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SMART Rotor Project Summary

Overview of Results from 2010-2013 Project

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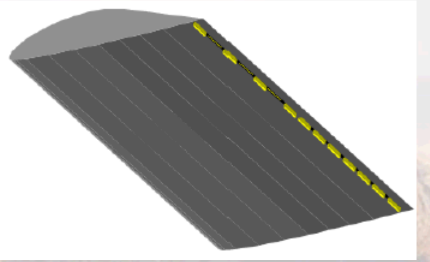
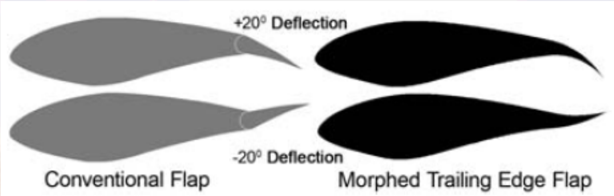
Background

- **Rotor aerodynamic loads impact the design of the entire wind turbine**
- **Potential reduction in cost of wind energy via passive or active load control**
  - Component weight
  - Extended life through fatigue reduction
- **Active aero devices provide additional fast-acting degrees of freedom beyond conventional yaw, blade pitch, and rotor speed (generator torque control)**





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High-level View of Active Aero

- **Most research shows primary role in once-per-revolution loads (1P) and some effect at 2P and 3P**
  - In this regard it is similar to cyclic or individual pitch
  - However, active aero is likely better suited for this task due to smaller size
- **Active aero's role in other design load cases besides fatigue needs to be investigated.**
- **Two published field tests**
  - Both experienced integration and reliability problems with the active aero devices
  - Design-for-manufacture and design for reliability/maintenance will be key for longer-term field tests and ultimate integration into production turbines.

Recently Published Field Tests

Entity	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
speed	33/43 rpm	33/43 rpm	55 rpm
pitch	variable	variable	fixed
Number of Active Blades	1	1	3
Device (TEF = Trailing Edge Flap)	flexible TEF	hinged TEF	hinged TEF
number per blade, installed	3	3	3
number per blade, functional during test	3	1	3
percent of span, installed	15%	15%	20%
percent of span, functional during test	15%	5%	20%
percent of chord	13-18%	13-18%	20%
Structural Sensors	strain, accel	strain, accel	strain, accel
Aerodynamic Sensors	Pitot tubes (3)	Pitot tubes (3)	none working
Achieved closed-loop control?	no	yes	no
Fatigue load reduction	n/a	reported 14%	n/a

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

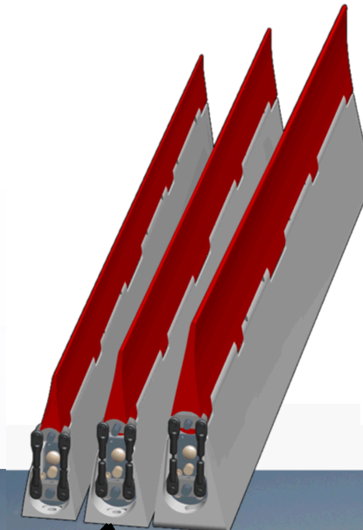
Project Overview

SMART rotor project goals

- Evaluate adequacy of simulation tools for active aerodynamic load control
- Gain insight into the challenges of integration

Conventional hinged flaps chosen

- expectation of good aerodynamic control authority
- relative simplicity of integration
- but not necessary the ideal actuator for active aero

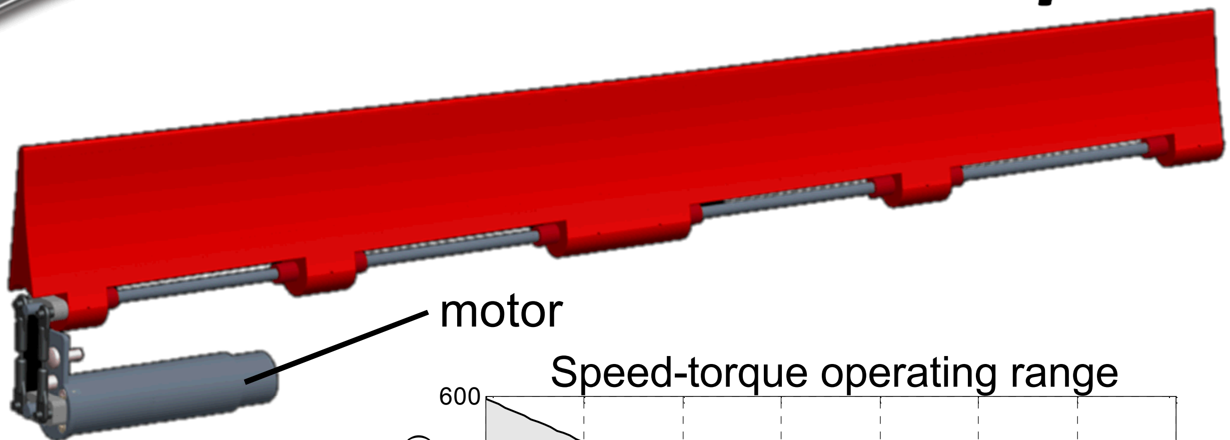


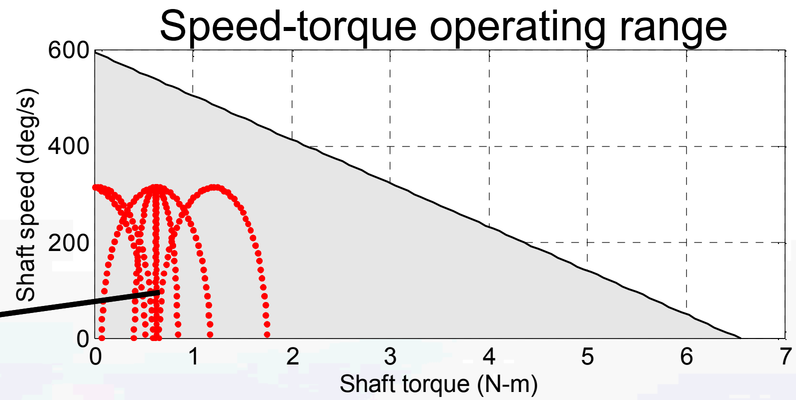
Test Turbine

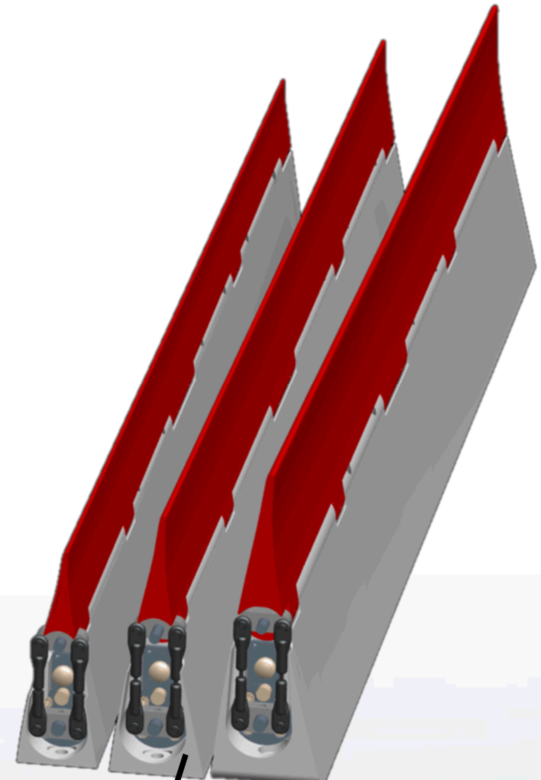
- Micon 65/13M (modified)
- Hub height: 23m (75ft)
- Rotor diameter: 19m
- Generator rated at 115kW
- Nominal rotor speed: 55 rpm
- Fixed pitch

