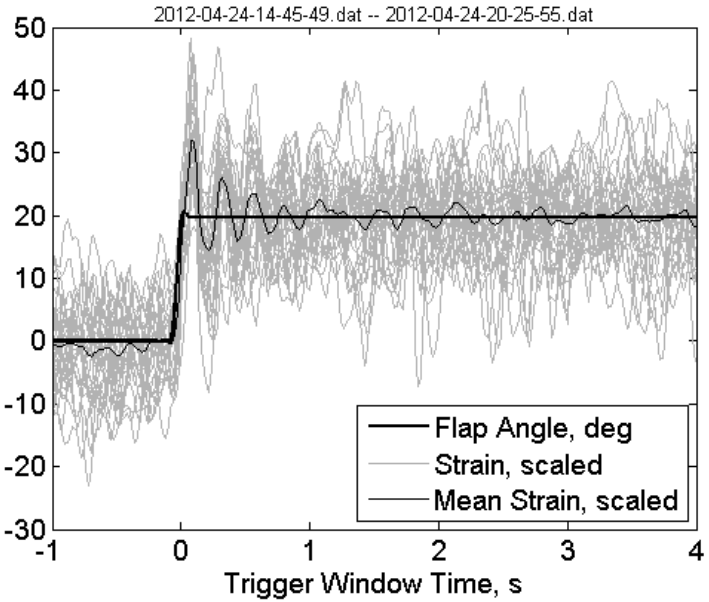




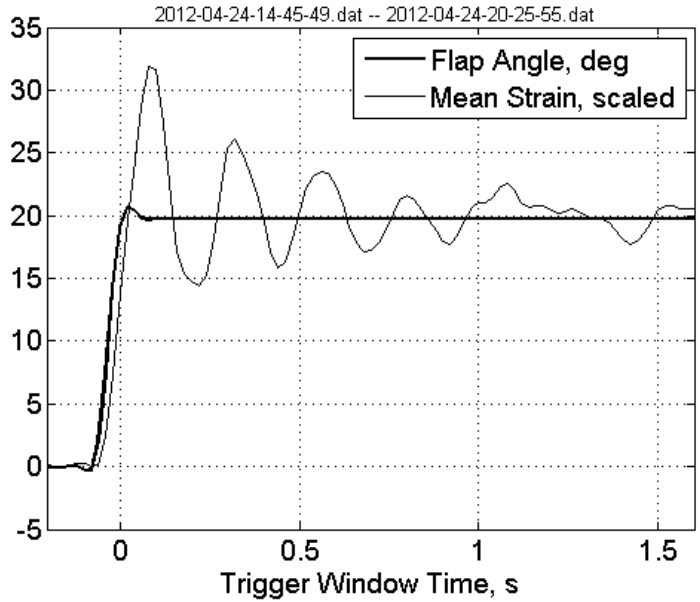
Accomplishments and Progress

Advanced signal processing allowed concise quantification

- Wind inflow is highly variable which makes every test run different
- Ensemble average of many responses to the same flap motion uncovers the repeatable behavior
- The result enables fundamental time scale and damping identification



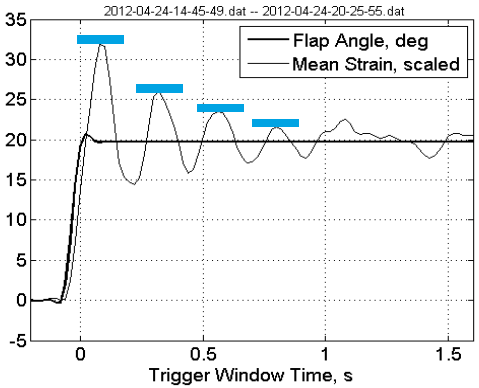
29 individual responses (gray)



Ensemble average response

Observed Combined Aero-Structural Damping

- Damping added by aerodynamic forces is typically difficult to quantify
- Combined damping estimated to be 1.3-3.2% of critical damping
- Amount of damping appears to depend on amplitude of blade motion

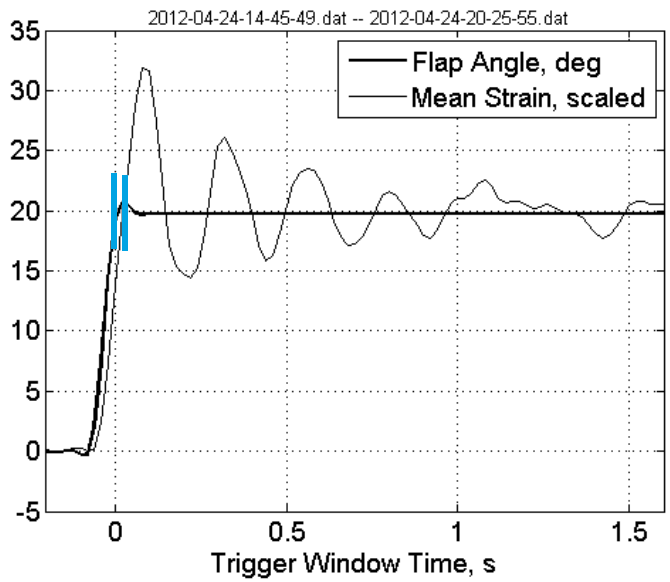


Peak	Maximum	Time, s		Peaks	Log Decrement	Damping Ratio	Time Difference, s	$1/\Delta T$, s^{-1}
u_1	30.38	0.0799		$u_2 - u_1$	0.202	0.032	0.2396	4.17
u_2	24.83	0.3195		$u_3 - u_2$	0.097	0.015	0.2397	4.17
u_3	22.54	0.5592		$u_4 - u_3$	0.080	0.013	0.2396	4.17
u_4	20.81	0.7988						