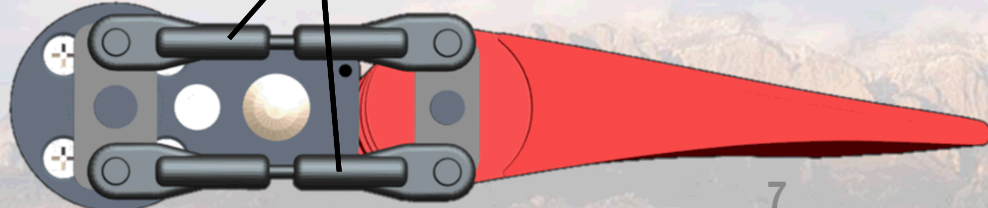
- Trailing edge flaps
  - 20% chord rigid flaps
  - Outer 6 feet (20%) of blade span

Flap Module Design

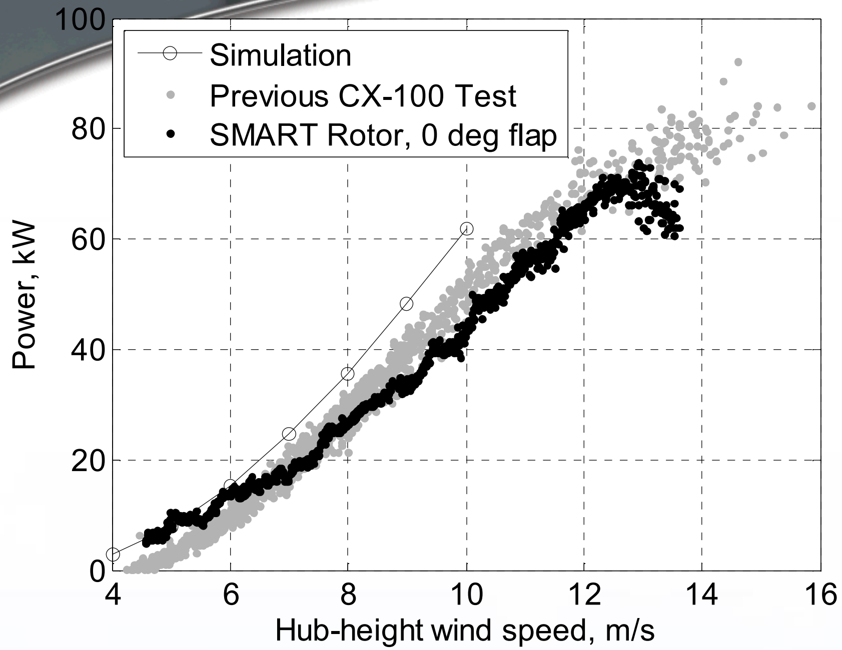






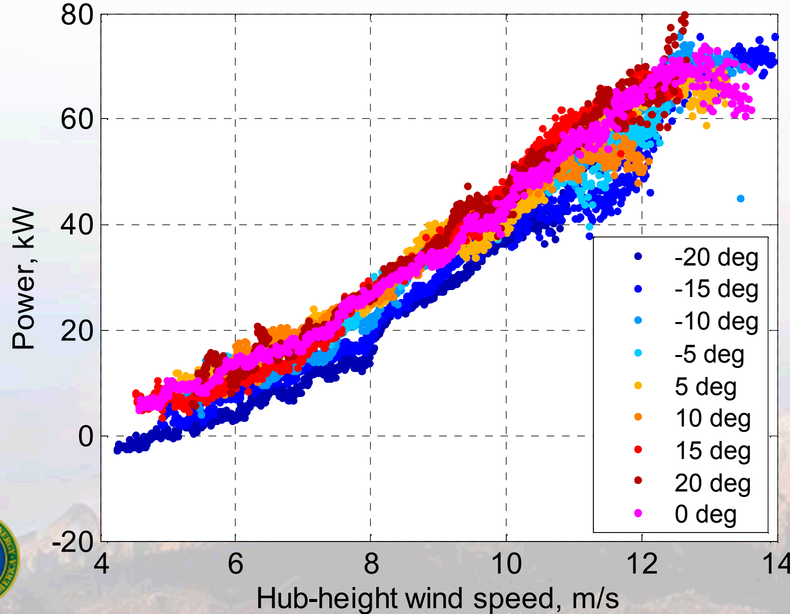


Power Output



Comparison of the SMART rotor power curve (black dots), calculated over 30 minutes of operation at 0° flap angle, to that of a previous field test of the first CX-100 blade set (gray dots). Also shown is the predicted power curve from FAST simulation.

- The simulation over-predicts the power in both cases.
- SMART Rotor power is roughly 15% lower than baseline CX-100 power and reduction is seen mostly between 7 and 12 m/s. Possible explanations:
  - Lack of stiffness in flap mechanism results in negative flap offset under load which in turn reduces lift.
  - Blade twist distribution or blade pitch setting is different.
  - Aerodynamic losses due to modified blade geometry.



Power curves from the SMART rotor for nine settings of the flaps between the maximum flap angles of -20 and +20 degrees. The positive flap angles tend to produce slightly more power at higher wind speeds and the negative flap angles tend to produce noticeably less power than the 0 degree flap angle. This behavior is to be expected on a fixed-speed machine - the unmodified blade geometry is most efficient over one range of wind speeds but the flaps can shift the efficient operating range.

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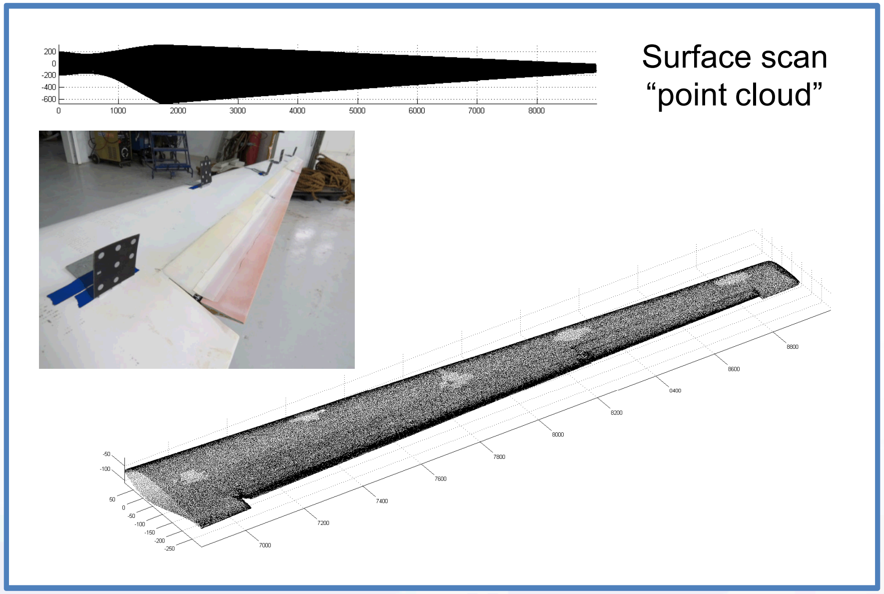
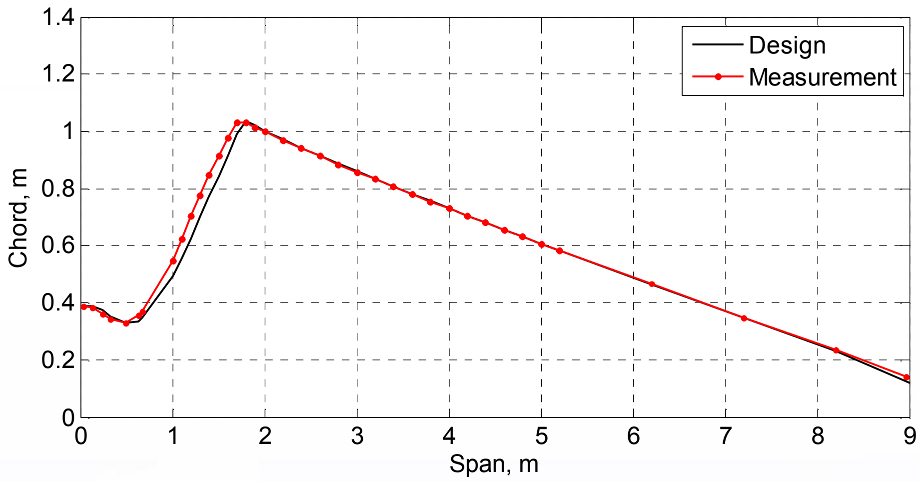
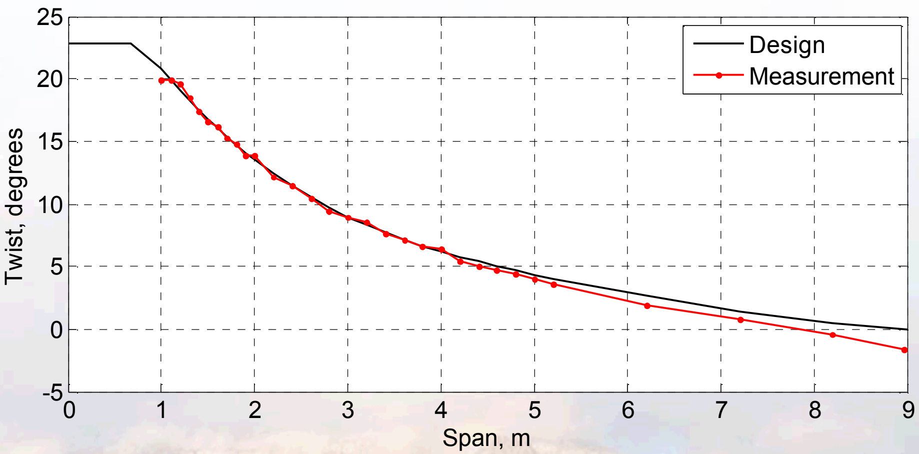
Blade Surface Scan

We scanned surface of all three blades to better understand observed differences between test and simulation.







Measured chord distribution matches design almost exactly.

Measured twist distribution is off at blade tip by 1.4 degrees, with potential to decrease expected power output.

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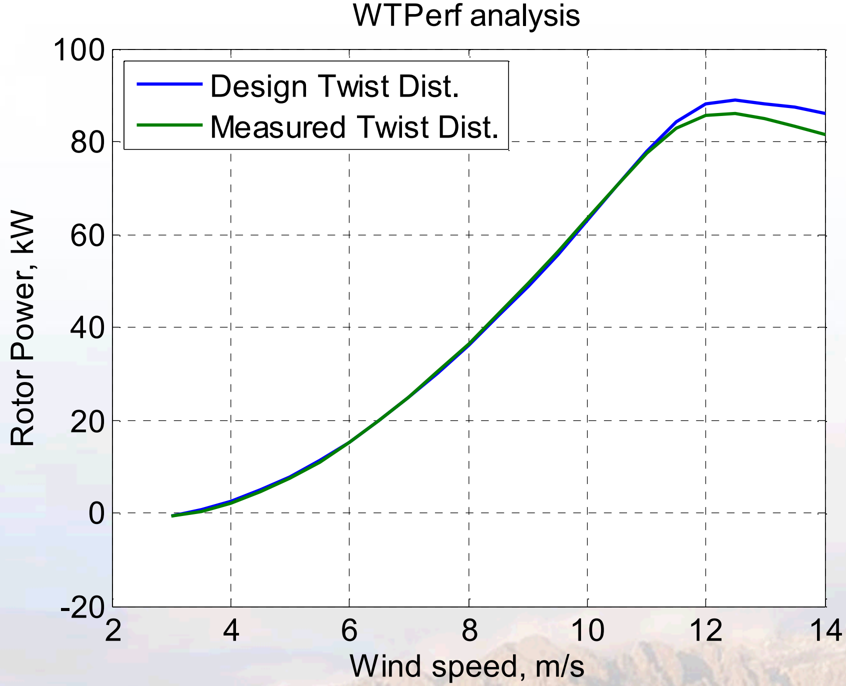
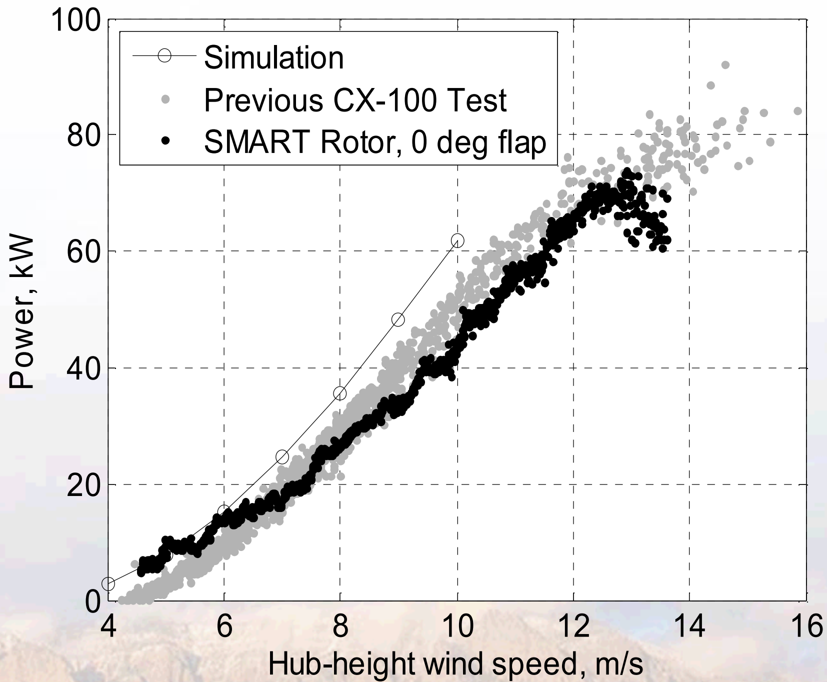
Effect of geometry variation

Initial analysis indicates the reduced outboard blade twist of 1.4 degrees mainly affects the power roll-off after 12 m/s wind.



Increased roll-off is observed in measured power of SMART rotor, however it is much more dramatic.

Additional analysis is needed.