Flaps can be used to characterize turbine dynamics and calibrate fundamental aerodynamics properties

Observed Response Time Delay

- Observed 0.02 second delay in structural response
- Local section airflow adjustment can be related to structural response
- Evaluate accuracy of simulation tools



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Wake Response	Rotor Radius / Wind Speed	1.2 sec

Observed 0.02 second delay in strain response

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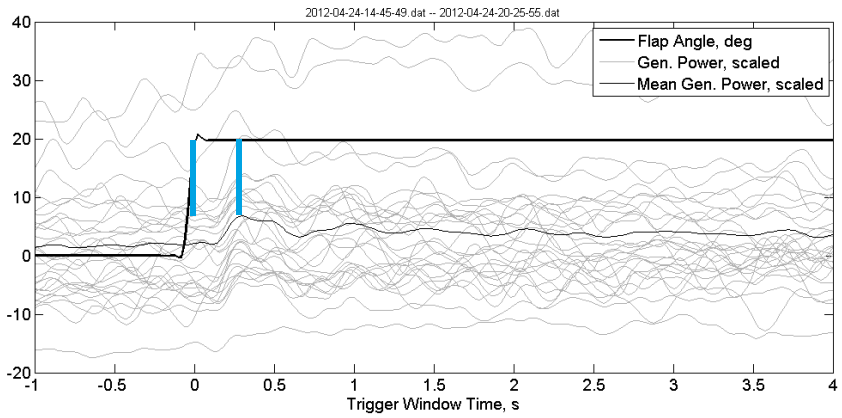
Observed Power Response

- Important to capture power output accurately in simulation
- Observed 0.3 second delay in power response
- Power response and wake response are closely related, and flaps can be used to investigate the relation



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Wake Response	Rotor Radius / Wind Speed	1.2 sec

Observed 0.3 second delay in power response

Project Plan & Schedule

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Summary	
WBS Number or Agreement Number	WE 3.1.7 (FY13)
Project Number	21112
Agreement Number	22527

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Wind Energy Forecasting Methods and Validation for Tall Turbine Resource Assessment												
Q1 Milestone: Complete AIAA conference papers												
Q2 Milestone: Complete SMART open-loop testing												
Q3 Milestone: Complete draft report on SMART field test												
Q4 Milestone: Submit conference abstract on AALC test/model comparison												
Q1 Milestone: Complete SAND report documenting field test & data sets												
Q2 Milestone: Progress update memo on data analysis												
Q3 Milestone: Submit article to peer-reviewed journal												
Q4 Milestone: Publish SAND report detailing conclusions from data analysis												
Current work and future research												

Comments

- FY13 Q1&2 saw decrease in available staff time as resources were devoted to SWiFT installation.

Project Budget

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Budget History					
FY2012		FY2013		FY2014	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$875K	--	$350K	--	$0	--

- $141k of FY13 funding was carried over into FY14

Research Integration & Collaboration

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Partners, Subcontractors, and Collaborators:

- USDA-ARS staff at Bushland Test Site
- University research collaboration
  - University of California, Davis (C.P. van Dam)
  - TU Delft (Thanasis Barlas, Jan-Willem van Wingerden, Lars Bernhammer)
- Subcontract: Creaform, blade surface geometry scan

Communications and Technology Transfer:

Sandia Project Reports

- J.C. Berg, M.F. Barone, and N.C. Yoder. "SMART Wind Turbine Rotor: Data Analysis and Conclusions." Sandia Report SAND2014-0712, January 2014.
- J.C. Berg, B.R. Resor, J.A. Paquette, and J.R. White. "SMART Wind Turbine Rotor: Design and Field Test." Sandia Report SAND2014-0681, January 2014.

Conference Proceedings

- J.C. Berg, M.F. Barone, and B.R. Resor. "Field Test Results from the Sandia SMART Rotor." Proceedings of the 51st AIAA Aerospace Sciences Meeting, Grapevine, TX, January 2013.
- J.C. Berg, D.E. Berg, and J.R. White. "Fabrication, Integration, and Initial Testing of a SMART Rotor." Proceedings of the 50th AIAA Aerospace Sciences Meeting, Nashville, TN, January 2012.

Next Steps and Future Research

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Proposed future research:

- Based on the acquired experience, develop updated models that advance the state of the art and allow for design optimization of future active load control rotors.
- Utilize lessons learned and updated models to produce second generation AALC rotor.
- Implement closed-loop control utilizing a variety of controls approaches and sensors to progress TRL for technology transfer to industry.