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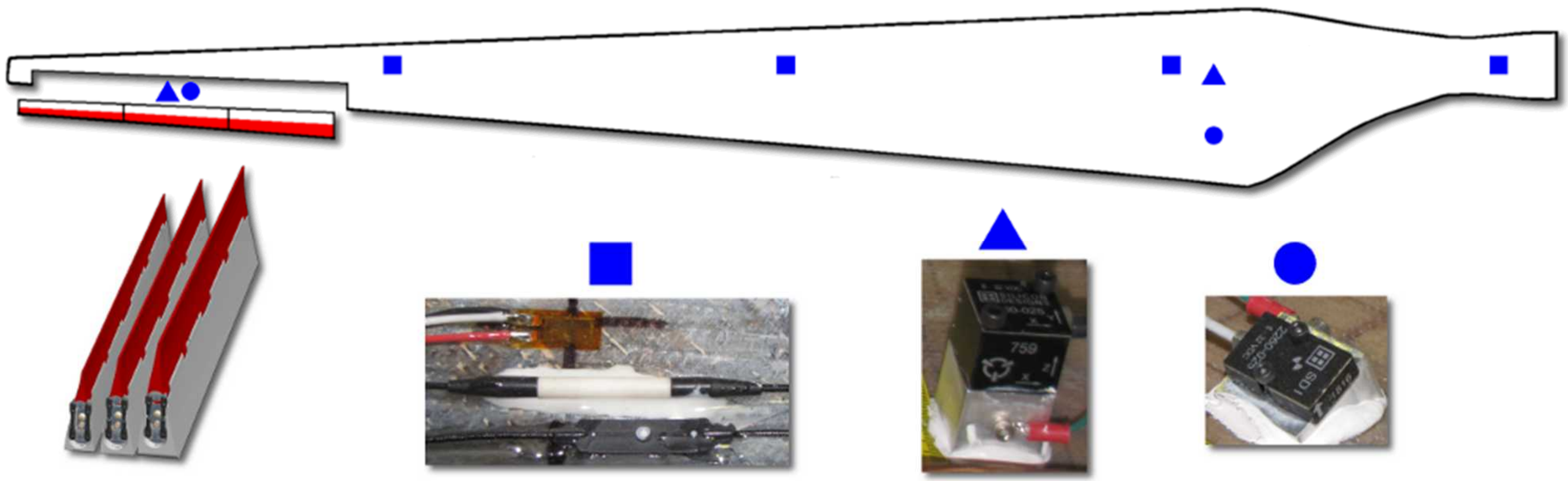
Blade Sensors



Motor shaft angle

Motor current

Foil strain gage

Fiber-optic temperature

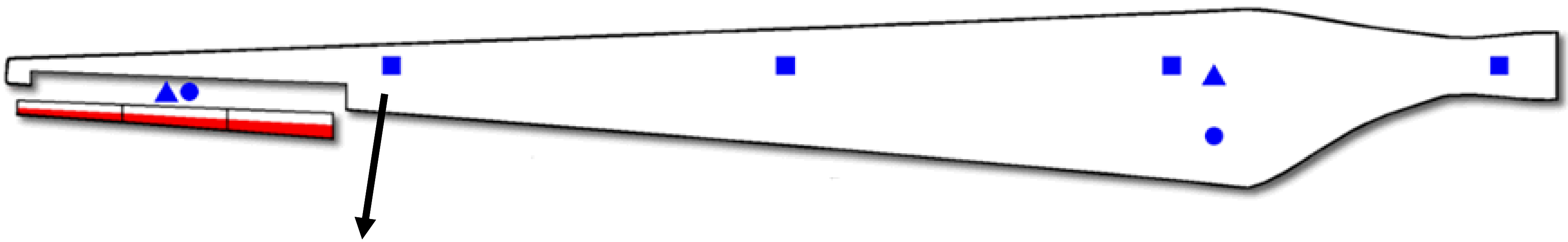
Fiber-optic strain

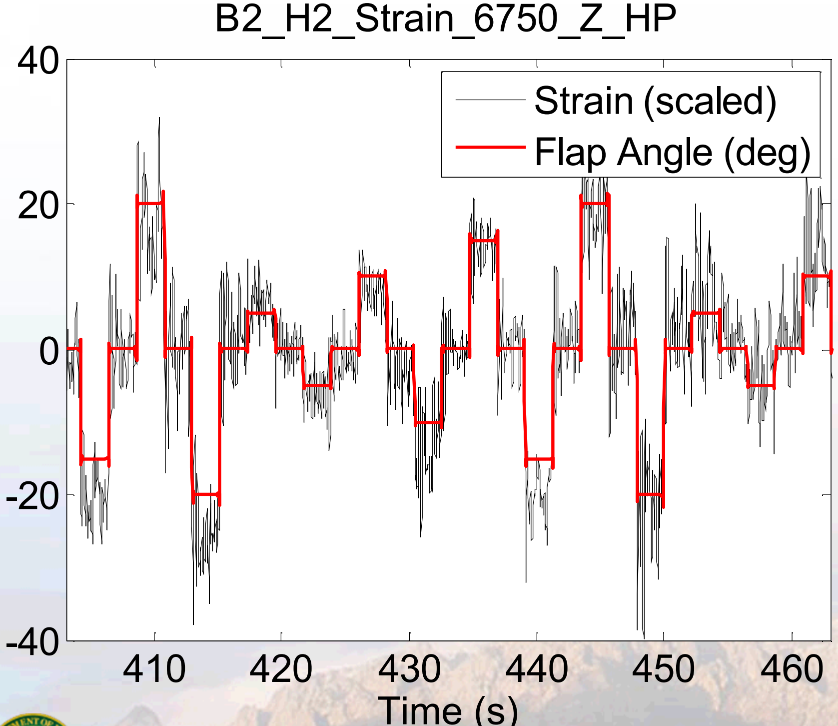
Tri-axial accelerometer

Uni-axial accelerometer

There are 132 data channels on the rotor alone!

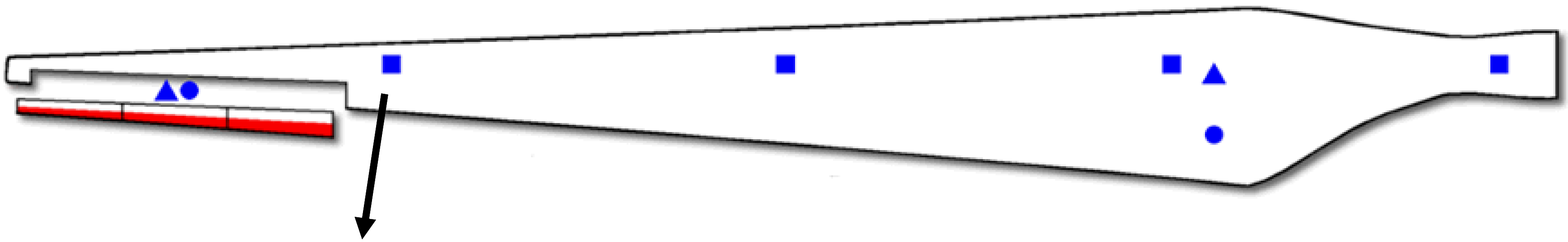
Raw Strain Response

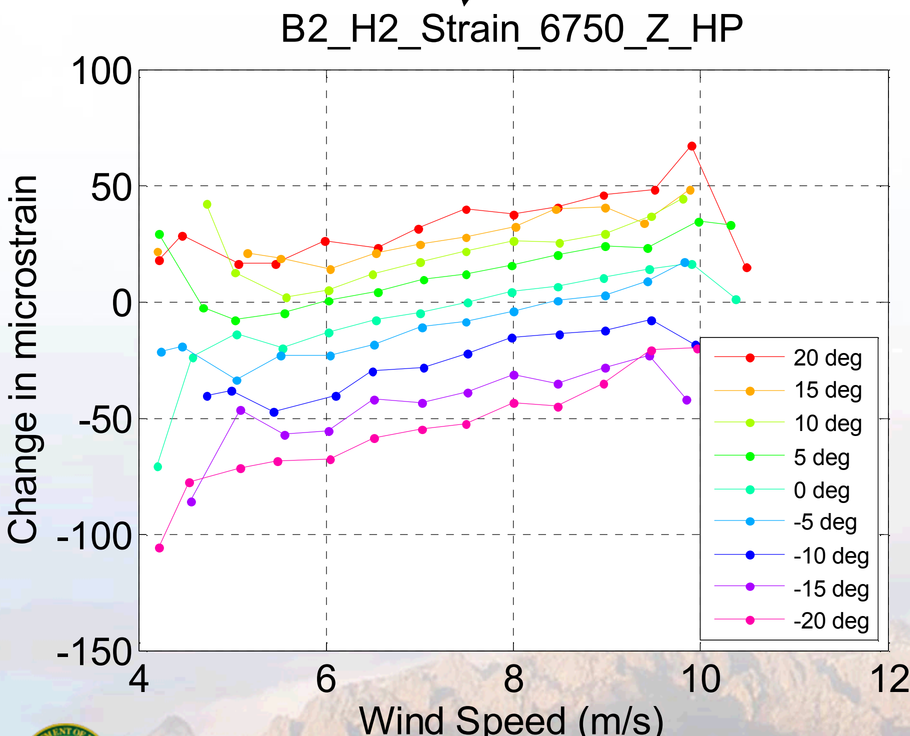




Data binned according to wind speed, then results averaged for each flap angle…

Mean Strain Response vs. Wind Speed

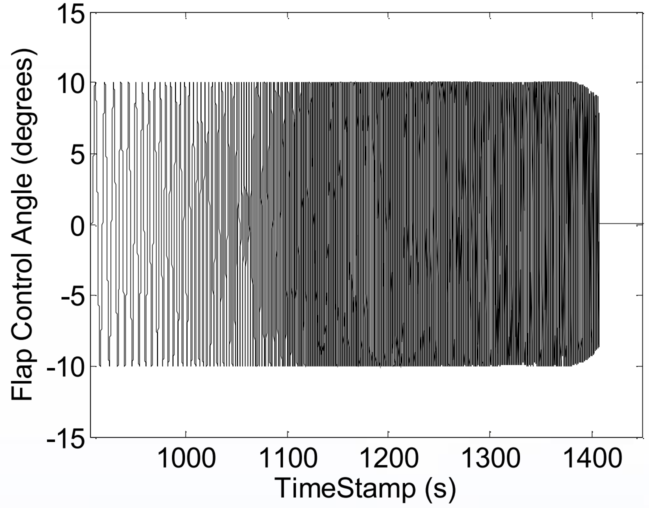


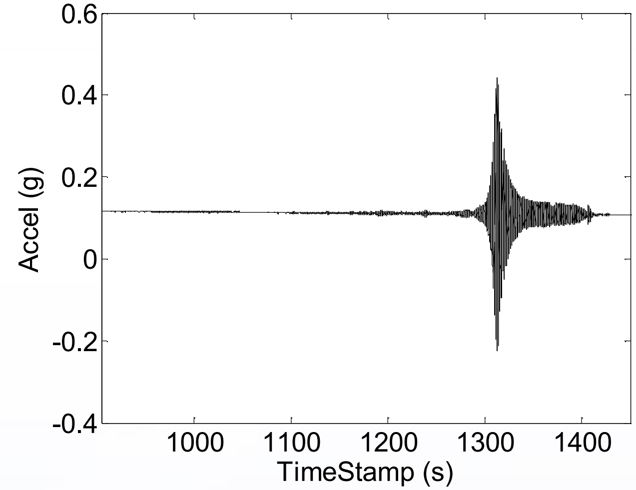


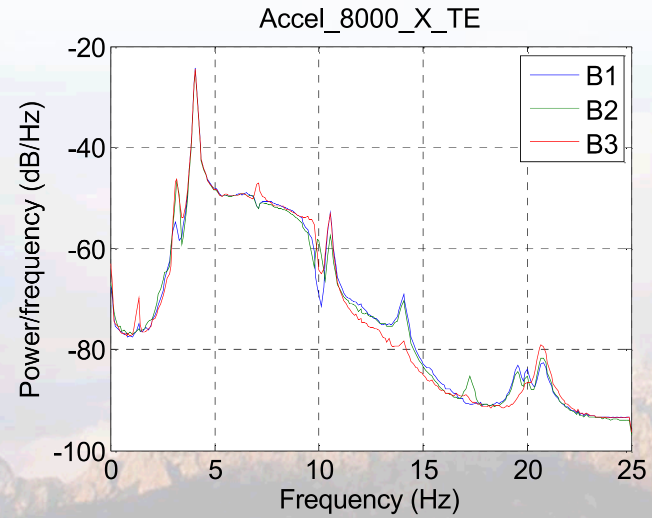
The overall character of these curves matches the expectations from simulation.

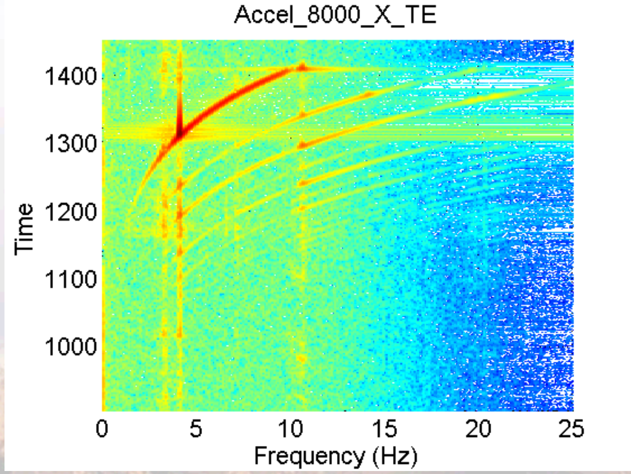
The change in strain for positive flap deflections is somewhat less than that for negative flap angles, likely due to the initiation of stall with high positive flap angles.

System ID – Parked Rotor Sine Sweep

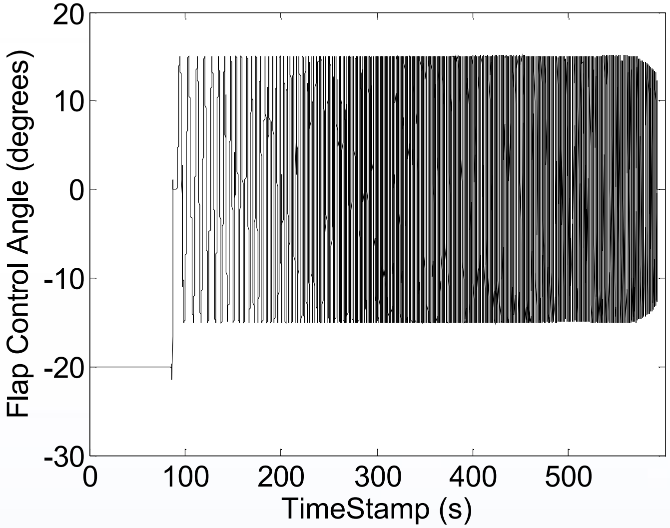


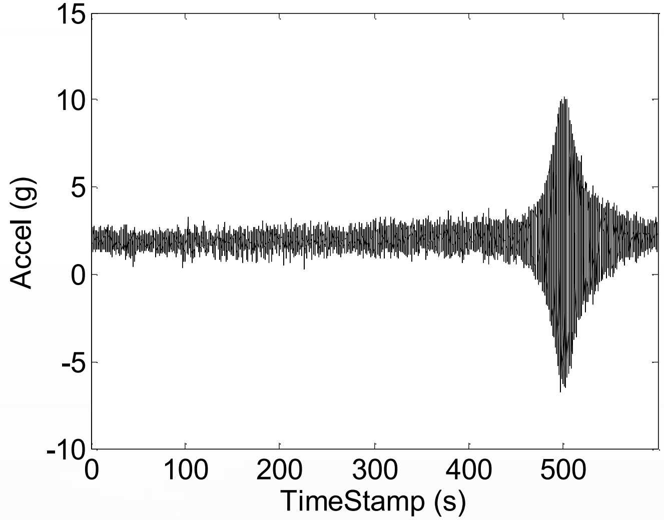


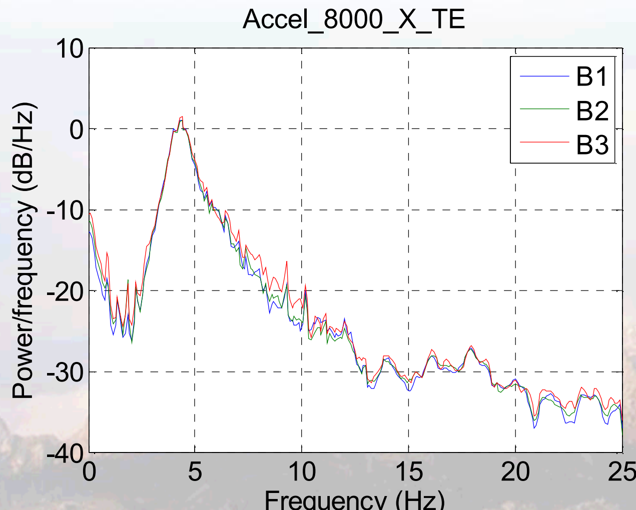


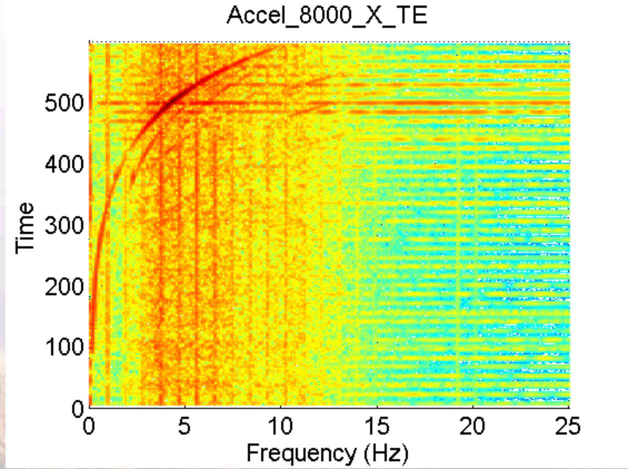


System ID – Operational Sine Sweep



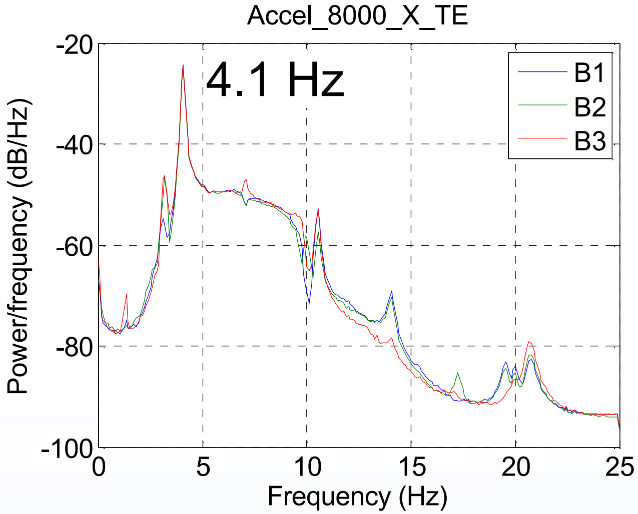


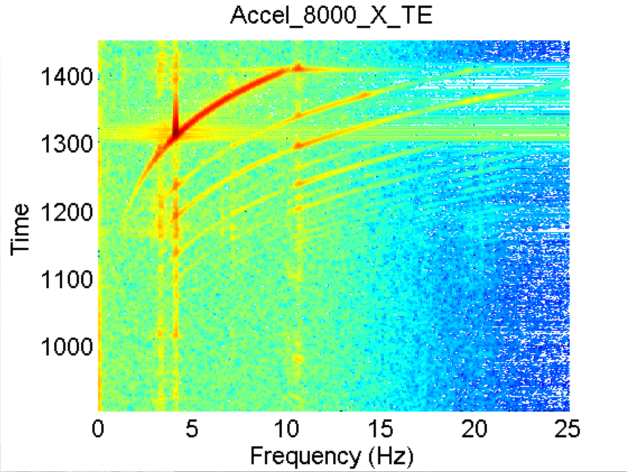




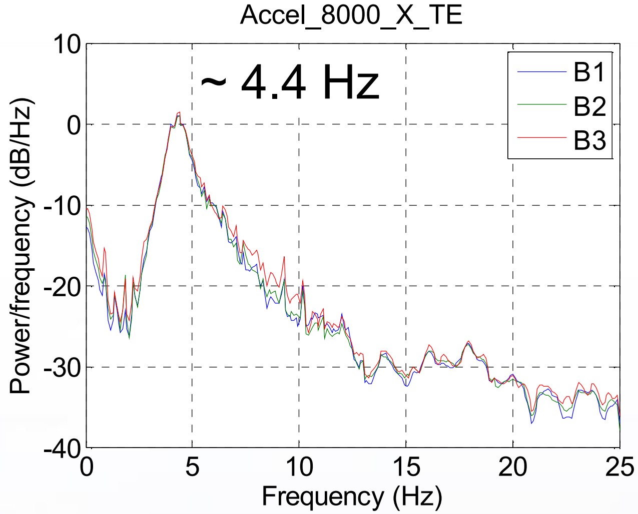
System ID - Comparison

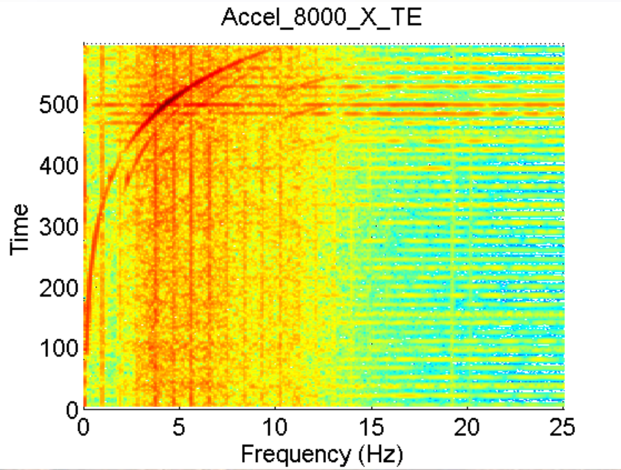
Parked rotor





Operating



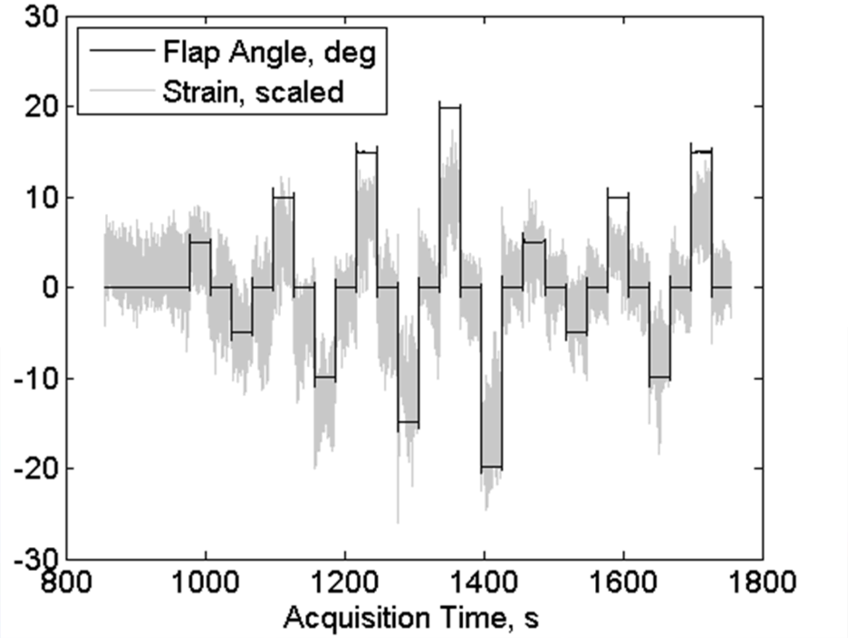


Time Scales for Active Aero on Sandia Test Turbine

Process	Time Scale Definition	Time Scale
AALC Device Actuation	Actuation Period	0.03 - 2.0 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	0.005 sec
Local Section Flow Adjustment	5-10x Section Flow Time Scale	0.025 - 0.05 sec
Wake Response	Rotor Radius / Wind Speed	1.1 sec

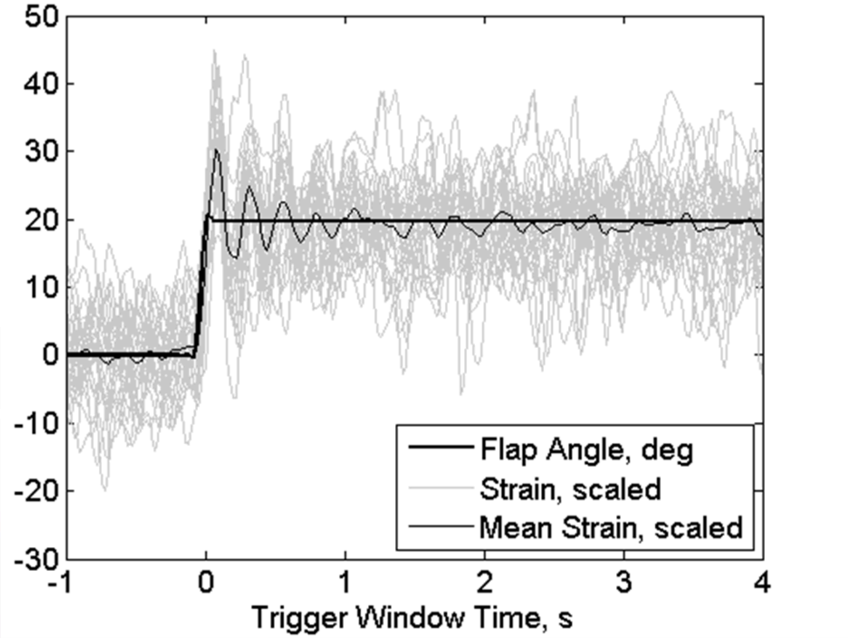
Time-Domain Average Response

Typical blade strain response to series of flap motions

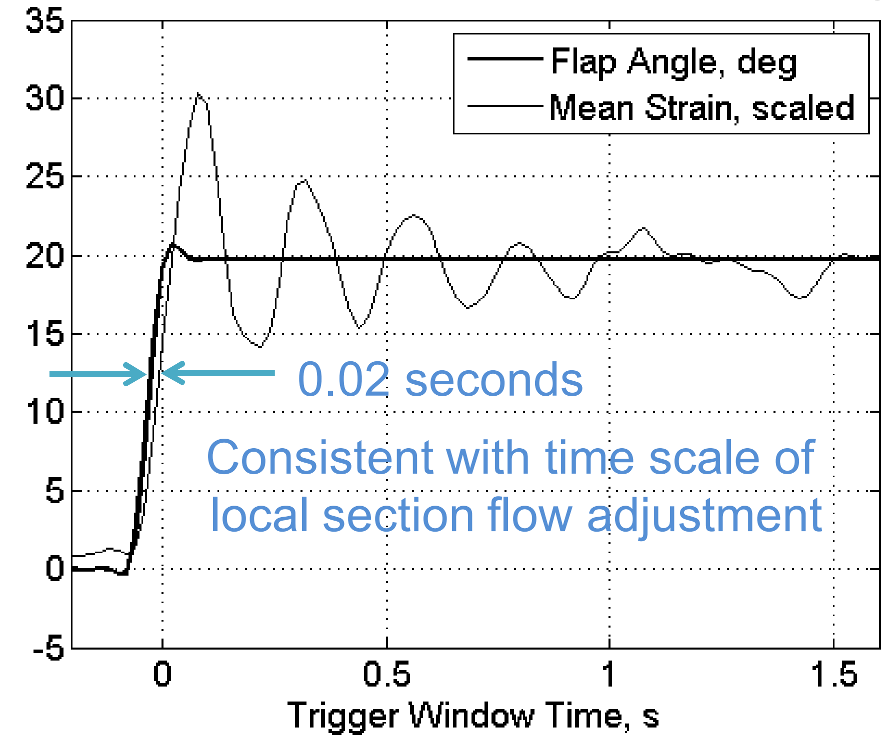


29 individual responses were recorded

Average reveals underlying dynamics



Flapwise Blade Strain



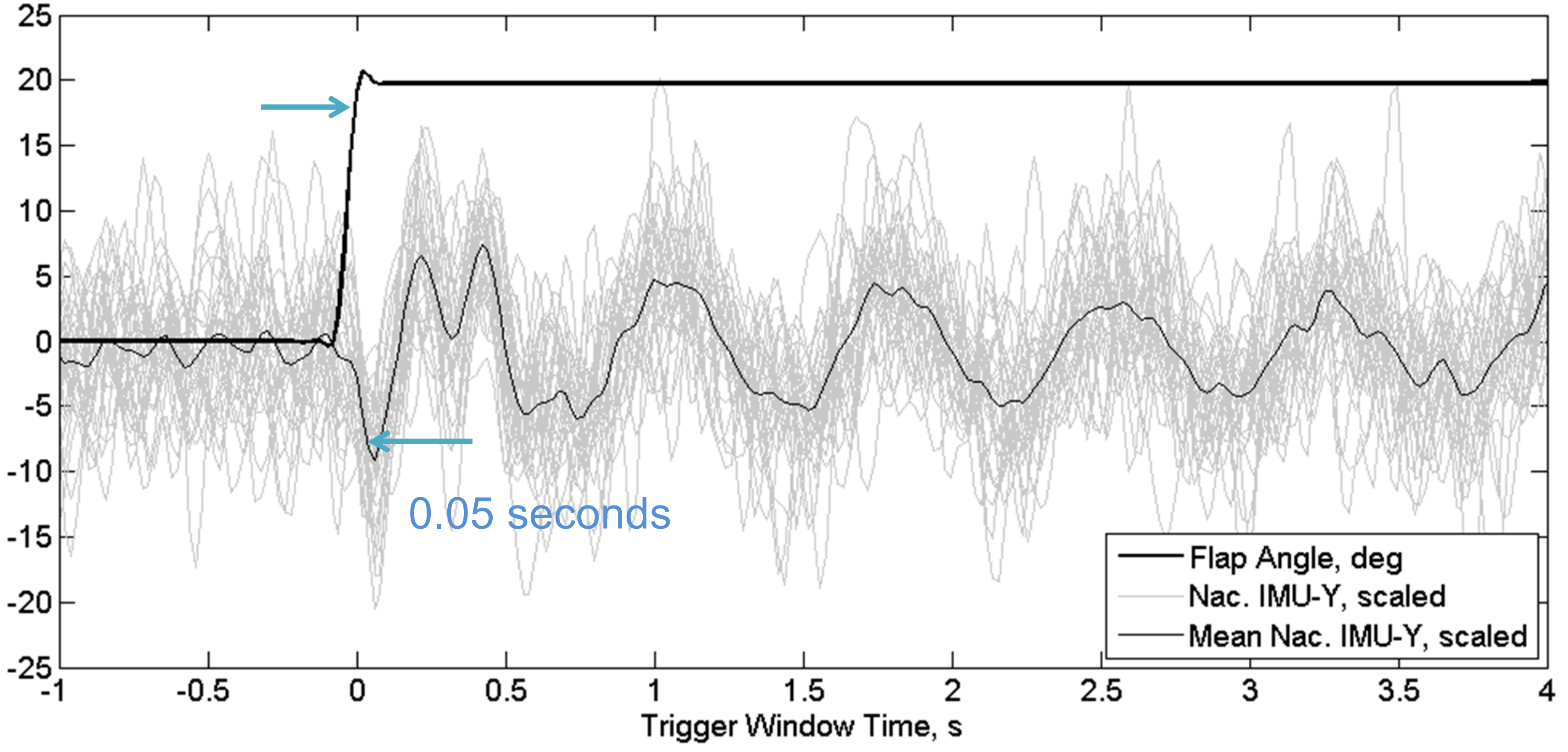
Log decrement: $\delta = \ln \frac{u_i}{u_{i+1}} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$

Damping ratio: $\zeta \approx \frac{\delta}{2\pi}$

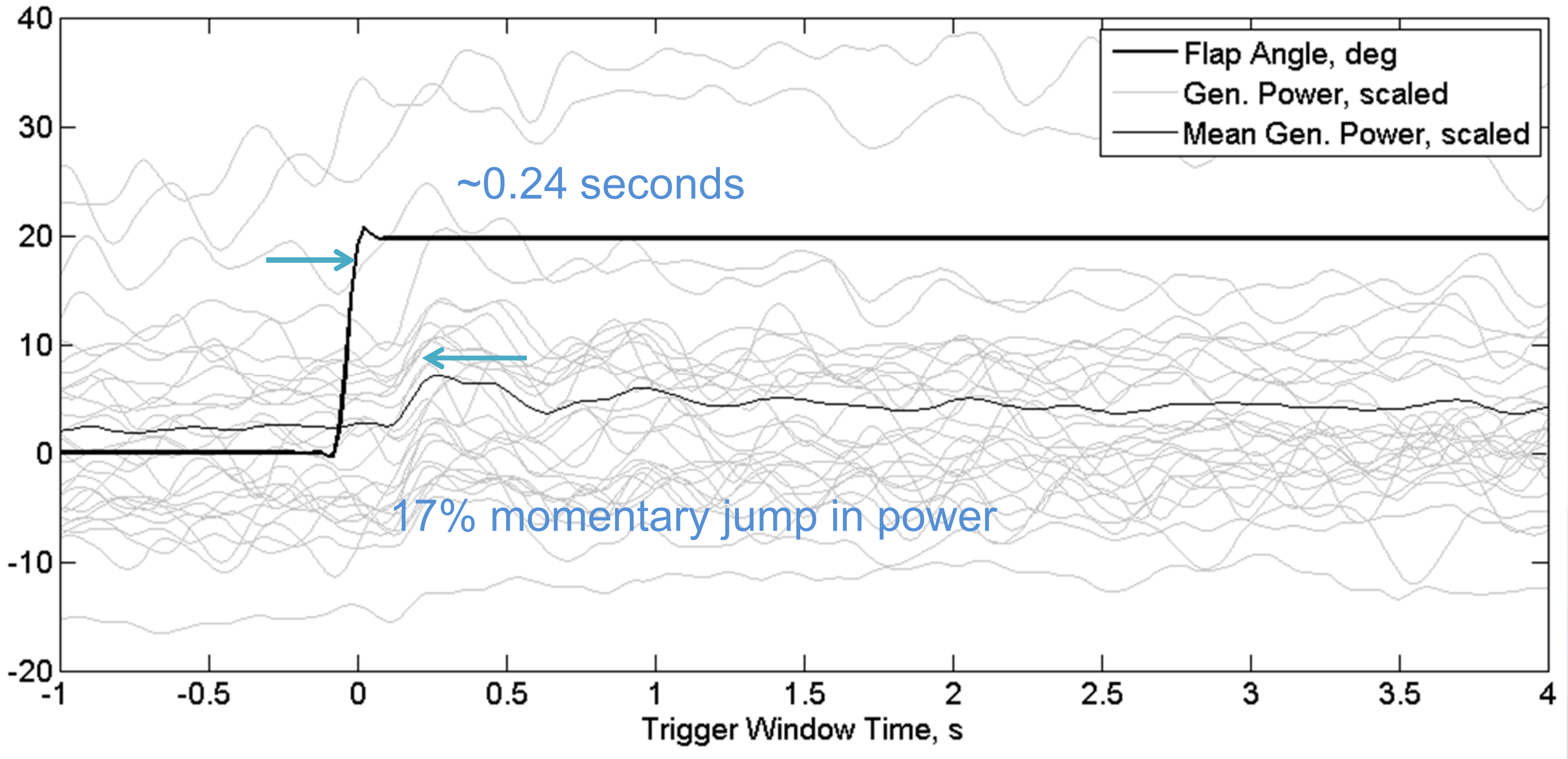
Damped free vibration theory is not strictly applicable, but provides some insight.

Peak	Maximum	Time, s		Peaks	Log Decrement	Damping Ratio	Time Difference, s	1 / ΔT, 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						

Tower Top Acceleration, Side-to-Side



Generator Power



Project Reports

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SANDIA REPORT
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Printed January 2014

SMART Wind Turbine Rotor: Design and Field Test

Jonathan C. Berg, Brian R. Resor, Joshua A. Paquette, and Jonathan R. White

Prepared by
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SMART Wind Turbine Rotor: Data Analysis and Conclusions

Jonathan C. Berg, Matthew F. Barone, and Nathanael C. Yoder

Prepared by
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